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Innovazione in azione
progetti, competenze, risorse

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title

Innovative and non-invasive industrial systems for the characterization of the damp content and the recovery of the historical walls affected by rising damp

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INTRODUCTION

Since 2017, the Italian Ministry of Education, University and Research (M.I.U.R.) has promoted the high level of training of Doctor of Philosophy who respond to the needs expressed by the national production system. Following the indications provided by the European Community through the Intelligent National Specialisation Strategies (S.N.S.I.) 2014/2020, "industrial PhD" for disciplinary fields with a strong scientific-technological vocation have been financed, with the funds of the National Operational Programmes for Research and Innovation (PON RI).

The goal of SNSI is to identify actions aimed at pursuing the social and economic progress of the Member States of the European Community, through the optimization of research in the key of innovation: *"the growth and development of a territory depends mainly on the capacity to innovate, to be increasingly "smart" and to attract and integrate skills, knowledge, needs and technologies to improve the quality of life of citizens and strengthen the competitiveness between companies."*[1]

One of the main indicators of an economic system's inclination to innovate is represented by its expenditure invested on research and development in relation to the country's Gross Domestic Product. This parameter depends on the degree of cooperation that can be established between universities and the business system.

In this context, the action I.1 of PONRI for the five-year period 2014-2020 invited universities located in some Italian regions to submit PhD projects to be carried out in partnership with a company operating on the national territory and an institution based in another country of the European Community, in order *"to qualify, in the industrial sense, the formative experiences with forecast of repercussions both on the productive systems of the territories involved in the program and on the employment, after obtaining the doctorate".*[2]

1 M.I.U.R.
Strategia nazionale di specializzazione intelligente 2014-2020

The research project presented in this thesis has been judged by the M.I.U.R. to be in accordance with the development trajectories identified by SNSI and, therefore, deserving of the award of funding for a three-year doctoral research grant.

The research, carried out at the Department of Civil, Construction and Environmental Engineering (D.I.C.E.A.) of the University of Naples Federico II, has been finalized to the experimentation of ***Innovative and non-invasive industrial systems for the characterization of the damp content and for the recovery of the historical walls affected by rising damp.***

The project was developed in partnership between the University of Naples Federico II, the Escuela Tecnica Superior de Edificacion of the Polytechnic University of Madrid and the Italian company Leonardo Solutions srl, engaged in the dehumidification of historic masonry.

The basic requirement that ensured that the project was eligible for funding was that the research topic develops one of the twelve areas of “Regional specialization areas” characterized by a strong scientific-technological vocation, identified by SNSI for the valorization of the competitive capacities of the national industrial and scientific system. The evaluation of the submitted project proposal was carried out by ANVUR, the National Agency for Evaluation of the University System and Research, using specific criteria indicators, relating to:

a. the proposed research
b. the activity to be carried out with the enterprise
c. the activity to be carried out abroad
d. the training activity to be carried out at the University
e. the contribution to the pursuit of horizontal principles

The development of the PhD project highlighted the complex articulation of industrial research in terms of the coordination of the parties involved and the influences coming from different scientific fields.

The need to achieve results with subsequent impact on the social and economic development of the country imposed, in fact, to widen the boundaries of research every time in relation to the levels of depth required by each disciplinary field involved.

2 M.I.U.R. Dipartimento per la Formazione Superiore e per la Ricerca
Decreto per la presentazione di domande di finanziamento di borse di dottorato aggiuntive rispetto a quelle già finanziate dalle Università per l’a.a. 2016/2017 – ciclo XXXII

1. THE RESEARCH PROJECT

The research fits in the twelfth area of specialization identified by SNSI relating to "Technologies for Cultural Heritage" (§ 5.3.13) and specifically concerns the industrial sphere relating to the management of historical artistic and architectural heritage, understood as the whole of *"activities dealing with the conservation, enjoyment and valorization of cultural heritage, both in its tangible dimensions and in its intangible ones"*.

Recognizing the potential value of Italian Cultural Heritage and the high skills developed over the years in the field of restoration in our country, the project has aimed to widen the field of technologies for the diagnosis and rehabilitation of the historical buildings, with particular attention to the architectural and monumental heritage.

Deepening an already well-established research strand within the DICEA, based on the study on the causes of degradation of historic buildings made with masonry structures and on recovery techniques, the project develops the topic of the rehabilitation of buildings affected by moisture from rising damp.

This pathology is one of the most frequent causes of decay which leads to a reduction in the mechanical and thermal performance of masonries. Nonetheless, scientific research and common practice are still very much linked to the adoption of traditional rehabilitation measures which have proved, over time, to have great limitations, especially for their application in the field of Cultural Heritage.

1.1 State of the art and critical issues emerged

Scientific bibliography has investigated the effects of water on building materials in terms of alteration of physical characteristics, thermal properties and mechanical resistance for the material. Many researchers had already carried out studies to assess the variation in mechanical resistance of building materials, with tests done on both natural stone (tuffs and limestone) both on artificial stone (bricks). However, no studies had been found to demonstrate the impact of the conditioning methods of the samples tested (imbibition and drying cycles) on the reduction of their mechanical performances.

Still others had identified the deviation between the energy modelling values of the building envelope and the real thermal behaviour on site due to the presence of moisture in the masonry. However, no references were found to surveys which determined the percentages of variation in these performances, in terms of increasing the thermal conductivity of materials in relation to their degree of saturation. In addition, no studies have been found investigating the thermal performance of materials with lower imbibition degrees, ranging between 15% and 30%. In these ranges, which are closer to the actual working conditions of masonry buildings, the mechanical strengths are not subject to major changes, while the thermal performance of the building envelope is already significantly altered, to the detriment of the cleanliness degree of internal environments, the level of indoor comfort and the energy expenditure of the buildings.

Regarding the state of scientific production and industrial research on the diagnosis of wet masonries, important problems have emerged on the technologies and instruments currently offered by the market. On the one hand, methods of qualitative diagnosis of the phenomenon, which make use of non-invasive investigations, are not able to provide exhaustive data on the state of saturation of masonry in all its thickness, by limiting itself to describing what happens in the first superficial centimetres; on the other hand, the more accurate methods of measurement promote the execution of invasive tests by taking samples from the investigated walls. This second approach is not applicable to buildings with historical and architectural interest for which it is necessary to limit the interpretation of the phenomenon that appears rather rough and susceptible of many variables.

Finally, with regarding to the methods of restoration of masonry affected by rising damp, the scientific references show that the application of traditional mechanical, chemical, evaporative and electrical methods (inversion of charge) is still too frequent but, at the same time, that they fail to intervene on the cause of the ascent and are often rather invasive to be applied in the context of Cultural Heritage.

1.2 EXPECTED GOALS AND INNOVATION FEATURES

On the basis of the critical issues arising from the study of the state of the art and through the partnership with the company Leonardo Solutions srl, creator of a modern

Charge Neutralization Technology (CNT) able to conditioning the electrical behaviour of water and to affect the phenomenon of the rising damp in a non-invasive way, the research wanted to pursue **Three main goals**:

1. **To quantify the variation in the performance of building materials** subjected to different degrees of imbibition;
2. **To test new systems for the diagnosis** of the phenomenon aimed at classifying the conservation status of masonries and the ongoing monitoring of the rehabilitation systems adopted;
3. **To verify the effectiveness of the Charge Neutralization Technology** in interrupting the dynamics of the capillary ascent in a non-invasive way, applicable therefore in the context of Cultural Heritage.

These objectives have been pursued by developing **3 ELEMENTS OF ORIGINALITY**:

A **first innovative element**, related to the first goal, has been investigated through the development of experimental surveys to verify two interesting parameters:

- The influence that the method of conditioning the test samples has on the variation of the mechanical strengths of the materials under dry, semi-saturated and saturated conditions;
- The variation of the thermal performance of the materials relating to the saturation degree, considering also the level of imbibition closer to the real conditions of the masonries in situ.

With regard to the testing of devices for the diagnosis of moisture and the ongoing monitoring of the rehabilitation systems adopted, the research aimed to develop a **second innovative element**: starting from analysing how the IDROSCAN probe works, that is produced by Leonardo Solution as a tool to estimate the drying times of a masonry subject to the action of the CNT, an experiment has been developed with the aim to relate the measurements provided by the device with the saturation range of the masonry and to define, in this way, its conservation status. The probe, in this mind, has been used not as a tool of simple estimation of the times of intervention but as an instrument to achieve a direct and non-invasive diagnosis.

Finally, regarding the methods of recovery of masonries affected by rising damp, having highlighted the limits of traditional intervention methods in the context of Cultural Heritage and recognizing that the CNT provides several innovative elements that overcome the criticalities of other methods, the research aimed at developing an experimental survey to verify its performance. This test was carried out by developing alongside three on site trials of the CNT device system and a large data collection about the installations already carried out and monitored by the Leonardo Solutions throughout the national territory. The processing of the collected data has allowed to build a *case history* useful to verify the durability of the interventions and to determine the parameters to be investigated for the performance verification of devices and methods for the restoration of the wet masonry. To date, there are no certification protocols and testing of these methods and, therefore, the performance audit sheet represents a **third innovative element** aimed at developing good practices for the design of the rehabilitation interventions, their monitoring over the time and their final testing.

1.3 RESEARCH STRUCTURE

In order to achieve the identified goals, the research was developed by providing, in addition to a bibliographic and documentary study of the state of the art, the execution of direct tests on materials and devices, carried out partly in the laboratory and partly on site (Fig. 1.1):

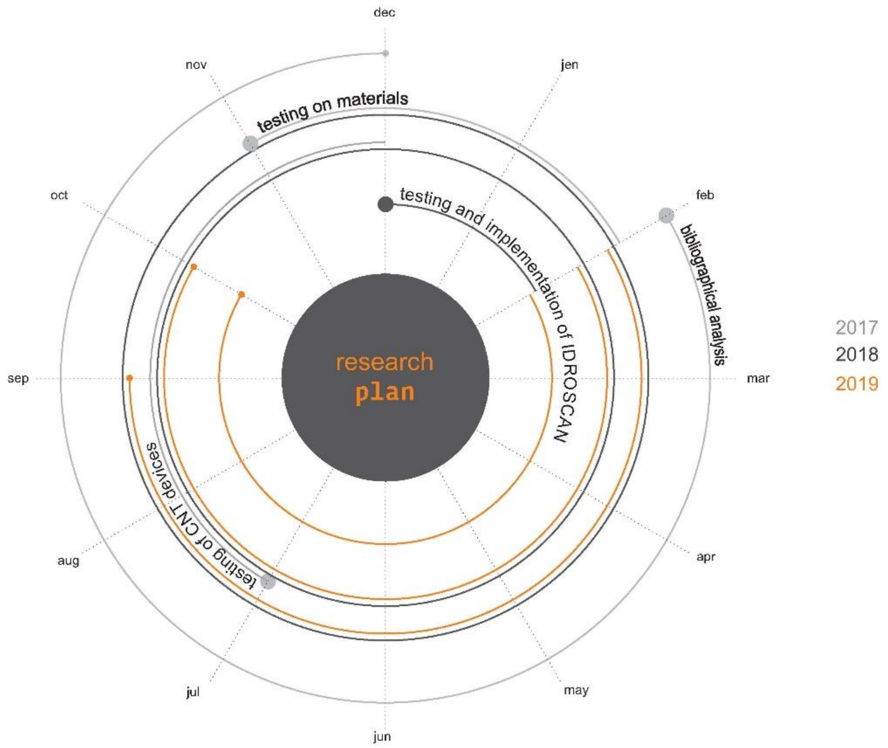


Fig. 1.1 - Research plan

The project has been divided into:

- a phase of **bibliographical analysis** and document investigation;
- a phase of **testing on materials**;
- a phase of **testing and implementation of the IDROSCAN probe** as an innovative and non-invasive industrial tool for the characterization of the wet content;
- a phase of **testing and performance verification of CNT devices** for the rehabilitation of wet masonries.

The phase of **bibliographic analysis** and documentary investigation, developed through the critical consulting of national and international scientific references, provided a study on the themes of: rising damp; the effects that this phenomenon has on building materials; traditional interventions for the recovery and their effectiveness; technologies for the diagnosis and measurement of the moisture content inside the historic walls; the relevant European and national standards.

For further details of the studies carried out, see Chapter 2.

The phase of **testing on materials** has required a preliminary deepening on the typical materials used in the local construction in Madrid and Naples. Having thus determined the recurrent products in the two construction traditions, laboratory tests were carried out to assess the variation in their mechanical and thermal performance in relation to the degree of saturation, as well as the impact of conditioning methods on the samples tested. The tests were then made on bricks, a material strongly recurrent in the architectural culture of Madrid, and on the yellow tuff of Naples, a typical stone of the Campania building tradition.

The selection of the bricks to be used for the test, made directly a one of the most popular factory that produces bricks for the restoration of the historical buildings of Madrid, and the deepening about their manufacturing process, were carried out under the supervision of Professor Marina Fumo of the DICEA of the University of Naples Federico II.

The tests on bricks were conducted at the Polytechnic University of Madrid, in synergy with the Laboratory of “Tecnología Edificatoria y Medio Ambiente” coordinated by Professor Mercedes del Rìo Merino; the tests on Neapolitan yellow tuff, instead, were conducted in the Geotechnical Laboratory of DICEA, in collaboration with Professor Massimo Ramondini.

The test methodology and the results obtained are better described in Chapter 4.

The **testing phase of innovative and non-invasive industrialised systems for the characterisation of wet content**, required a preliminary study about how the IDROSCAN probe works, made during the research period carried out at the head office of the industrial partner Leonardo Solutions srl, in collaboration with the tutor Engineer Michele Rossetto.

Basing on this knowledge, an experimental programme has been developed to relate the values recorded by the probe to the known wet contents of a sample with different degrees of saturation. The instrument response curve thus obtained was intersected with the trial and bibliographical reference data, identifying ranges that describe the conservation status of the masonry; the “diagnosis ranges” provide the opportunity to convert the measurements that the probe makes simply touching the masonry into saturation values and, therefore, to use the device as a quantitative, instantaneous and non-invasive diagnostic tool.

This test, better described in chapter 5, has been also developed at the Geotechnical Laboratory of DICEA.

Finally, the **performance testing of CNT devices** was developed in two subsequent moments. The first, carried out in collaboration with the company partner, provided for a collection of data from installations made throughout the country. It was therefore possible to catalogue the interventions identifying the study cases that are most relevant to the research topics in relation to the historical and architectural value of the buildings and to the conditions of the site. The cataloguing is merged into the processing of a “case history”.

Relating to the analyses carried out, three new sites were selected to promote the verification of this Technology by installing the integrated system consisting of CNT devices, IDROSCAN probes and UR-T sensors. The test, which provided for collaboration with public and private insitutions in Italy and Spain, has been carried out:

- at E.T.S. de Ingenieros de Minas y Energía of the Universidad Politecnica de Madrid, thanks to the collaboration with Director of the School Dr José Luis Parra;
- at the Cuartel el Conde Duque, thanks to the collaboration agreement with the Departamento de Patrimonio Histórico, Ayuntamiento de Madrid, represented by the Architect María José Rodriguez Relaño;
- at the Crypt of the Pontifical Basilica of Pompeii, through an agreement concluded with the Pontifical Shrine of the Beata Maria Vergine del S. Rosario.

The operation of the devices has been monitored over 18 months by verifying the progress of the drying process of the masonries under the action of the CNT, both with qualitative tests (comparison of thermographic images) either by quantitative measurements of wet contents (weighting tests). The latter were carried out at the Laboratory of the Department of Chemical Engineering, Materials and Industrial Production of the University of Naples Federico II, in collaboration with Professor Fabio Iucolano.

All the phases of research, design and application of trial plans, in Italy and abroad, have been developed with the supervision of Professor Roberto Castelluccio, teacher at the DICEA of Federico II and tutor of the doctorate in Civil Systems Engineering.

The results of this research have been presented in various national and international conferences and published in the related Proceedings, quoted in the chapter PERSONAL BIBLIOGRAPHICAL REFERENCES. Among the others:

- the monograph entitled *“The renovation of the walls affected by moisture from capillary rise. The CNT method”* (V. Vitiello and R. Castelluccio, 2019), published by Luciano Editore, which was presented in Matera in April 2019 during the international conference specially organized on the topic of rising damp. The event involved the participation of public and private institutions (6 Universities, 5 Ministries, 5 Provincial Professional Orders) engaged in the theme of the rehabilitation of wet walls, with interests of scientific, industrial, academic and professional research;

- the article entitled *“Experimental research to evaluate the percentage change of thermal and mechanical performances of bricks in historical buildings due to moisture”* (V. Vitiello, R. Castelluccio and M. Del Rio Merino), accepted and publishing by the Journal Construction and Building Materials.

2. RISING DAMP: FROM DIAGNOSIS TO RECOVERY PROJECT[1]

Rising damp is one of the most frequent and widespread causes of degradation of the historical buildings.

The phenomenon is activated due to the capability of porous building materials to absorb, with only contact, the water from the foundation soils and to allow its migration within the entire masonry structure. In its ascent, the fluid progressively occupies the volume of the capillary ducts and reaches the high sections then, under a difference of pressure and temperature with the external environment, moves on the free surface of the wall and evaporates to the outside. Without the aqueous solution, the salts contained in it crystallize by increasing in volume; this results in stresses that produce swelling, detachments and degradation phenomena at the evaporation section, that can be superficial (plaster) or internal (masonry). (Fig. 2.1)

Fig. 2.1 - Surface degradation phenomenon at hygroscopic salt deposits

The presence of moisture determines, on the architectural scale, the activation of degradation processes that modify, in different features, the characteristics and properties of the building materials. When this happens to a small extent, it is also possible to intervene with light-type remediation methods; however, sometimes the effects of the disease can compromise the static resistance of the structures or cause the irreversible loss of material. In the context of architecture with particular historical and architectural value, the

1 V. Vitiello and R. Castelluccio
Il risanamento delle murature affette da umidità da risalita capillare. Il metodo CNT

phenomenon can represent a factor of strong vulnerability for the preservation of the artistic and documentary value of parts of the building.

In order to understand the forces that rule the dynamics of the capillary ascent, it is necessary to undertake the study from the microscopic scale, analysing the movement of the water inside the very small capillary ducts of the building materials. Depending on the type of material, the microcrystalline structure and the physical and electrical properties that determine its interaction with water, it is possible to define the greater or lesser aptitude of the entire masonry texture to allow or hinder the achievement of high heights of the damp front and to trigger processes of degradation for the building materials.

2.1 Physical phenomenon and maximum raising height

The dynamic of the rising damp is the result of the complex interaction of physical, chemical and electrical forces acting on the masonry-water system[2]. The characteristic that most affects the activation of the phenomenon is the porosity ***n*** of stone materials, natural or artificial, expressed as the ratio between the volume of voids and the total volume (Eq. 2.1):

$$n = \frac{V_v}{V}$$

Eq. 2.1

n	porosity
V	total volume
V_v	volume of voids

Therefore, the presence of voids connected to each other forming a capillary system, defines the propensity of a material to absorb water and to transport it upwards. This movement depends substantially on two factors: the *capillarity* and the *electro-capillarity* (or *electrophysical attraction*).

Capillarity is a physical phenomenon that describes the ability of a liquid to move within a capillary tube by opposing the natural action of gravity force.

Without external forces, the molecules of a liquid are held together by cohesive forces by means of which they can move within it without ever dispersing (Brown, 1827). On a molecule surrounded by other molecules the result of the cohesive forces is zero, while, near

2 Z. Zhang
A review of rising damp in masonry buildings

the free surface, the molecules are subject only to the forces exerted by the underlying or lateral molecules and therefore attracted towards the inner liquid.

For this reason, although they have not an own shape, liquids tend to assume the geometry of a sphere; this property is called *surface tension* τ (Fig. 2.2).

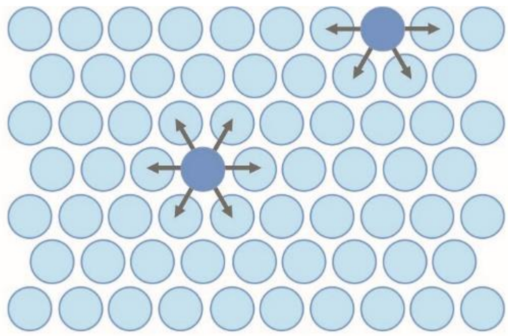


Fig. 2.2 – Adhesion forces between the fluid molecules

When the liquid is inside a capillary tube, that may be presented as a hollow cylindrical container, the forces of cohesion linked to the surface tension are opposed by the adhesion forces that the walls of the tube exert on the lateral surface of the liquid; this ability of the fluid to maintain contact with a solid wall is called *wetting*. If the forces of cohesion prevail over the forces of adhesion of the walls, the curve of the free surface of the water, defined *meniscus*, is convex and the liquid tends to descend; vice versa, if the forces of adhesion of the walls prevail over the forces of cohesion, the curvature of the meniscus is concave and the liquid tends to rise to a higher altitude than that reached by the effect of the pressure alone. (Fig. 2.3)

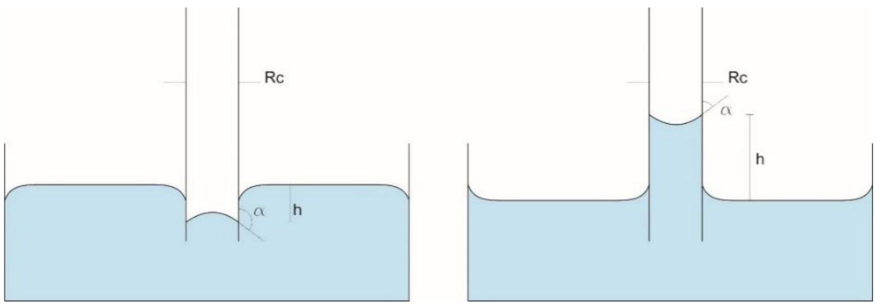


Fig. 2.3 – (Left) convex meniscus – (Right) concave meniscus

The ascent height inside the capillary tube can be calculated by setting the *Law of Jurin* expressed by the Eq. 2.2:

$$h = \frac{2\tau\ cos\alpha}{\rho g\ R_c}$$

Eq. 2.2

h height from the free surface
τ superficial tension
α angle between meniscus and tube walls (wettable)
ρ liquid density
g gravitational acceleration
R_c radius of the capillary tube

The expression indicates that the maximum rise is directly proportional to the value of the surface tension and is inversely proportional to the size of the tube.

The second parameter that affects the dynamics of the ascent concerns the **electro-capillarity**, that is the electrophysical attraction that is generated between the walls of the capillary pores and the molecules of water depending on the chemical nature of the substances involved.

Construction materials are generally rich in Silica, a semi-metal semiconductor second only to oxygen for abundance in the Earth's crust and, therefore, present both in natural stones and in the clay, which is the main component of artificial stone materials. The isotope of Silica makes the wall capillaries behaving as an electrified surface. The water, under the action of the electrical potential produced, behaves like an ionic solution in a condition of non-equilibrium, directing the molecules with the positive pole towards the walls of the capillaries, negatively charged, and forming with them ionic bonds. The distribution of the charges at the interface between solid and fluid can therefore be outlined using the model of the *double layer of Helmholtz* (Fig. 2.4).

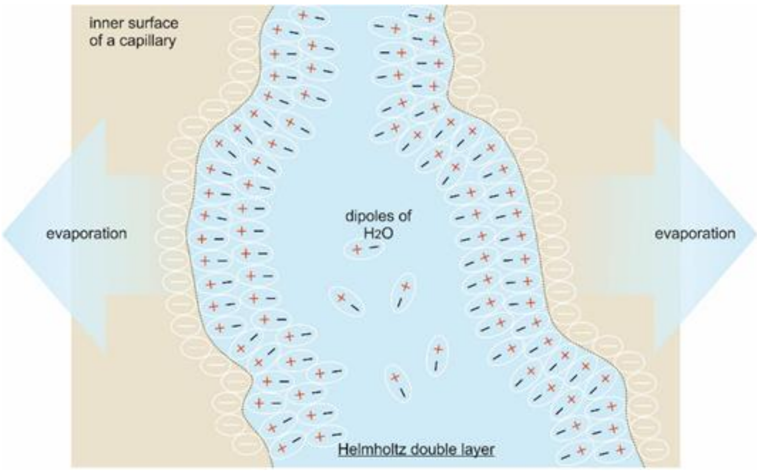


Fig. 2.4 – Helmholtz double layer model

The migration of the water and the natural evaporation produce the movement of the double layer of Helmholtz, from which a difference of electrical potential is generated that feeds the ascent of the water inside the masonry, with variable intensity from 10÷20 mV (in case of weak or absent ascent) up to 300÷500 mV (in case of strong ascent).

THE MAXIMUM RAISING HEIGHT

The theoretical limit of the **damp front**, that is the maximum rise height of the water inside a capillary system, is defined by the equilibrium of all the forces acting on the masonry-water system: some of them promote the ascent others, instead, as the gravitational force and viscosity of the fluid, hinder it.

As a result of viscosity, the average flow rate of a real fluid inside a cylindrical duct, in a laminar mode, is greatly reduced, as described by the *Hagen-Poiseuille Law* (Eq. 2.3):

$$vm = \frac{\mathrm{R}^2\,\Delta\mathrm{p}}{8\,\eta\,\mathrm{l}}$$

Eq. 2.3

- R radius of the duct
- $\Delta\mathrm{p}$ difference of pressure between the ends of the pipe
- η fluid viscosity
- l length of duct

At the macroscopic scale, the maximum height of the damp front in a wall subjected to the phenomenon of rising damp is strongly influenced also by the evaporative component. The relationship between these two factors is described by the model of *Sharp Front Theory*[3] designed by the researchers Christopher Hall and William D. Hoff.

The theory assumes that the phenomenon of ascent is the result of an equilibrium between the amount of water absorbed from the foundation soil ***U*** and the amount of water evaporating through the free surface ***E*** (Fig. 2.5).

3 C. Hall and W.D. Hoff
Rising damp: capillary rise dynamics in walls

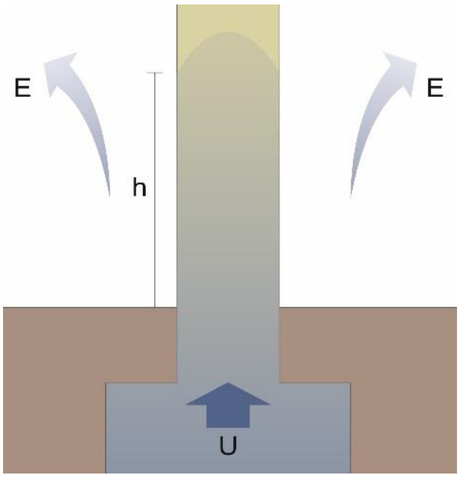


Fig. 2.5 - Schematizzazione della dinamica di risalita ed evaporazione

Expressing with ***i*** the amount of water absorbed in a masonry section of thickness ***b***, which is a function of the degree of absorption of the stone material ***S*** and the time elapsed ***t***, the relation is (Eq. 2.4):

$$U = \mathrm{b}\,\frac{di}{dt}$$

Eq. 2.4

Imposing the equality between the factor $\boldsymbol{i} = \mathbf{S}\,\mathbf{t}^{\mathbf{1/2}}$, which describes the amount of water absorbed in time ***t*** by a masonry section, and the factor $\boldsymbol{i} = \boldsymbol{\theta_w}\,\boldsymbol{h}$, which represents the quantity of water present overall up to the maximum ascent height, the relation is (Eq. 2.5):

$$h = \frac{b\,S^2}{2\,\theta_w\,h}$$

Eq. 2.5

S absorption degree
t elapsed time
θ_w content of water in the wet wall
h maximum ascent height
b wall thickness

The amount of water evaporated, on the other hand, depends only on the ascent height ***h*** and evaporation rate ***e***, which varies according to the environmental parameters (Eq. 2.6):

$$E = \mathrm{e\,h}$$

Eq. 2.6

The relation gives (Eq. 2.7):

$$h = S \left(\frac{b}{2\ e\ \theta w}\right)^{1/2}$$

Eq. 2.7

The equation shows the inverse proportionality between the evaporative phenomenon and the ascent height. The contribution of parameter ***b*** in the mathematical relationship confirms that the disposal of the damp content from the interior of the masonry to the external environment takes place to a greater extent in the case of low thickness masonries.

The theoretical model described deviates from the actual behaviour of masonry due to the change in the absorption value of the different rows and of the mortar layers, which may be more or less absorbent if they are made with lime or cement.

2.2 EFFECTS OF MOISTURE ON MATERIALS AND BUILDINGS

The most evident demonstration of the presence of moisture in the masonry is given by the formation of saline efflorescence and mould, the crystallization of the salts after evaporation and the consequent spraying and loss of material. The effects of moisture on the decay of mechanical and thermal performance of masonry are less evident at the visual inspection but considerably more damaging.

EFFECTS OF MOISTURE ON THE MECHANICAL PROPERTIES OF MASONRIES

The masonry can be outlined as a heterogeneous material composed of natural stone ashes or artificial bricks lodged with mortar, defined anisotropic for resistance and deformability. Its mechanical characteristics depend on the constituent elements and the direction of load application. In order to assess the impact of the presence of moisture on the reduction of mechanical performance, it is necessary to define how the standards require that it must be determined.

The Technical Standards for Construction (NTC) of 2018 classify the mechanical behaviour of masonry relating to:

- the **characteristic compression strength f_k**, that is the nominal value of the tension that produces the breaking under simple compression[4];

4 UNI EN 1052-1:2001
Metodi di prova per murature. Determinazione della resistenza a compressione

- the **shear strength without axial action f_{vk0}**, that is the nominal value of the tension that produces the breaking under simple shear, without normal stress[5];
- the ***normal modulus of secant elasticity E***, that represents the deformation behaviour of the material.

The UNI EN 772-1 standard takes into account the influence of moisture on the variation of the mechanical performance of the building materials and, therefore, it establishes to correct the values of the compressive strengths of tested materials by applying different coefficients depending on the conditioning state of the wet content (§ 7.3):

- 1.0 in the case of air drying or with a water content of 6%;
- 0.8 in the case of drying in the oven;
- 1.2 in the case of complete immersion conditioning.

Therefore, in the case of a saturated masonry, a reduction in compressive strength of 20% is estimated compared to the resistance in dry conditions.

Considering that the properties describing the mechanical behaviour of a masonry are mainly influenced by the strength values of the constituent stone elements, several tests have been developed to investigate the change in mechanical behaviour of building materials containing different moisture quantities. The results of this research have shown that the presence of moisture leads to a greater reduction in mechanical performance than expected by the standard [6,7].

The laboratory surveys conducted by the researchers of the University of Sannio and the University of Naples Federico II[8] have shown that the mechanical performances of stones undergo a sharp reduction corresponding to the degree of saturation increase. The tests were carried out on seven different types of tuff taken from different quarries: Neapolitan

5 UNI EN 052-3:2003
Metodi di prova per murature. Parte 3: Determinazione della resistenza iniziale a taglio

6 A. B. Hawkins and B. J. McConnell
Sensitivity of sandstone strength and deformability to changes in moisture content.

7 Z.A. Erguler, R. Ulusay
Water-induced variations in mechanical properties of clay-bearing rocks.

8 R. Ceroni, M. Pece, G. Manfredi, G. Marcari, S. Voto
Analisi e caratterizzazione meccanica di murature di tufo

yellow tuff, Campania grey tuff, Puglia white tuff, light and dark tuff of Rome, light and dark tuff of Viterbo. The cube samples with 100 mm side were first dried (saturation conditions S=0) and then subjected to single axial compression with application of the load controlling the related deformations, according to UNI 9724-3[9] standard. The types of Neapolitan yellow tuff and the Campania grey tuff have been tested also under conditions of complete saturation (S=1) and saturation at 50% (S=0.5).

The results of the tests showed a reduction in the mean compressive strength which, under saturated and semi-saturated conditions, reached a value 40% lower than the resistance of the samples tested under dry conditions. (Fig. 2.6)

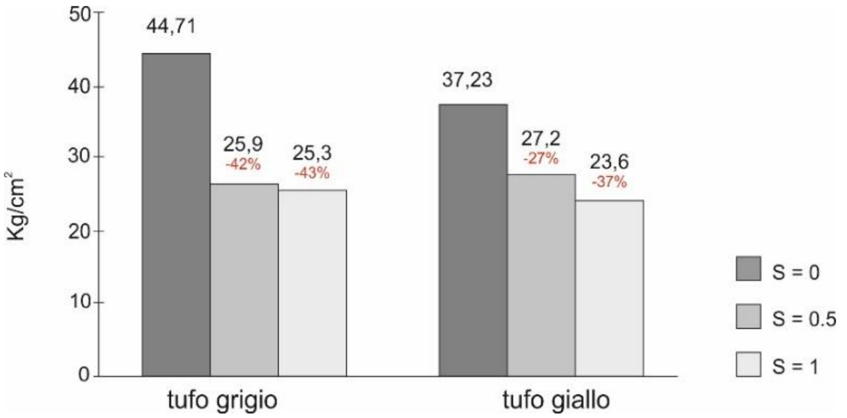
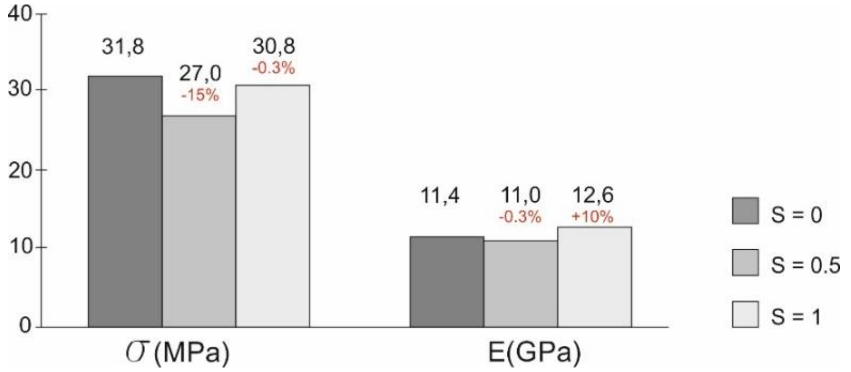


Fig. 2.6 - Valutazione della resistenza meccanica del tufo con diversi gradi di saturazione

Similar tests have been done by researchers at the University of Bologna[10] on brick bricks; in this case both individual elements and samples of wall have been tested under dry and wet conditions, packed with lime-based mortar and cement mortar. (Fig. 2.7)



9 UNI 9724-3:1990
Materiali lapidei. Determinazione della resistenza a compressione semplice

10 E. Franzoni, C. Gentilini, G. Graziani and S. Bandini
Compressive behaviour of brick masonry triplets in wet and dry conditions

Fig. 2.7 - Evaluation of mechanical strength and Young's Module in bricks with different degrees of saturation

Once again, there was a reduction in the compressive strength of the bricks in saturated conditions, even if less than what had been achieved in the tests made on tuff.

Therefore, it is possible to conclude that the presence of moisture leads to a reduction in the mechanical characteristics of masonry which, to a different extent, may affect the static safety of buildings.

EFFECTS OF MOISTURE ON THE THERMAL PROPERTIES OF MASONRIES

In addition to the mechanical performance of the building materials, the presence of water also negatively affects the reduction of thermal performance and, therefore, the ability to contain the transmission of heat flows through the entire building envelope. It has been shown that even small damp contents can have a great impact on two specific properties of materials: *thermal expansion* and *thermal conductivity*.

Thermal expansion $\boldsymbol{\varepsilon_i}$ represents the capacity of a material to increase its volume with the increase in temperature, according to the proportion (Eq. 2.8):

$$\varepsilon_i = \alpha_i \, \Delta T$$

Eq. 2.8

α_i thermal expansion coefficient [°C^{-1}]
ΔT difference between the initial and the final temperature $(T - T_0)$

This property can be quantified by the *specific heat* (of the solid part of the material, of the air contained in its voids and of the water when the material is soaked) which represents the amount of energy needed to increase in 1°C the temperature of a mass of 1 kg under constant pressure conditions [J Kg^{-1} K^{-1}].

Thermal conductivity $\boldsymbol{\lambda}$, expressed in [W m^{-1} K^{-1}], represents, instead, the aptitude of a material to transmit heat and can be calculated by the equation (Eq. 2.9):

$$\lambda(T) = \rho(T) \cdot c_p(T) \cdot a(T)$$

Eq. 2.9

ρ material density
c_p specific heat

a thermal diffusion, specific property of the material describing how quickly it reacts to a temperature change

The heat flow ***J*** passing through the wall thickness is proportional to the temperature gradient (the derivative of the temperature related to the length crossed) and can be expressed with the relation (Eq. 2.10):

$$J = -\lambda \frac{dT}{dx}$$

Eq. 2.10

The heat flow through a unit surface subjected to a temperature difference of 1°C is defined as **transmittance U**, expressed in [W m^{-2} K^{-1}]. The transmittance of a constructive element is linked to the conductivity of the various layers through the relation expressed by Eq. 2.11:

$$U = \frac{1}{\Sigma R_i} \qquad dove \qquad R_i = \frac{d_i}{\lambda_i}$$

Eq. 2.11

R_i thermal resistance of each layer (tanning, insulator, plaster, etc.)
d_i thickness of each layer
λ_i thermal conductivity of each layer

The calculation of the transmittance of the building envelope can be done by applying the indications provided by UNI EN ISO 6946[11] for opaque components and UNI EN ISO 6946[12] for transparent components and fixtures.

The current standards about the control of energy consumption, which are subject to the so-called “Decree of Minimum Requirements”[13], stipulate that every technological element of the building envelope must comply with certain limit values of transmittance. However, the determination of the real energy behaviour of the wall coverings is not immediate, also due to the presence of moisture which alters the physical characteristics and thermal performance of the building materials.

11 UNI EN ISO 6946:2018
Componenti ed elementi per edilizia - Resistenza termica e trasmittanza termica - Metodi di calcolo

12 UNI EN ISO 10077:2018.
Prestazione termica di finestre, porte e chiusure oscuranti - Calcolo della trasmittanza termica

13 Decreto interministeriale n.39 del 2015. Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici"

In the 90s, some researchers of the Colegio Universitario CEU-Arquitectura of the Polytechnic University of Madrid [14] conducted a study to assess the capability of clay materials to expand for moisture. The survey was carried out on 18 test specimens with different conditions of steam absorption and showed that Madrilenian clay can have an expansion near to 0,6mm/m due to the presence of water. About 30% of this deformation take place during the first week after the manufacturing of the wall.

The mathematical description of the material expansion phenomenon as a function of the clay firing time is provided by the *Power-Law of Moisture Expansion Kinetics*[15] elaborated by the researchers C. Hall and W.D. Hoff (Eq. 2.12):

$$\varepsilon = \mathrm{b} + \mathrm{a}\, t^{1/4}$$

Eq. 2.12

- ε expansion tension to moisture
- t firing time
- b constant that describes the expansion that takes place immediately after cooking and that stabilizes in a few days
- a property of the material describing the progressive expansion in the long-term defined as ***moisture expansivity***

The first component of the process, related to the expansion during the short period **b**, occurs in a very short time and, depending on the environmental hygrometric conditions, may be reversible; the parameter $\mathbf{a}\, \boldsymbol{t^{1/4}}$ describes, instead, the expansion that takes place during the long period due to the chemical reaction between the clay and the moisture and that can be reversed only by baking the material at 500°C. Expressing the *expansivity moisture* of the material in [years$^{-1/4}$], the component $\boldsymbol{t^{1/4}}$ defines the expansion reached in one year.

Relating the relation to the parameter $\boldsymbol{a}$ and placing $\boldsymbol{\varepsilon} - \mathbf{b} = \boldsymbol{\varepsilon_2} = \mathbf{a}\, \boldsymbol{t^{1/4}}$, the researchers extracted the linear law that allows to evaluate the expansion of the material depending on the thermo-hygrometric conditions (Fig. 2.8).

14 F.D.I. Gordejuela
Expansíon por la humedad de productos cerámicos españoles: revision de la normative

15 C. Hall and W.D. Hoff
Moisture Expansivity of Fired-Clay Ceramics.

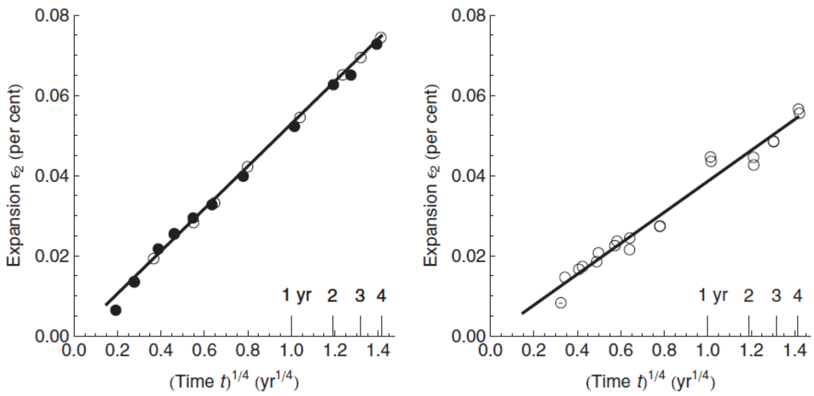


Fig. 2.8 - Expansion curves over 4 years;

(left) in a controlled environment at 18°C and 75% RH, (right) in natural environmental conditions[16]

Finally, the presence of moisture also has a considerable effect on the thermal inertia of building materials and consequently on the energy performance of the stone components of the building envelope, recording a reduction in indoor comfort.

When the water, that is a good heat conductor, comes into contact with the building materials tends to penetrate their internal porous structure, occupying the voids and replacing the still air, which participates predominantly to the contribution of the thermal inertia of the materials.

This condition results in greater energy expenditure due to heat loss and alters the theoretical values used for calculating the thermal performance of the envelope and for the design of plant and technology efficiency systems.

The energy analysis of existing buildings, carried out in the numerous studies[17, 18, 19, 20], including those conducted by the University of Rome TRE[21] and the Universitat Politècnica

16 C. Hall and W.D. Hoff
Moisture Expansivity of Fired-Clay Ceramics.

17 A. Foucquier, S. Robert, F. Suard, L. Stephan, A. Jay
State of the art in building modelling and energy performances prediction: a review.

18 P. Baker
U-Values and Traditional Buildings. In Situ Measurements and Their Comparison to Calculated Values.

19 L. Kosmina. *In-situ measurement of U-value*

20 S. Doran. *Field Investigations of the thermal performance of construction elements as built*

21 L. Evangelisti, C. Guattari, P. Gori and R. De Lieto Vollaro
In situ thermal transmittance measurements for investigating differences between wall models and actual…..

de Catalunya Barcelona [22], evidenced a strong discrepancy between the theoretical performances, drawn from accurate models of buildings in their working conditions, and the real behaviour of the technological elements detected *in situ*.

Scientists at the University of Salford[23] in the United Kingdom found that, sometimes, the difference between the project values and those recorded on site, defined ***prediction gap***, exceeds of 18%; this discrepancy, due to the extreme variability of the permeability to air parameters of the building envelope and to the moisture inside the walls, results in a substantial difference between the theoretical consumption of the building and the real ones.

It is possible to conclude that moisture causes a substantial change in the static and energy behaviour of masonry, affecting structural safety and environmental welfare parameters. Therefore, it is essential that the planning of an intervention of recovery, consolidation or thermal efficiency, considers the correct characterization of the materials and their state of preservation obtained through an in-depth diagnosis of the masonry and of the materials which it is made with.

2.3 DIAGNOSIS METHODS: EFFECTIVENESS AND INTERFERENCE WITH CULTURAL HERITAGE

Bibliographic studies have widely demonstrated that the presence of water inside the walls, as well as being seriously damaging to the building elements, represents a factor of high vulnerability for human health. The Ministry of Health, in fact, classifies moisture in masonry as one of the main pollutants of indoor air due to: the reduction of thermal insulation; the degradation of materials; the creation of moulds in environments humid with poor ventilation.[24]

The analogy between the human organism and the building organism leads to consider the moisture as a real pathology, whose healing can be achieved only through a methodological approach similar to that adopted in the context of interventions for recovery, restoration and

22 K. Gaspar, M. Casals and M. Gangolells
A comparison of standardized calculation methods for in situ measurements of facades U-value.

23 A. Marshall, R. Fittonb, W. Swanb, D. Farmerc, D. Johnstonc, M. Benjaberb, Y. Ji
Domestic building fabric performance: closing the gap between thein situ measured and modelled performance

24 Opuscolo Ministero della Salute: Umidità e muffe

consolidation of the building heritage, to be developed through a systematic set of operations, including:

- A first **phase of diagnosis**, in which it is necessary to define the type of moisture and classify the degree of imbibition of the walls, in order to determine their state of preservation or the alteration of the finishes;
- The development of a **project phase**, based on the criteria of minimum intervention, environmental and material compatibility and the use of technologies and products certified and/or validated by independent research institutions.
- A **monitoring and testing plan** for the operation carried out, the effectiveness of which can only be evaluated over time.

TIPI DI UMIDITÀ

Among the preparatory operations for the diagnosis of wet masonry there is the determination of the type of moisture, which is a function of the cause of the ingress of water into the wall structure (Fig. 2.9).

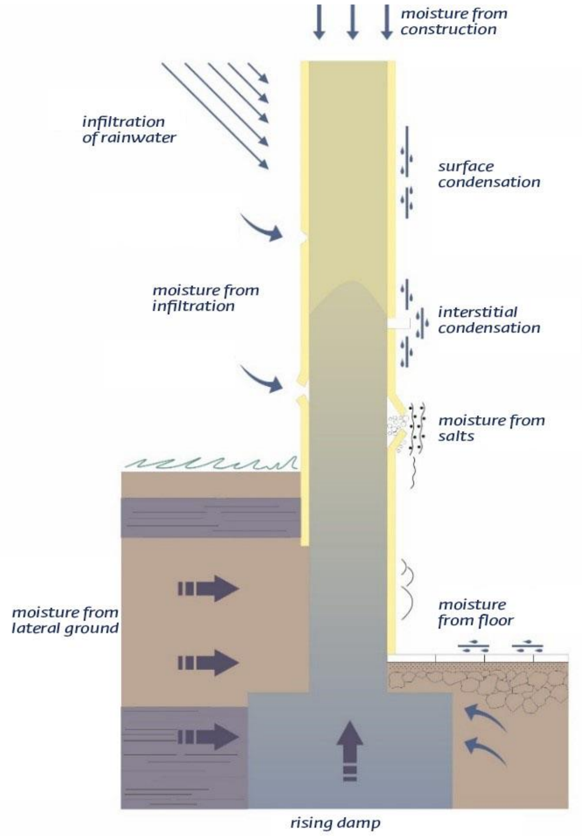


Fig. 2.9 - Causes of moisture formation

Relating to the cause that originates the pathology four types of moisture can be distinguished:

Moisture from construction develops due to the presence of a water content in the materials after their manufacturing, that is manifested shortly after the completion of the construction in the form of concentrated and irregular stains which, after a period, tend to decrease. Disease elimination interventions essentially consist of creating the environmental conditions conducive to the natural or forced evaporation of the excess water present.

The **moisture from infiltration** originates by the penetration, inside the building elements, of water from the outside. The causes of the disease are generally due to *accidental infiltrations,* due to technological-construction defects, to the break of the building's plants, *or to infiltrations of rainwater*, as consequence of the degradation of the protective layers (plasters, waterproofing…). In both cases, the remediation measures consist in eliminating the cause, either by repairing the failure of the malfunctioning plants (in case of accidental infiltration) or by sealing the surface protection layers (in case of infiltration by rainwater).

To this family also belong the phenomena of damp from counterthrust, determined from the wet soils that "push" the water inside the retaining walls for the hydrostatic overpressure.

The **moisture from condensation** is originated from the passage of state from Vapour to Liquid of the water contained in the air, due to the thermo-hygrometric and pressure factors, described by the law represented in the abacus of Mollier. The phenomena of condensation can occur both on the external surface of the walls (surface condensation) and in the internal thickness (interstitial condensation). The measures needed to eliminate this pathology must aim to: balance the vapour content of ambient water; regulate the heat flows through the walls; contain surface temperatures, in order to prevent the attainment of critical thermo-hygrometric condensation conditions. They consist in ensuring the correct level of thermal insulation, replacement of air, air conditioning and dehumidification of the rooms, depending on external climatic conditions, of the use of indoor environments and of what else affects environmental parameters.

The last type of humidity concerns the phenomenon of the **rising damp**, which dynamics and acting forces have already been widely described. The dissertation about the consolidation measures is included in the paragraph 2.4.

The diagnostic phase is therefore based on a set of visual and instrumental analyses that allow to classify the type of moisture and to measure its characteristic parameters; between these analyses, the distribution of the wet content concentration allows to determine, with greater certainty, the origin and the type of pathology (Fig. 2.10).

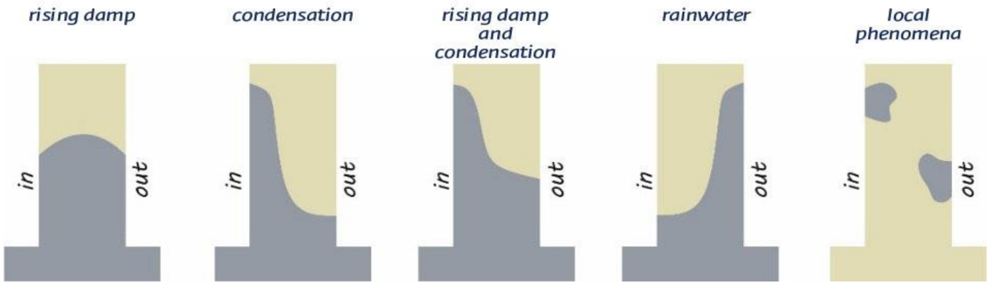


Fig. 2.10 - Trend in the concentration of wet content and type of moisture

QUALITATIVE AND NON-INVASIVE METHODS FOR DIAGNOSIS

The diagnosis of moisture phenomena requires, first of all, a visual investigation and a graphical and photographic survey of the places, aimed at the localization of degradation phenomena. The capillary ascent, for example, is manifested with a distribution of the humid contents rather evident in correspondence of the basal areas of the walls, with development seamless and decreasing in height. The maximum ascent height is signed by an area where the deposition of salts is highlighted, while in the lower areas there are detachments and swelling of the finishing layers.

The visual investigation of the pathology can be completed by means of non-invasive instrumental diagnosis using:

- IRT infrared thermography, which determines the distribution of surface temperatures associated with evaporative phenomena;
- measurement of the temperature and surface moisture parameters of the masonry;
- measurement of temperature, environmental humidity and dew point values.

The **IRT infrared thermographic investigation** is based on the physical principle of measuring the emissivity of the walls. Starting from the assumption that the water inside a masonry affects its ability to transmit heat to the outside, it is possible to use the method as a tool for the superficial diagnosis of thermo-hygrometric anomalies. The survey, therefore, allows to evaluate the presence of moisture by reading the variation of the heat emission that is recorded in the first centimetres of the wall at the moist portion. [25]

25 G. Roche
La Termografia per l'edilizia e l'industria. Manuale operativo per le verifiche termografiche.

The survey uses an infrared thermo-camera, capable of recording the thermal emission of a body in the infrared band through a sensitive element, the *detector*. By applying an appropriate calibration curve, the captured images are transformed into thermal maps with colour variations corresponding to the relative temperature variations. In the thermographic relief of a wall affected by moisture from rising damp, the presence of water makes the masonry portion corresponding to the attack with the soil colder, this condition is framed by the instrument with a range of colours, generally from blue to green. As the distance from the floor is increased, the dry portion of the wall is detected with a range of colours generally from yellow to red. The boundary between the green and the yellow represents the limit damp front, that is the maximum height of ascent.

The Italian standard for the execution of thermographic surveys and related reports is represented by UNI EN 13187 [26].

Experimental studies demonstrated the potential of the use of infrared thermography in the interpretation of the dynamics of the capillary ascent and the evaporative component of the process according to environmental conditions [27, 28]. The results of these researches, however, have highlighted the large number of factors affecting the thermal behaviour of surfaces and hence the correct interpretation of thermographic images, related to the properties of the materials and the conditions of the investigated environments. The result is the extreme complexity of constructing a correspondence between the chromatic gradation of a thermography and a metric scale of measurement.

METHODS FOR MEASURING WATER CONTENT

Following the qualitative evaluation of the pathology, direct tests must be carried out to determine the exact quantity of water in the walls and, therefore, to define the intervention to be taken. This will be more or less light in relation to the measured moisture content; for the extreme case in which the survey should demonstrate that the saturation level of the material has reached levels corresponding to great reduction of mechanical strength, the designer might suggest to restore the damaged masonry through the “reinsertion” technique.

26 UNI EN 13187:2000
Prestazione termica degli edifici – Rivelazione qualitativa delle irregolarità termiche negli involucri edilizi

27 N. Ludwig, E. Rosina and A. Sansonetti
Evaluation and monitoring of water diffusion into stone porous materials by means of innovative IRT techniques.

28 E. Barreira, R.M.S.F. Almeida and J.M.P.Q. Delgado
Infrared thermography for assessing moisture related phenomena in building components.

Some researchers are testing new tools for non-invasive quantitative diagnosis involving the use of optical fiber or georadar in the cultural heritage[29, 30]; however, to date, The only two standardized and scientifically recognized methods for the measurement of the moisture inside the walls are the **weight method (or gravimetric)** and the **calcium carbide method**, respectively regulated by UNI 11085[31] and UNI 11121[32]. Both involve invasive investigations with sampling of stone material from the wall for laboratory testing.

In order to determine the amount of excess water in the sample, the percentage of **physiological moisture $C_{a,f}$** should first be determined, that represents the *moisture content of the material in thermodynamic equilibrium with the environment under standard conditions of temperature and hygrometric degree*[33], which is calculated by the relation (Eq. 2.13):

$$C_{a,f} = \frac{(M_f - M_s)}{M_s} \; x \; 100$$

Eq 2.13

M_f mass of the sample in thermodynamic equilibrium with the environment
M_s mass of sample l drying

This rate corresponds to the amount of water contained in the material under the normal working conditions of the building.

In the application of both measurement methods it must therefore be considered that not all the quantity of water C_a corresponds to excess humidity: a percentage is related to physiological humidity that is, theoretically, the value to which the recovery must strive.

The **weight method** is based on the principle that a sample of stone lose its mass after drying by heating. The test shall be carried out by:

29 G.M. Carlomagno, R. Di Maio, M. Fedi and C. Meola
Integration of infrared thermography and high-frequency electromagnetic methods in archaeological surveys.

30 R. Di Maio
Electrical geophysical methods to non-destructive evaluation of architectural structures.

31 UNI EN 11085:2003
Materiali lapidei naturali. Determinazione del contenuto d'acqua: metodo ponderale

32 UNI 11121:2004
Materiali lapidei naturali … - Determinazione in campo del contenuto di acqua con il metodo al carburo di calcio

33 G. Alfano, F. R. d'Ambrosio e G. Riccio
L'umidità ascendente

- a balance with an accuracy of 0,01 g;
- an electric heating laboratory stove capable of maintaining the drying temperature with a stability and uniformity of 2°C;
- a dryer with silica gel indicator (cobalt chloride).

Because of the great heterogeneity of the wall and of its surrounding conditions, a reasonably meaningful number of sampling points are identified for each wall investigated to interpret the data collected. At each point a sample of powder material between 2 and 50 g was extracted; the operation is performed with a drill working at low speed (less than 150 rpm/min) to ensure that the mass is not heated, resulting in a reduction of the moisture content by evaporation. The wet mass of the samples $\boldsymbol{M_w}$ shall be determined from their weight recorded immediately after the extraction; subsequently, the samples are tested in laboratory involving cycles of 4 hours of drying in the oven at 105°C and subsequent cooling in the dryer until the ambient temperature is reached. At the end of each step, the samples are weighed again, and the test can be considered completed when the difference between two successive weights is less than 0,1%. The mass corresponding to this value represents the dry mass $\boldsymbol{M_d}$.

The water content $\boldsymbol{C_w}$ referred to the dry mass of each sample is determined by applying Eq. 2.14:

$$C_w = \frac{(M_w - M_d)}{M_d} \; x \; 100$$

Eq. 2.14

M_w wet mass of the sample
M_d dry mass of the sample

This method is rather invasive and cannot be used in the architectures with great historical-artistic value, with decorated surfaces or mosaics, because the execution of holes for the extraction of samples is not allowed. In these cases, although less precise in the processing of data, it is necessary to use qualitative methods for the verification and to calibrate interventions on the basis of superficial data acquired.

The **carbide method** bases on the reaction of the water contained in the samples taken from the wall with the calcium carbide, both inserted into a container; the chemical reaction produced between the two compounds results in an increase in internal pressure which is directly proportional to the amount of water contained in the samples. The test shall be carried out using:

- a steel vessel with a leak-proof lid;
- a pressure gauge for measuring the pressure in the vessel;

- 3 - 6 steel balls of different diameters (between 5 and 15 mm);
- a sieve with a mesh size of 2 mm;
- sealed glass ampoules containing calcium carbide.

The quantity of calcium carbide to be used must be greater than that stoichiometrically necessary to trigger the reaction with the water, which the standard identifies in the following table (Tab. 2.1):

Tab. 2.1: Standard UNI 11121:2004 - Water and calcium carbide in stoichiometric ratio

H_2O [g]	0,20	0,36	0,60	0,80	1,00	1,20	1,40	1,60	1,80	2,00
CaC_2 [g]	0,36	0,71	0,97	1,4	1,78	2,14	2,49	2,85	3,20	3,56

The executive method requires that the metal balls, calcium chloride and the sample of extracted material, previously sieved and weighed, are inserted into the vessel. Once hermetically closed, the container must be shaken vigorously for one minute with circular motion, to allow mixing and further crushing of the material.

The reaction between calcium chloride and the water present in the sample is shown by a progression of the internal pressure of the container read with the pressure gauge. The test is intended to be completed when the pressure stabilises. The wet content C_{ww} of the sample is obtained by comparing the pressure value read from the manometer with a calibration curve, represented in tabular form and based on the state equation between pressure, volume and temperature.

Knowing the quantity of water referred to the wet weight C_{ww}, the percentage value of water referred to the dry weight C_d can be obtained by applying the relation (Eq. 2.15):

$$C_d = \frac{C_{ww}}{(1 - \frac{C_{ww}}{100})}$$

Eq. 2.15

Laboratory measurements made at the University of Naples Federico II[34] have shown that the values provided by this method are generally lower, about 2-3%, than those obtained by the weight method. This evidence could be attributed to the fact that the gravimetric method also eliminates part of the water contained in the structure matrix of the material due to drying cycles in the oven.

34 G. Alfano, F. R. d'Ambrosio e G. Riccio
L'umidità ascendente

However, also the carbide method evidences limit of application in the context of Cultural Heritage, due to the necessity to extract samples of material directly on site.

The measured excess moisture values allow the designer to assess the decay degree of the masonry and to define the goals to achieve with the recovery works.

Diagnostic investigations are completed by the analysis of the type of salts deposited during the evaporative phase. These exert a hygroscopic action on the environmental humidity generating phenomena of superficial condensation which manifest with a distribution "spotted" at heights close to the limit of the humid front. The type and concentration of salt deposits may be investigated by ion chromatography tests on small samples of material in accordance with the procedure specified in UNI 11087:2003.[35]

2.4 INTERVENTIONS: EFFECTIVENESS AND INTERFERENCE WITH CULTURAL HERITAGE

Once the characteristic parameters of the material and its moisture content have been defined, it is necessary to choose the most appropriate recovery intervention which, obviously, must anticipate all other processes that would be affected by the prolonged pathological phenomena.

While for the types of moisture from construction, condensation and infiltration, the solution lies in the elimination of the cause and in the subsequent restoration of the masonry without further feeding of the damp content, for the capillary ascent the traditional methods, not having been able to intervene on the cause of the phenomenon, they have concentrated exclusively on the restoration of the masonry through the barrier of the ascent path or through the removal of water flows.

In relation to the principle of barrage or removal of damp contents, traditional methods of intervention are distinguished in **mechanical** methods, **chemical** methods, **evaporative** methods, **electrical** methods.

All have demonstrated over time some application limits linked both to the persistence of the absorption to the origin, and to their invasiveness that makes them incompatible with the interventions of restoration of the Cultural Heritage.

35 UNI 11087:2003
Beni Culturali. Materiali lapidei naturali e artificiali. Determinazione contenuto Sali solubili….

MECHANICAL METHODS: PRINCIPLES AND LIMITS

The mechanical interventions provide for the limitation of the contact surface between the foundation and the ground, through the reduction of the masonry sections (Koch method) or the insertion of waterproof elements following the cutting of the masonry (by means of the "replacement technique" or the use of thin barriers).

The **Koch method** assumes that the rate of water absorption is directly proportional to the surface of contact of the masonry with the foundation soil and, therefore, that the reduction of the section at the base of a masonry affects the absorption parameters. Laboratory tests have shown that the reduction of absorbent sections (which is achieved by replacing continuous masonry with arc structures) has the sole effect of slowing down the process of absorption of the wet content which, however, in a medium or long time, it reaches the maximum ascent height.

The **"replacement technique"** provides for the replacement of porous materials with other anti-capillary materials. Its application is conditioned, besides the difficulty and the long-time of realization, also by the necessity that the wall texture has low thickness and regular joints.

More frequently, on the other hand, it is the execution of a mechanical cut at the base of the masonry and the introduction of **anti-rising barriers**.

The limitations of mechanical interventions reside, first, in the failure to remove the cause of the disease: the construction of a physical barrier to the capillary ascent leads to conditions of critical vulnerability to the masonry portion below the impermeable layers where water contents continue to thicken. Moreover, these interventions modify the tensile state of the basal sections of the buildings and introduce surfaces of material discontinuity which, in seismic zone, could result in a relative shift between the two disconnected portions of the building under the action of horizontal loads.

CHEMICAL METHIDS: PRINCIPLES AND LIMITS

The chemical interventions, like the mechanical ones, promote the formation of a barrier to the capillary ascent through the injection of fluids, with particular consolidating or water-repellent characteristics, inside the walls. Depending on the viscosity of the material, these substances may be introduced by **slow infusion** or **low pressure**.

Like the mechanical methods, also chemical interventions have the limit of creating a barrier to the ascent that leaves the masonry sections placed below the waterproof layer in the critical conditions of wetting. The choice of injection compounds should be developed carefully by checking the compatibility with the materials that make up the wall support and its finishes.

EVAPORATIVE METHODS: PRINCIPLES AND LIMITS

The class of evaporative methods entrusts the recovery function of the masonry to the increase of the evaporative component of masonries, to be pursued by:

- introduction of **syphons or atmospheric drains** to drain the water flows within the masonry;
- substitution of the finishing layers with **recovery plasters** which, being characterized by larger voids than traditional plasters, increase the evaporative capacity of the walls;
- realization of **counter-walls** and **ventilation channels** (natural or forced).

The use of **syphons and drains** has been strongly criticized already by Massari who, in his text, called them *"pseudoscientific and useless interventions"*[36]. The physical phenomenon of functioning of these elements is based on the hypothesis that the external dry air will replace the air inside the siphon with consequent removal of humidity; but this dynamic occurs only in some thermo-hygrometric environmental conditions.

The **recovery plasters**, thanks to the formation of the macro-porous capillary structure, accelerate the disposal of water contents inside the masonry and, at the same time, they manage to absorb the increase in volume due to the crystallization of the dissolved salts in the ascent water, curbing the phenomena of superficial decay related to the formation of microlesions and pulverization of the material.

The construction of **walls and ventilation channels** to force the evaporation process is the subject of numerous experimental campaigns[37] in which the relationship between the effectiveness of the intervention and the thickness of the walls has been demonstrated, verifying that the acceleration of evaporation is greater in the walls of small thickness and decreases appreciably as it increases. When properly performed, these interventions improve the liveability conditions of indoor environments by limiting the manifestation of

36 G. Massari
Risanamento igienico dei locali umidi: rimedi pratici per i vari casi

37 I. Torres
Wall base ventilation system to treat rising damp: The influence of the size of channel

degradation effects. However, like all other evaporative methods, even these interventions have the limit of not acting on the elimination of the cause of the ascent. It is shown, in fact, that they activate a flywheel by means the quantity of water which is removed by evaporation is also recalled by the foundation soils. Moreover, the replacement of plaster (sometimes decorated) or the realization of ventilation channels, are certainly not compatible with the intervention in the context of Cultural Heritage.

ELECTRICAL METHODS: PRINCIPLES AND LIMITS

The fourth category of traditional interventions belongs to the class of **electrical methods**, which aim to condition the movement of fluid within the masonry by introducing an electric field that cancels or opposes the natural one that develops between the walls of the capillary system and the molecules of water, reversing the flow and "pushing" the water down. In this category there are:

- the **passive electrosmosis** method, which consists in the cancellation of the difference of potential by the introduction of a metal bar between the masonry and the ground; this method was soon abandoned due to its insufficient performance.
- the **active electrosmosis** method, which entrusts its effectiveness to the introduction of an artificial electric field inside the masonry (obtained by passing current in two electrodes connected to a unit of control) which exceeds the value of the natural electric field and reverses the trend of the capillary flow.
- the method of **electrosmosis foresi**, evolution of the previous, which uses the electric field introduced to convey inside the capillary system some water-repellent substances capable of modifying the surface tension in order to weaken the force of attraction exerted on the water and hinder the ascent.

Unlike the previous methods, electrical interventions aim to act on the cause of the disease by reversing its dynamics; the completion of the recovery process, by eliminating the residual wet contents in the masonry, is entrusted to natural evaporation through the external surface.

This type of intervention finds its limits in the interaction with the masonry, which is the propagation medium of the wave, and in the calibration of the electric field according to the variability of the natural potential during the time and within the space. Moreover, in the context of Cultural Heritage there are still elements of incompatibility related to the invasiveness of the installation that requires the execution of rather deep holes in the masonry for the insertion of electrodes or the creation of tracks to pass the cables.

The attention of researchers to the electrical component of the ascent has paved the way for the development of further techniques aimed at eliminating the pathology at its origin.

In this perspective, overcoming the limits determined by the variables of the masonry, the study and the verification of an innovative and non-invasive system, that arises as evolution of the previous electrical methods, has been deepened. This method, named ***"Charge Neutralization Technology"*** **CNT®** and patented by Domodry, unlike the reverse charge methods, uses a particular electromagnetic wave that acts exclusively on the molecule of water subjected to the natural electric field, making it neutral to the electrostatic attraction exerted by the masonry.

2.5 CHARGE NEUTRALIZATION TECHNOLOGY CNT®

The technical datasheets provided by Leonardo Solutions clarify how the CNT® works, basing on the scientific principles of electro-capillarity[38] and electro-wetting[39].

The first principle is described by the model of the "double layer of Helmholtz", discussed in section 2.1. The phenomenon of electro-wetting, on the other hand, can be described as the property to modify the capability of a liquid to maintain its contact with a solid wall through the application of an electromagnetic field, and therefore to modify the values of the surface tension exerted by the walls of the capillary pores on the molecule of water.

The electromagnetic field capable of carrying out this action is driven by the CNT device, which consists of an inductor driven by a low frequency generator, from 40 to 60 Hz. The emitted magnetic field is very low and not perceptible or harmful to humans or animals, lower than the magnetic field produced by a battery feeder for mobile phones.

Its action determines the "neutralisation" of the water molecules compared to the attraction force exerted by the capillary walls; this produces the interruption of the ascent dynamics. The water in excess in the masonry is disposed of by natural evaporation.

38 M.W.J. Prins, W.J. J. Welters, J.W. Weekamp
Fluid control in multichannel structures by electrocapillary pressure

39 H. Moon, S.K. Cho, R.L. Garrell, C.J. Kim
Low voltage electrowetting-on-dielectric

The advantage of this technology to act directly on water allows to apply the method regardless of the type of building material or masonry texture. Moreover, it is also characterized by two further aspects that make it particularly suitable to be applied also in the field of Cultural Heritage: non-invasiveness and reversibility.

From an operational perspective, the intervention is carried out through the installation of one or more devices CNT®, which dimensions are 24 x 20 x 7,4 cm, that is connected to the electricity with a low consumption. Depending on the model the device can act on a spherical range of action from 6 to 15 m. This feature allows the designer to choose the most suitable position for the device and excludes any interaction with artistic surfaces.

This device is integrated in a sensor system able to monitor in real time changes both in temperature and humidity values of the indoor air (by means of Relative Humidity - Temperature Hr-T probes), both changes in the water content of the wall thickness by means of IDROSCAN non-invasive test probes (Fig. 2.11).

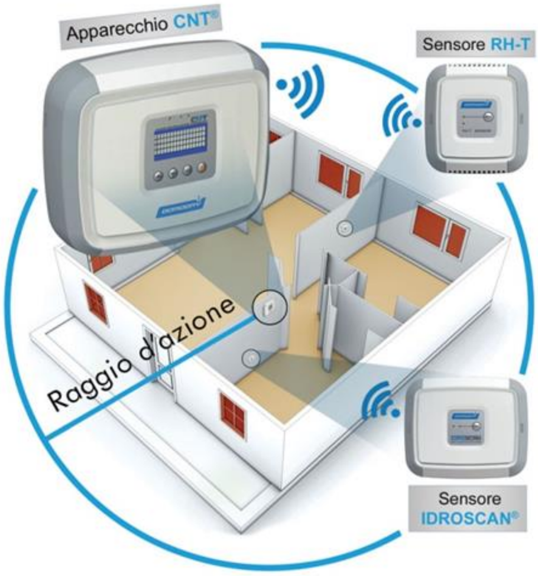


Fig. 2.11 - CNT® system integrated with sensors Hr-T and IDROSCAN

Remote connection of the system to the data center allows the technicians to detect any changes or anomalies during its operation: by checking the hours of operation recorded by the CNT device, for example, it is possible to understand whether there have been more or less long periods of process interruption (in case of prolonged power supply detachments) while the change in data of Hr-T probes can provide information about the activation, even for short periods, of control systems for the internal microclimate.

The data recorded by the IDROSCAN experimental probes, however, to date, allow only to monitor the trend of the drying process of the masonry: This information is mainly used by the company to indicate to the customer the time needed to reach a good level of drying and to plan the subsequent restoration of the degraded finishes. However, in the context of the research project, starting from the principle of operation of this probe, tests have been developed to determine an instrument response curve of the device to be used as a tool for non-invasive diagnosis and monitoring of the conservation status of a wet wall. For further information see Chapter 5.

COMBINED METHODS FOR THE RECOVERY

It is important to point out that the CNT method is not an intervention in itself because, in order to complete the recovery process, it is necessary that after the neutralisation, and thus the elimination of the cause of water absorption from the soil, the masonry expels the residual water content until it reaches values of humidity close to the physiological one of the materials of which it is constituted.

Therefore, it is interesting to investigate the potential to combine the CNT method with interventions of evaporative type or conditioning and control of the thermo-hygrometric parameters of the environment, to affect the second component of the recovery by increasing the capacity of walls and surface layers to dispose of residual moisture.

Combining different technologies allows to design remediation interventions with very high-performance levels in terms of reduction of internal moisture content and maintenance of health conditions over time.

3. RESEARCH DEVELOPMENT BETWEEN SPAIN AND ITALY

On the basis of the bibliographical studies carried out on the topic of rising damp it has benne possible to determine: the effects produced from the pathology on the construction materials; the methods and the instruments of diagnosis and monitoring existing on the market; the measures commonly adopted for the recovery of wet masonry; and finally the innovative methods proposed by the company partner of this research. Downstream of these knowledges, the research project was structured around three objectives, presented and discussed in Chapter 1, relating to:

1. **To quantify the change of traditional building materials performances** when they're subjected to different degrees of imbibition;
2. **To test new systems for the diagnosis** of the capillary rise aimed at classifying the level of conservation of the wet masonries and monitor the recovery systems efficiency;
3. **To verify the effectiveness of the Charge Neutralization Technology** to interrupt the dynamics of the capillary ascent in a definitive and above all non-invasive way, therefore applicable in the context of Cultural Heritage.

The choice of materials to be used for the experimental investigations could not prescind from the study of the materials and the constructive techniques that characterize the two areas in which the research project was developed: the city of Madrid and the Metropolitan City of Naples.

Considering that the project has paid particular attention to the area of Cultural Heritage, the study has been focused mainly on the materials and construction techniques of historic buildings with a supporting masonry structure, for which the walls of the building assume, in addition to the fundamental role of absorbing the loads and carrying them to the foundation, also that of closing and protection in relation to the external environment.

These types of construction are certainly more sensitive to the pathology of raising damp due to different features, related to the age of architecture and the natural aging degree of the building materials. In addition, the materials used for the construction of walls, are often characterized by a porous structure that facilitates the entry and movement of the water.

In these cases, the presence of moisture is a factor of the highest vulnerability both for static safety and for maintaining the conditions of thermo-hygrometric comfort, still for the preservation of the decorated finishes that characterize them.

3.1 USE OF NATURAL STONE IN THE MADRID CONSTRUCTION TRADITION

The constructive tradition in Madrid is based on the use of two distinct families of materials, both linked to the geographical nature of the site: natural stones, extracted from the mountain range in the North, and the bricks, produced from the dough of the clay present in the central part of the area with water.

The complex geo-morphological shape of the territory and the absence of important navigable waterways, have historically conditioned the choice of stone material because of the availability and ease of extraction of stones as well as the supply to the sites of construction. [1]

The geo-morphological structure of the city is characterized by the presence of two large regions: the Sierra and the Depresión[2]. The Sierra constitutes the mountainous profile of the north-western part, rich of materials with prevailing silica composition; the Depresión, instead, is constituted for the most part by materials of debris nature and occupies the central, eastern and south-eastern areas.

The natural stones used in the construction field are divided into two groups (Fig. 3.1):

- igneous and metamorphic rocks from the region of the Guadarrama mountain to the North-West, formed by granites, porphyries and slates. The material mainly extracted from this region, classified as **Berroqueña stone**, includes Alpedretes and Zarzalejo;
- sedimentary rocks of the region North-East of Madrid and siliceous stones closer to the city, classified as **Redueña stone**, by the name of the area;
- sedimentary rocks from the **Colmenar** region in the South-East of Madrid;

1 R. Fort, M. Alvarez de Buergo, E.M. Perez-Monserrat and M.J. Varas-Muriel
Ruta geomonumental: la piedra tradicional utilizada en la construcción del patrimonio arquitectónico de Madrid

2 Consejería de medio ambiente y ordenación del territorio
La geomorfología de la comunidad de Madrid

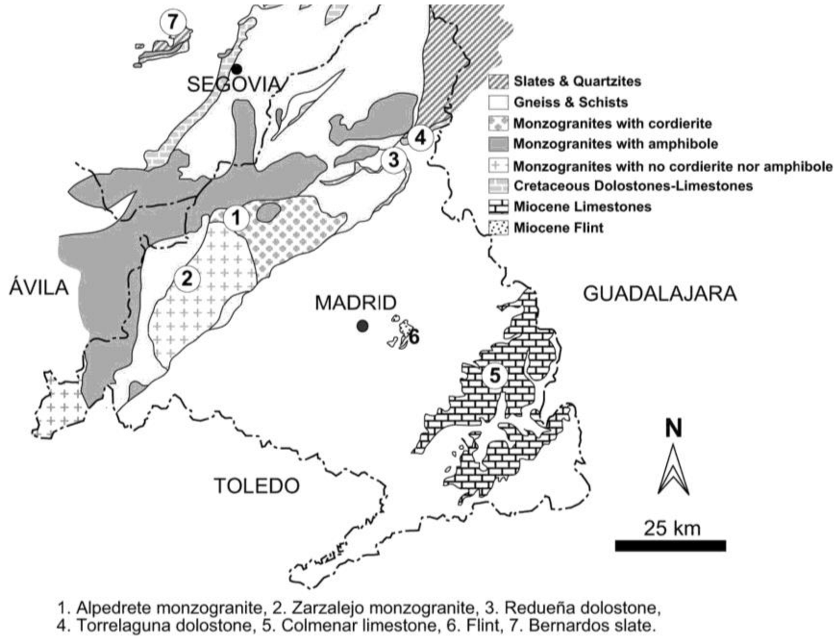


Fig. 3.1 – Map of Madrid's geology

ARCHITECTURE OF NATURAL STONE IN MADRID

The first signs of the use of the local silica stone, mixed with dolomia and bricks, are found in the Muslim outpost built in the second half of the IX century to defend the city of Toledo. The sturdiness and durability of the stone made it particularly suitable for the construction of defensive structures while its ease of finding from quarries close to the city greatly reduced the transport risks.

Both conditions determined the success in the use of the local stone until the XXII century when, thanks to the advent of more modern way to extract and transport, the extraction of the Redueña from the area in the North-East of the region became possible. Today there are very few traces about Redueña stones in the structures of the city. At the same time also the extraction of the Berroqueña stone from the area in the North of the city became possible; the latter was used in the construction of emblematic monuments such as the royal monastery of S. Lorenzo in El Escorial, the Prado Museum and the Puerta del Sol (Fig. 3.2).

Fig. 3.2 – St Lorenzo El Escorial monastery – One of the entries

During the XVIII century the further development of techniques for the extraction of stone material from underground quarries facilitated the supply of limestone from the southern area of the region, the Colmenar, used for the completion of the Royal Palace of Madrid to replace the original Berroqueña stone. The new stone, recognizable in the decorative elements, columns, balustrades and sculptures, gives great durability to the monumental royal residence, ensuring its excellent state of conservation (Fig. 3.3).

Fig. 3.3 – Madrid Royal Palace – View from Plaza de la Armeria

The contamination of traditional Madrilenian stones can be found in the small building of *San Nicolás de los servitas,* one of the most ancient churches in Madrid, that was built using four types of traditional stone material: the silica stone for the foundation walls; the Redueña stone for the apse and for the curved geometries, the Berroqueña granite on the two entrances of the church; and the brick in the bell tower.

The construction of the first railway axis from Madrid to Aranjuez in the XIX century determined the possibility to transport other types of material from any part of the country. Berroqueña and Colmenar stones were preferred for their excellent mechanical characteristics and durability and are still considered today the traditional stones of the local constructive culture, recognizable both in the decorative apparatuses and in the structural parts of the most representative historical buildings of the city. [3]

DURABILITY OF NATURAL MADRILENIAN STONE

The durability of natural stone depends above all on its petro-physical, and petrochemical composition, which determines its greater or lesser aptitude to trigger reactions between mineralogical components.

By analysing the most commonly used stones in the local construction tradition, it is noted that the Berroqueña stone family, with its characteristic ochre tone, includes three different types of granite with different grain sizes, which vary from one grain size to one3 mm at a size of 2-3 mm [4] but similar properties[5]. The three types are composed of biotite, in percentage of 10% 15%, mineral that promotes the crystallization of the salts between its layers and the release of iron as a result of the hydrolysis process. Both phenomena represent dangerous causes of degradation for the material and are more frequent in stones with grains of about 2-3 mm than those with finer grain sizes.

The Colmenar has better quality and durability than the Berroqueña; this white limestone is extracted near the city of Colmenar de Oreja and takes its name from this place. This stone shows, in relation to the parameters of porosity, absorption, ultrasonic speed and anisotropy, a greater durability also compared to Redueña, that is a limestone with ochre tone used mainly as a decorative element.

Experimental studies carried out on rocks subjected to ageing cycles have shown that the characteristics of the stones vary greatly depending on the natural degradation of the material with consequent loss of physical and mechanical performance.

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3 R. Fort, M. Alvarez de Buergo, E.M. Perez-Monserrat and M.J. Varas-Muriel
Ruta geomonumental: la piedra tradicional en la construcción del patrimonio arquitectónico de Madrid

4 D.M. Freire-Lista and R. Fort.
The region of the Piedra Berroqueña: A potential Global Heritage Stone Province

5 R. Fort, M. Alvarez de Buergo, E.M. Perez-Monserrat, M. Gomez-Heras, M.J. Varas-Muriel, D.M. Freire
Evolution in the use of natural building stone in Madrid

3.2 USE OF BRICKS IN THE MADRID CONSTRUCTION TRADITION

The Madrilenian building tradition is also strongly characterized by the use of bricks, linked to the influence of Roman architecture throughout the region or more likely due to the stylistic contamination of Arab domination. The architectural production with exposed brick that blends the Romanesque and Gothic tastes with Arabic art, representative of many Spanish monuments, is classified with the *neo-mudéjar* name.

The possibility to create new different masonry textures in relation to the arrangement of bricks in the plan, classified in the term *aparejo en el ladrillo*[6], gave the material not only the dignity of a structural element but at the same time the role of architectural and decorative element (Fig. 3.4).

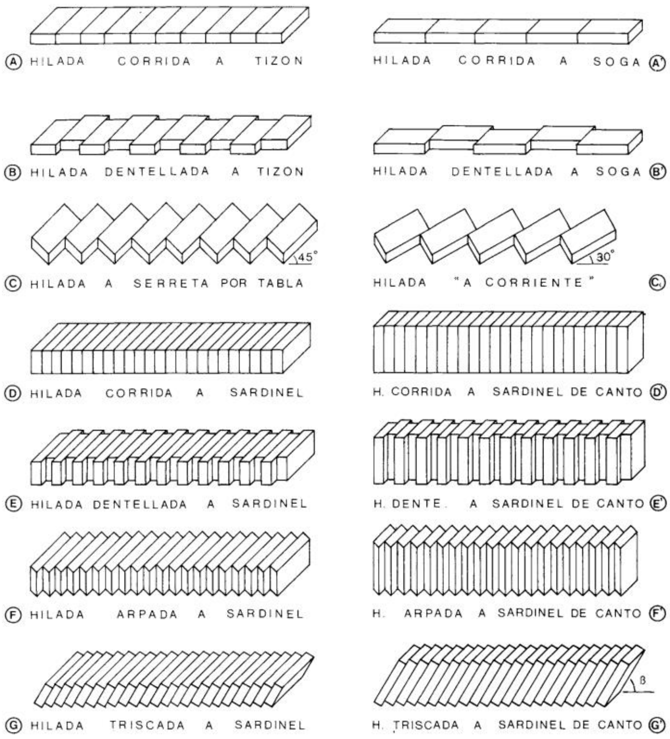


Fig. 3.4 – Argilés – Possible disposal for bricks rows

Depending on the time in which these architectures were built there are different sizes of the bricks, regulated by the standards in force at the time[7]. Until the 19th century, bricks were made using human proportions. The Madrid Ordinance of 1820 established measures of

6 J. M. A. Argilés
La Arquitectura de ladrillos del siglo XIX: racionalidad y modernidad. Informes de la Construcción

7 A. R. Sánchez
Evolucion de las dimensiones de los ladrillos y su coordinación

"seventeen fingers in length, thirteen in width and three fingers of average thickness", corresponding to elements of size 31.5 x 24 x 6.5 cm[8]. The subsequent Ordinance of 1857 instead provided a proportion between the sides of 3÷4, with elements of dimensions equal to about 29,6 x 20,9 x 3,7 cm.

The Construction Treaty drawn up in the first half of the 20th century defined the proportions between the sides of the element but did not specify the relationship with the height[9]. It is necessary to wait for the industrialization process of the 1920's to arrive at the production of prefabricated brick elements with controlled physical characteristics and standardized form. In 1942, in accordance with the International Metric System, it was decided to align the size of the bricks to the measures of 25 x 12 x 5 cm.

ARCHITECTURE OF BRICKS

Thanks to the possibility of being used in more than one architectural taste, this type of construction was adopted throughout Europe, becoming representative both for the Romanesque and Gothic stylistic research (Fig. 3.5).

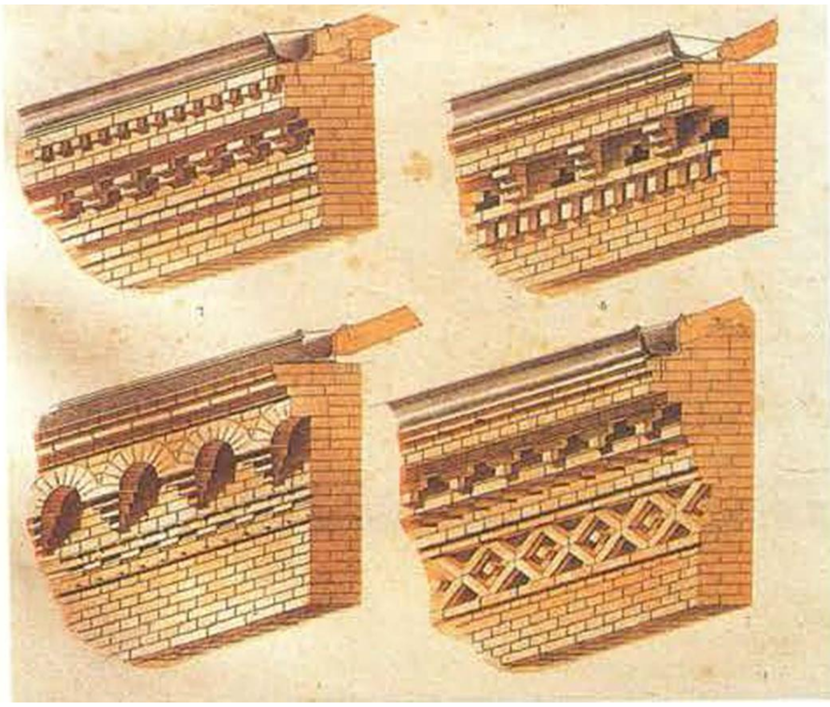


Fig. 3.5 – Argilés_Architectures of bricks

8 T. Ardemans
Ordenanzas de Madrid, y otras diferentes, Madrid.

9 F. Ger y Lobez
Tratado de construcción civil

In Spain, and in other countries less affected by seismic phenomena, the possibility to realize light vertical structures, mostly dimensioned for vertical loads, allowed the architecture of the brick to replace the traditional construction types in natural stone; the latter, on the contrary, were characterized by important masses and remarkable wall thicknesses. Moreover, the prefabricated character of the brick elements and the possibility to compose architectures according to modular schemes greatly optimized the construction time.

BRICKS DURABILITY

Brick walls often show physico-chemical degradation phenomena, due to the interaction with the external environment, which is evidenced by the formation of saline efflorescences and micro bio-organisms on the surface layers, erosion, spraying and loss of material (Fig. 3.6).

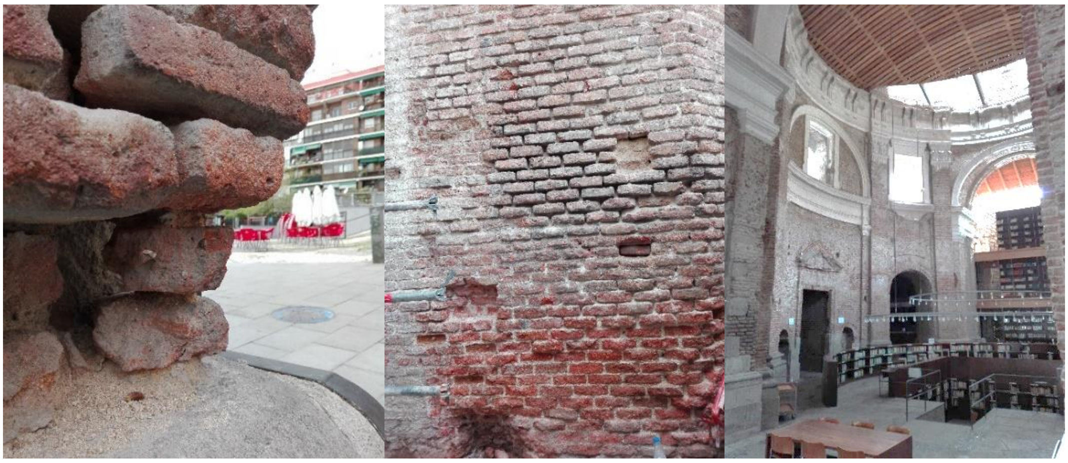


Fig. 3.6 – Escuelas Pías library (Lavapiés) - Details of deterioration of the bricks

The material's ability to maintain its properties over time has been evaluated in several experimental studies, some of which have already been described in Chapter 2.

All the studies have shown a relationship between the onset of decay and the absorption capacity of brick products which, moreover, increases over time with the increase of their ageing. In presence of rising damp, then, the water contents increase because to the absorbent capacity of the material is added also a component of pressure of the fluid in the capillary system.

3.3 USE OF NATURAL STONE IN THE NEAPOLITAN CONSTRUCTION TRADITION

The Neapolitan construction tradition is strongly linked to the presence of the two eruptive centers of Somma-Vesuvio and the Campi Flegrei that, over the centuries, have provided material resources with very high performance levels to be used for the construction of walls (tuffs) for the realization of decorative elements and monuments, as well as exceptional resistance (piperns and lava stone) and for the composition of mortars and conglomerates already greatly appreciated and experienced by the Romans for their extreme lightness (pumice) and for the capacity to transfer their hydraulic properties (pozzolane).

From the volcanic activity of Somma-Vesuvio derive the **laves**, known as *pietrarsa*, rocks characterized by very high mechanical resistance, hardness and compactness, whose colour varies from ash grey to reddish brown. This material has found wide employment as freestone and, in the format of *basoli*, for the road paving. Of the same origin is the **Vesuvian rubble**, *scheggioni* coming from the crushing of the lava rocks and used for the realization of very resistant masonries. From the slag of greater lightness produced during the eruption, however, were obtained **pumices and lapilli** frequently used for the filling of the vaults and for obtaining light conglomerates.

The nature of the products of Campi Flegrei, on the other hand, is closely linked to the conditions that have occurred during the eruptive phenomena, to the metamorphism caused by the gases released by the pyroclastic deposites still hot, and bradisismic phenomena which have led to subsequent sinking of materials in the sea. Among the products of this activity is the **piperno**, gray coloured rock that includes darker stains, called "*flames*", consisting of lava shreds embedded in the main matrix; used until modern age, has then fallen into disuse due to its poor resistance to wear.

Another product of this volcanic activity is the **bell grey tuff (or pipernoid)**, with grey colour and dark elements very similar to the flames of the piperno, characterized by poor durability but also by great workability that has favoured its use as rough stone. Then you add the yellow tuffs, which differ by the time of the eruption that produced them.

The **stratified yellow tuff** adheres to the oldest eruptions and is found in modest outcrops; it is characterized by a large quantity of pumices and slags that give the stratified aspect and the granulometric variety to the various layers.

Much more abundant and widely used since the foundation of the city is, instead, the **chaotic yellow tuff (or Neapolitan)**, soft and workable rock preferred for its characteristics of good resistance in relation to the specific weight and the low cost. In the geological stratification the Neapolitan yellow tuff is usually covered by a layer of **tasso**, a coarse-grained pozzolana which, mixed with lime, provides a very resistant compound, and one of a **mappamonte**, a very tender and scarcely resistant rock[10].

There is no doubt that the rock that best connotes the local constructive culture is the Neapolitan yellow tuff[11]. This material has been strongly used both for the realization of modest buildings and for the construction of some of the most emblematic architectures of the Historical City and the image of Naples in the World, some of which have wished to enhance the material consistency keeping it visible. This is the case of the most famous military structures (Castel dell'Ovo, Castel Nuovo, Castel Sant'Elmo) and of various religious buildings (Monastery of Santa Chiara, Pappacoda Chapel, Church of S. Domenico Maggiore, etc.) (Fig. 3.7).

Fig. 3.7 – From left: Castel dell'Ovo, S. Domenico Maggiore, Basilica dSanta Chiara

""Thanks to its great workability, this material has always been quarried over the centuries easily and reduced in blocks, also assuming for such reasons an absolutely primary role in the sacred, civil and military architecture as structural and decorative material in much of the historical centers of Southern Italy such as Lazio, Campania, Puglia and Sicily" [12].

10 A. Aveta
Materiali e tecniche tradizionali nel napoletano. Note per il restauro architettonico

11 G. Ausiello
La tradizione costruttiva mediterranea

12 R. Ceroni, M. Pece, G. Manfredi, G. Marcari, S. Voto
Analisi e caratterizzazione meccanica di murature di tufo

NEAPOLITAN YELLOW TUFF

"Its real name is chaotic yellow tuff. However, it is also called Neapolitan yellow tuff…. almost to mean that this is the true, typical, Neapolitan rock, the most abundant and used as building material, for any kind of construction and that contributed to give a particular character to the architecture of the region…. It is this material, therefore, that shapes and substantiates the architecture of nature in the Neapolitan area constituting, in the inhabited area and in much of the Campi Flegrei area, almost the only rocky formation in which we have come across"[13].

The Tufo Giallo Napoletano (TGN) is the product of the third cycle of volcanic activity of the Campi Flegrei, characterized as the second in importance in the Campania area. "*During the eruption, 40 km^3 of magma was emitted from a centre located in the Campi Flegrei, covering an area of about 1,000 km^2. The deposits connected with the eruption of the TGN can be found in the Neapolitan-Phlegraean area and in the Piana Campana up to the reliefs of the Apennines. Although the eruptive centre was in the Campi Flegrei, the outcrops closest to the centre can be found only at a distance of a few km from the centre. Also, in the Gulf of Naples are found deposits, currently submerged, attributable to the TGN.*" [14] (Fig. 3.8).

Fig. 3.8 – The eruption basin of the Neapolitan Yellow Tuff

13 P. Nicotera, P. Lucini
La costituzione geologica

14 INGV – Sezione Napoli
Il Tufo Giallo Napoletano

According to Rittman, the eruptive formation of the rock recalls *“that of the mixed pyroclastic materials erupted in such quantity and in such short time to form a very hot and very mobile suspension that flooded vast areas with great speed. Only such a mechanism explains the perfectly chaotic nature of the tuff, the partial devetrification of its pumices and its exceptional stability”*[15]. In support of this assumption the author observes how the devetrification of the pumices would show that the material, still very hot, has undergone a slow cooling. The mechanism of an eruption of yellow tuff is, in fact, described by the scholar as *“an enormous quantity of magma very rich in gas, but not very hot and therefore viscous, which rises in the duct pushing in the head a colder and more viscous mass of lava. Once at the mouth this forms a dome that, extending laterally, is torn giving free way to the magma below. This first explodes in rhythmic activity (lower stratified materials) and then in a series of explosions that are more and more accelerated to culminate in a gigantic explosion that emits such a quantity of pyroclastic material of all sizes to form with gases a dense and heavy suspension that soon falls, in the form of a burning cloud, overflowing from the crater and sliding down the flanks of the volcano with great speed. The mobility of these fiery drooping clouds is extraordinary and allows the pyroclastic masses suspended in the hot gases to reach distances of tens of kilometres depositing along the route huge amounts of chaotic tuffs. In the main mass no sorting is possible, only the highest parts of the burning clouds are depleted of gross materials. A small percentage of the ash remains thus suspended a little longer and settles to the roof of the chaotic tuff, forming the mappamonte”.*

Architecture of Neapolitan Yellow Tuff

The construction process of the buildings in yellow tuff began with the extraction of the material from the rocky bank. It was common, in the local construction culture, that the mining site coincided with the plot where the new building was to be built. Small blocks were extracted from the underground caves, which facilitated the handling and transport of the material to the construction site. Alternatively, the extraction could be carried out by making “bell shafts”: *“the tufa bank – reached from the top by means of a well, usually circular, excavated from the ground plan –was penetrated for 4-5 meters, after which the extraction of the material began by enlarging, gradually, the cave towards the bottom making a bell.”*[16]

15 A. Rittmann
Sintesi geologica dei Campi Flegrei

16 R. Castelluccio
I fenomeni di umidità sulle murature in tufo giallo napoletano – La risalita capillare, gli int. con intonaci da ris.

Some of the great cavities thus obtained, which during the time have been used in various ways, are still open and visible and characterize the spatial configuration of the “underground Naples”. Going down into the wells and along the tunnels, we note the signs of the extraction, which was realized with a pick with two points with vertical blade, the *smarra*. Each part of the extracted material was used in the construction process.[17]

The stone blocks were usually done onsite forming rows with 1 cm thick joints of pozzolanic mortar, taking care that the adjacent vertical courses were staggered.

For thin wall weaving, the width of the block was respected, while for larger wall thicknesses the “sack technique” was used, obtained by the creation of two walls in which some blocks were placed in a orthogonal (oriented according to the transversal direction of the masonry), so as to ensure the joint connection of the two planes with the central filling obtained with concrete mixed with fragments of tuff and stones (Fig. 3.9).

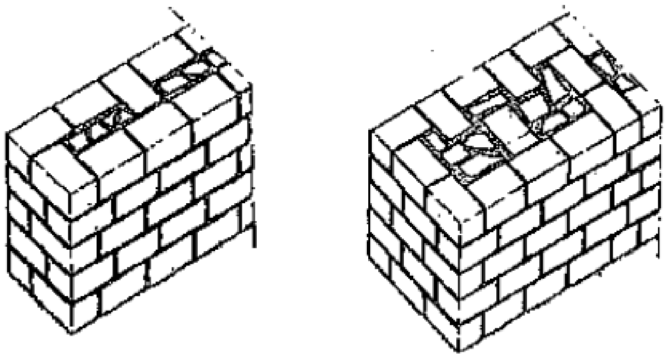


Fig. 3.9 – Disposal of blocks using the “sack technique” to realize walls of 70÷100cm thickness

In multi-storeyed buildings the thickness of the walls, thinner at the last levels, widened downwards by means of change in size that allowed to increase the resistant section of the construction element with the increase of the loads produced by the higher structures. This change in size, moreover, constituted a useful support for the slabs of the upper floors, usually constituted by wooden elements. The slabs of the ground floors and the basement, instead, were realized with vaults.

The load-bearing masonry buildings discharge the weight of the structure by means of **foundations** which, in relation to nature and to the “goodness” of the ground on which they rest, may be classified into surfaces, foundations made of frames or plateaus, and deep, foundations on pillars and arches or piles.

17 F. Penta
I materiali da costruzione dell’Italia meridionale

This system of foundations made the structure less rigid than that founded on continuous walls (Fig. 3.10).

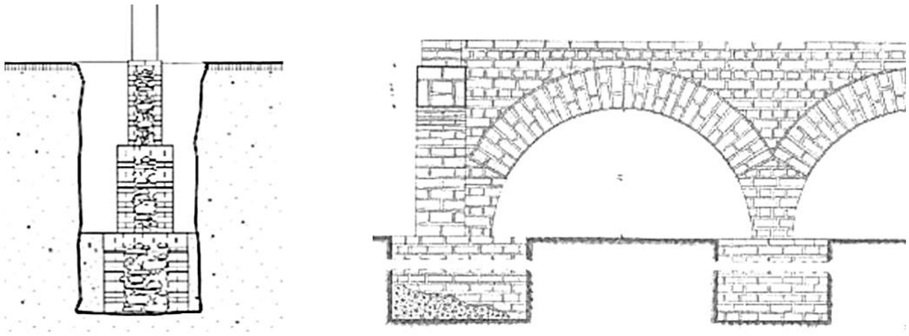


Fig. 3.10 – Continuous foundations (left) and foundations with arcs and columns (right)

Finally, among the types of deep foundations, there are the wooden piles, used mainly because of the capacity of the beaten poles to compress and then consolidate the earth in cases where groundwater was found.[18]

NEAPOLITAN YELLOW TUFF DURABILITY

Due to the great porosity that characterizes both the yellow tuff and the mortar, the walls made with this material are often affected by degradation phenomena due to physical, chemical and biological attacks.

Physical phenomena related to frost and thaw of the water contained in the porous structure, for example, can produce lesions and breakdown of the material; chemical alterations related to the crystallization of the dissolved salts in the water, on the other hand, they may lead to the formation of subflorescence and, consequently, to the exfoliation and detachment of surface crusts; the presence of moisture, finally, promotes the emergence of biological diseases linked to the formation of moulds and lichens which can damage the health of those who live the environments in which these phenomena are evident.

3.4 CHOICE OF BUILDINGS FOR IN SITU INVESTIGATION

As a result of the studies carried out, it was decided to develop experimental campaigns aimed at measuring the percentage variation in the mechanical and thermal

18 A. Aveta

Materiali e tecniche tradizionali nel napoletano. Note per il restauro architettonico performance of wet materials using the materials typical of the two local traditions (described in Chapter 4).

At the same time, the possibility of working in two territories very different for geography, orography and construction techniques made particularly interesting to start a campaign of tests of CNT devices and IDROSCAN probes inside historical buildings belonging to the Cultural Heritage of the two areas (described in chapter 6).

In order to determine the buildings for in-situ testing, several selection criteria have been identified, relating to:

1 Historical and architectural value of buildings
2 The functional destination
3 Materials and construction techniques
4 he presence of rising damp
5 The accessibility and availability of sites

The first criterion, relating to the **historical and architectural value of buildings**, has proved fundamental to focus the research in the field of Cultural Heritage; among the goals of the project, in fact, there are the performance verification and the test of non-invasive systems and devices, for the recovery or for the diagnosis and monitoring of the rising damp in the context of historical architectures.

The choice of the **functional destination** criterion assumes that the process of restoration of wet masonry consists of two phases: the interruption of the phenomenon and the evaporation of the residual wet content. The activation of the second factor depends on the architecture of the places but also on their degree of crowding connected to the functional destination; continuous ventilation of the environments provides favourable conditions for evaporation, while environments with a high number of occupants, poorly ventilated or with a high level of ambient humidity can hinder evaporation.

In addition, the functional destination of the environments to be restored also establishes the degree of vulnerability to the formation of moulds and allergen agents or to the preservation of the things contained (exhibition spaces, archives, food storage rooms, etc.).

Another criterion concerns **materials and construction techniques** because, as widely discussed, the dynamics of the capillary rise is closely related to the porous structure of the building materials and the way in which these masonries are made. Indeed, the principle of functioning of CNT systems declares to act regardless of the construction characteristics of the building. Therefore, it was interesting to carry out their performance test on buildings different under this view.

The criterion relating to the **presence of rising damp** is referred to the selection of buildings where the main pathology found was related to the dynamics of the ascent. It is not rare, in fact, that the phenomenon manifests itself together with other pathologies that intervene, in terms of water contributions to the masonry, with different dynamics. In underground environments, for example, the capillary rise is often added to humidity phenomena due to contact between the boundary walls and the soil. This criterion required preliminary investigations to be carried out on the buildings being screened in order to rule out the presence of concurrent factors prevailing on the capillary ascent.

Finally, the criterion of **accessibility and availability of sites** has resulted in a very strong selection among the case studies. The test, in fact, required a period of application of the devices of about 18 months, aimed at monitoring the drying process of the walls comparing similar climatic and seasonal data between them (with biannual verifications winter/summer or autumn/spring). Therefore, in order to monitor intervention throughout the recovery cycle and to obtain reasonably comparable data, the research partners were asked to ensure that the area was not subjected to maintenance works or distribution changes for the duration of the experiment. In fact, any work on finishes rather than openings or displacements of internal partitions would have changed the thermo-hygrometric conditions and the drying of walls under the action of CNT devices, thus altering the interpretation of the final data. Considering that the plan for the maintenance of the public buildings in Madrid is at least annual, it has been necessary to exclude many interesting cases and ask for maintenance work to be postponed on the buildings on which the intervention has taken place.

Applying the selection filters to a large group of case studies, in agreement with the Public and Private Authorities who have allowed the development of the test, three sites have been identified, that are:

- The Cuartel del Conde, Calle del Conde Duque, Madrid;
- The Chemstry Laborathory of E.T.S. de Ingenieros de Minas y Energía, C/ de Ríos Rosas, Madrid;
- The la Crypt of Pontificio Santuario della Beata M. Vergine of S. Rosario in Pompei.

THE CUARTEL DE CONDE DUQUE

Historical and architectural value _ The Cuartel de Conde Duque was born as a military building in the first twenty years of the 18th century, within the reorganization of the army wanted by King Philip V of Bourbon. The construction type of the *cuartel* was introduced as a residence for the army within the city[19], understood as a *"result against the dispersion of the garrison in the population, which guaranteed speed in case of urgent attack or defence and, ultimately, tranquillity and control"*[20].

Compared to the planimetric distribution of the spaces, typical of the French model in force until then, the Spanish military engineers soon understood that the more temperate climate in the region would cause difficult conditions of asphyxiation for horses during the summer. Therefore, they proposed to organize the cuartel in many building volumes separated by open spaces that guaranteed better ventilation and the possibility to water the horses in the fountains placed in the center of these spaces. The program of King Philip V of Bourbon, moreover, demanded that a new typology be prepared, able to contain 600 soldiers and 400 horses in a single building, that had a monumental character and strong impact on the urban plot of the city of Madrid. In this perspective, the monarch commissioned the project of the Cuartel de Conde Duque to the baroque architect Pedro de Ribera.

The project of Pedro de Ribera, a large building of about 25,000 m^2 with a rectangular plan, characterized by a baroque roof carved in stone, a large central square, two side patios and very large spaces for cavalry, was completed in 1730.

The original barracks of the guards of the Royal Corps changed several functional destinations hosting, during the 19th century: a military academy, an astronomical observatory and the first system of telegraphic communication that connected Madrid with Irán (Fig. 3.11).

19 VVAA
El Cuartel de Conde Duque de edificio militar a espacio cultural

20 J. Muller
Tratado de fortificaciòn, o arte de construir los edificios militares y civiles

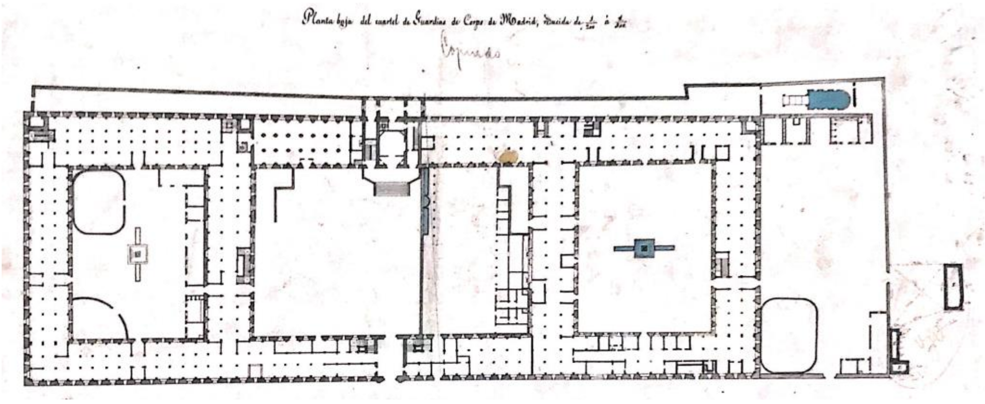


Fig. 3.11 – Map of the groud floor (Istituto Geografico Nacional, 1869 – 1870)

In 1869, a devastating fire destroyed the upper floors and the tower on the west façade (formerly used as a prison). Followed some projects of transformation of the building to the accommodation of artillery and cavalry.

In 1969, lost its military function, the building was acquired by the Ayuntamiento de Madrid who, under the direction of architect Julio Cano Lasso, began an important restoration work (Fig. 3.12).

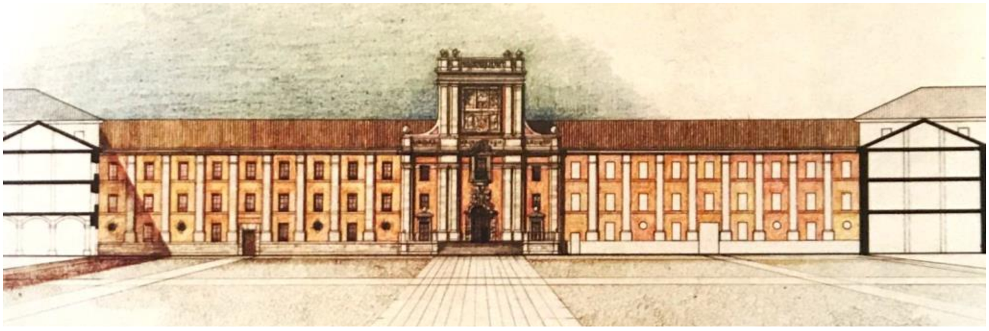


Fig. 3.12 – Restoration project of Julio Cano Lasso. (1981)

In 1976, the building was declared a historic-artistic monument, thus avoiding its demolition. In 1983, the Conde Duque became a cultural centre, dependent on the Ayuntamiento of Madrid. The restoration of the large complex was completed in 2011 by the recovery of the external and internal façades in exposed brick (Fig. 3.13).

Fig. 3.13 – The Cuartel de Conde Duque, view of the central court

Functional destination _ The building retains only in the name the sign of the original military destination. Today, in fact, it is one of the largest cultural centers of Madrid and hosts: on the ground floor and first floor, exhibition spaces, libraries, concert halls and representative spaces; on the second floor, the offices of the cultural center. The bovedas area, on the other hand, in which the test of the CNT device system was carried out, houses the large historical archive of the complex.

Materials and construction techniques_ Materials from different areas of the region have been used for the construction of the Conde Duque:[21]

- Wood from the mountains of Cuenca, El Espinar and Valsaín (Segovia) and Paular (Madrid);
- The lime extracted from Quijorna, Vaciamadrid and San Martín de la Vega (Madrid), Alameda de la Sagra (Toledo), and Tornes;
- The bricks produced in the furnaces of the convent of San Jeronímo and of Madrid, near the furnace of Villaverde, or of the Ribera (of the Tajo or of the Jarama);
- The tiles produced in the city of Toledo;

21 VVAA
El cuartel de Conde Duque de edificio militar a espacio cultural

- The stone extracted from Cerro de los Ángeles, Villaseca de la Sagra e Recas volta a crociera (Toledo), and Alpedrete (Madrid);
- The clay obtained from the sand of San Bernardino (Madrid).

The building consists of a supporting masonry structure that rests on continuous foundations. The complex has two levels below the ground floor, *sotano* -1 and *sotano* -2. The deepest is known as the zone of the *bovedas*, that is of the vaults, just because it is characterized by barrel coverings in brick that unload on reinforced walls, between the abutment, with chaotic textures in limestone (Fig. 3.14).

Fig. 3.14 – Detail in the zone of *bovedas.*

The other slabs, originally made up of wooden elements, were replaced with steel structures in the context of the several renovations after the fire. Also, the roof of the building, originally made of wood, was rebuilt with steel trusses.

The use of the brick is strongly recurrent in the façades and in many of the interiors in which it was left in sight while, for the columns of the ground floor and the decorative elements, they are made of natural stone.

The **presence of rising damp** _ At a first survey, the building did not show particular phenomena related to the presence of rising damp. It was only through the documentary analysis of the archival sources, which indicated the presence of very close aquifers, and the interview with the Office of Cultural Heritage, that it was possible to identify the areas that are really affected by this disease, which correspond to the sotano -2 area between the archive and the emeroteca (fig. 3.15 and 3.16).

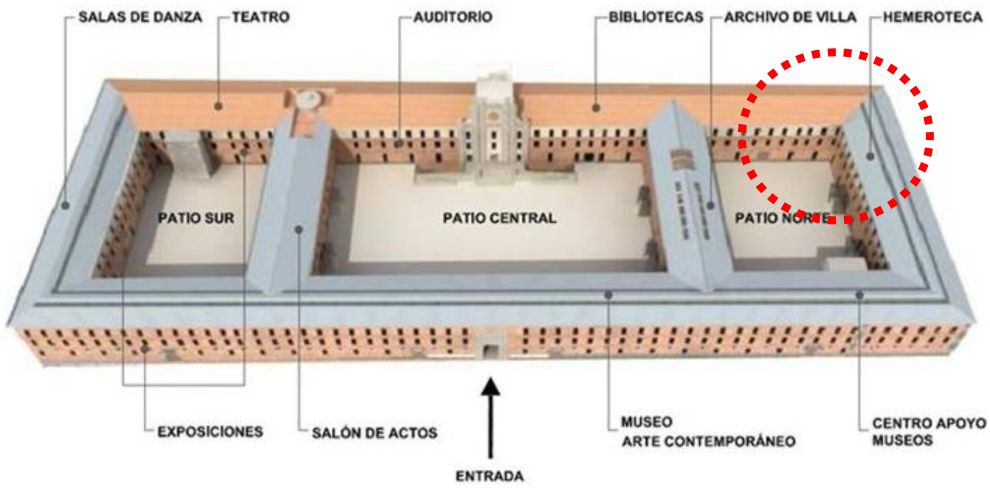


Fig. 3.15 – Identification of the area of intervention

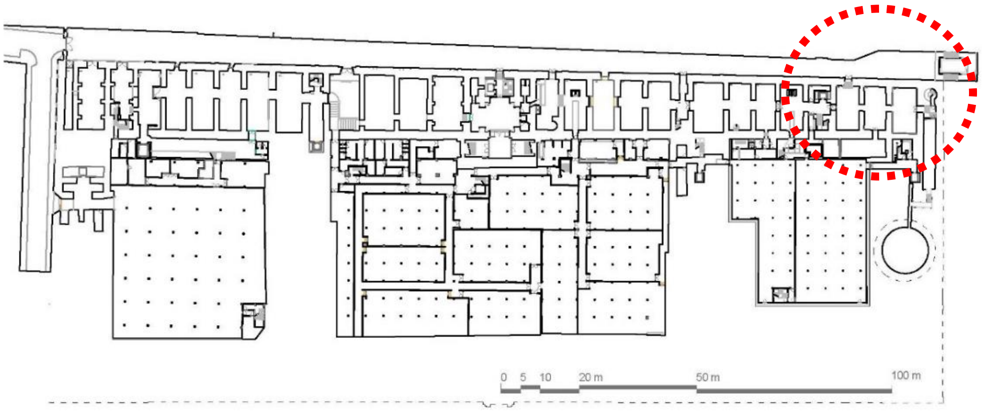


Fig. 3.16 – Identification of the area of intervention

This area, in fact, was historically close to a surfacing layer of water that was intercepted by the Guards of the Royal Body to feed the three fountains placed in the center of the courtyards to water and wash horses.

The first diagnosis did not highlight the phenomena of humidity because, in the framework of previous restoration works, in these rooms counter-walls and counter-vaults of ventilation were made to prevent the degradation of the documents contained in the archives. Nevertheless, the expedient of the ventilation channels was not an effective remedy to the solution of the problem which, instead, was clearly manifested to the outside (Fig. 3.17).

Fig. 3.17 – Interior with air ventilation channel detail (left) – external facade (right)

Accessibility and availability _ The area of intervention is currently unused precisely because of the unhealthy conditions of the environments that, moreover, do not allow to expand the near archive because of the danger of deterioration of the documents. As part of the test, a collaboration agreement has been signed with the Office of Historical Heritage of Madrid to ensure the postponement of the renovation of the softened finishes at the end of the monitoring period.

THE ESCUELA TÉCNICA SUPERIOR DE INGENIEROS DE MINAS Y ENERGÍA

Historical and architectural value[22] _ The institution of the School of Ingeneros de Minas was introduced in Spain under the reign of Charles III, with the Royal Ordinance of July 14, 1777. *“It is in this century of the Encyclopedia that science begins to be incorporated into empirical and experimental technologies. Mathematical knowledge is required as well as knowledge of minerals, starting with their chemical composition and crystallographic structures.”*

Some important results were soon achieved by the founders of the school: D. Fausto and Juan José de Elhàyar discovered the wolfram (or tungsten, the chemical element with symbol W whose atomic number is 74) and the foundation of the first Royal Mining Seminary of Mexico; the seminar was also attended by Professor Andrés Manuel del Ruo, known for being the first scientist to have isolated the vanadium (chemical element with symbol V whose atomic number is 23). At the end of the 18th century, Humboldt’s geological journeys through Hispanic America opened up the geology teachings in the Spanish and American Schools in parallel.

22 www.minasyenergia.upm.es

Until the middle of the 19th century, teaching was a mix of empirical, scientific and experimental knowledge. The Law on Public Education of 1857, then, created the title of Engineer setting itself as the starting point of a new concept of teaching.

The building of the Escuela Técnica Superior de Ingenieros de Minas Y Energía in calle de Ríos Rosas, was designed by the architect Velàzquez Bosco and inaugurated in 1896.

The teachings of the School were immediately closely linked to the development of techniques for the transformation of natural resources: non-ferrous metallurgy, for example, was introduced among the teachings only after the beginning of the production of steel in Asturias (1901). In the new guidelines in the studies were introduced the themes of Liquid Fuels, just two months after having thought of a national industry of refining, and hydrogeology. In the first half of the twentieth century were successfully conducted at the School of Radioactivity Studies and after 1946, those on nuclear energy as a basis for energy development for peaceful use.

The building is one of the oldest offices of the Polytechnic of Madrid. The architecture is very reminiscent of the main features of the work of Velàzquez Bosco, recurrent in the design of the Palacio de Velázquez, immersed in the wonderful context of the Parque de El Retiro and the Palacio de Fomento (current seat of the Ministry of the Middle Environment and the Middle Rural y Marino).

As for the latter, also the project of the School highlights the eclecticism of the author (the use in the same work of elements belonging to different artistic periods), the volumes and the decorations in ceramic on the facades, and the use of the *mansarda*, or French roof (Fig. 3.18, 3.19, 3.20).

Functional destination _ The building has maintained unaltered over time its original function. Still today it houses the E.T.S. de Ingenieros de Minas Y Energía. The test was conducted inside the chemistry laboratory in the basement. The environment is characterized by large crowds of classes and the production of fumes and vapours that certainly affect the thermo-hygrometric conditions also in terms of condensation. Conversely, the unhealthy conditions of the classroom and the inability to allow proper ventilation negatively affect the perceived degree of indoor comfort.

Destinazione funzionale _ L’edificio ha mantenuto inalterata nel tempo la funzione per cui era stato progettato. Ancora oggi ospita la sede della E.T.S. de Ingenieros de Minas Y

Fig. 3.18 – The E.T.S. de Ingenieros de Minas Y Energía (1906-1914)

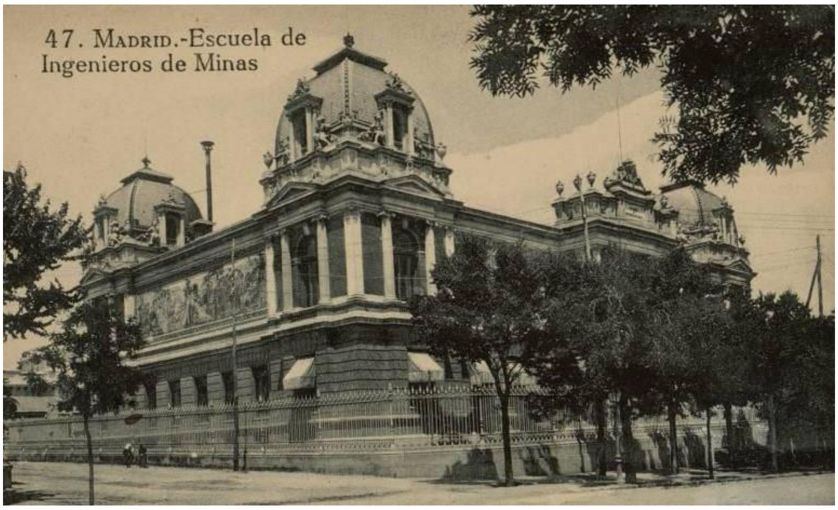


Fig. 3.19 – The completion of the School (1917)

Fig. 3.20 – The School today (2017)

Materials and construction techniques _ The building presents, as already mentioned, the coexistence of different materials and construction techniques merged together in the eclectic language representative of the work of Velasquez. It consists of a structure in supporting bricks which rests on a strong base of natural stone. Inside, the space is made dynamic by the presence of slender metal structures that overlook the atrium, also covered by a structure in iron and glass trusses (Fig. 3.21).

Fig. 3.21 – L'atrio (a sinistra) e la Biblioteca (a destra) della Scuola

The basement is organized in several laboratories, including that one of Chemistry. The whole level is bounded for three sides by an external cavedium, passable only for maintenance, that acts as element of separation to the filling ground, which is accessed by means of traps placed on the external perimeter (Fig. 3.22); the fourth side, instead, is in contiguity with the ground that fills the altitude jump.

Fig. 3.22 – Detail of the access trapdoors to the cavedium

Presence of rising damp _ The diagnosis of rising damp inside the investigated environment was not immediate. The particular position of the laboratory, placed in the basement at the corner between the internal facade of the building and the main facade, have requested a preliminary investigation to rule out two possible causes of the observed humidity phenomena: the water supply on the wall in direct contact with the ground and possible infiltrations from the lateral cavedium in which rainwater is conveyed (Fig. 3.23).

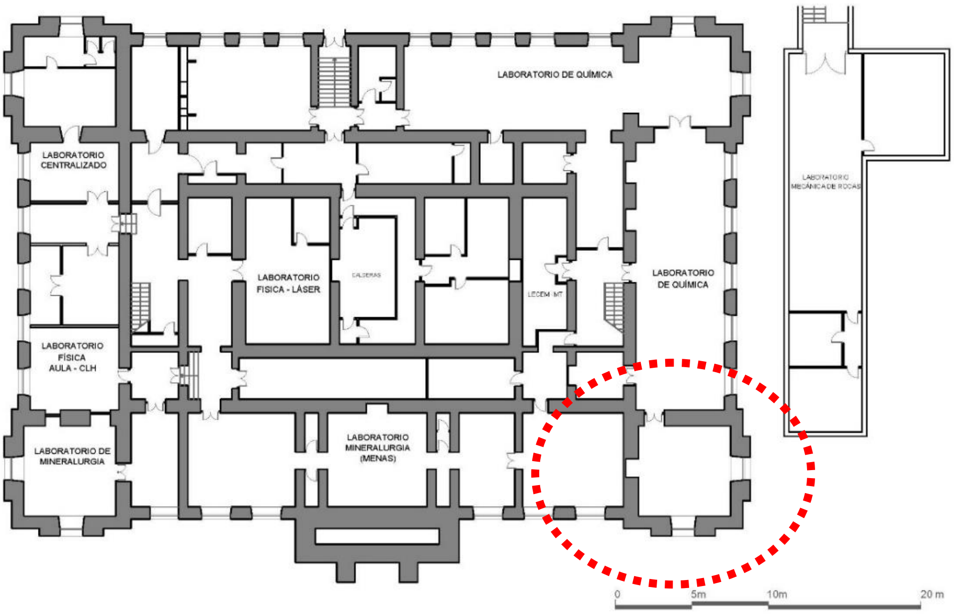


Fig. 3.23 – Identification of the area of intervention

Both components could be excluded from the results of the investigations, but it was accepted, as an initial assumption, that these circumstances could lead to unfavourable conditions for the disposal of the damp contents inside the wall. Added to this is the poor ventilation of the room, entrusted to a high window which is darkened by a technical volume (Fig. 3.24) and the extremely negative contribution, in terms of evaporative capacity, supplied by the cement finishes present on the entire interior wall of the laboratory and the ceramic tiles placed up to a height of about 1,50 m.

The combination of all parameters justifies the presence of the damp front limit at heights of 2,20 m, much greater than the normal operating conditions of a brick masonry.

Fig. 3.24 – Identification of the area of intervention

Accessibility and availability _ Throughout the trial period, academic activities have been carried out regularly pending full compatibility between the operation of the installed devices and the presence of people in the environments, in addition to the absence of interference with the rest of the instruments in the laboratory.

However, in order to monitor the intervention and to allow the ejection of the damp contents of the masonry, it was necessary to arrange the removal of the cement plaster in the measuring zone.

After 12 months from the installation, the School has expressed the need to restore the places before the start of the lessons; therefore, it was necessary to bring forward by one semester the conclusion of the test.

THE SANCTUARY OF BEATA MARIA VERGINE OF S. ROSARIO

Historical and architectural value[23] _ The foundation of the Sanctuary of Pompeii is due to the charity work of the Countess Marianna De Fusco Fornararo, originally belonging to a wealthy Apulian family, who moved to Naples in 1845 (when the city was the capital of the Regno di Napoli e delle Due Sicilie) with his mother who had been widowed for a few years. In Naples the Farnararo family settled in the palace of the Volpicelli family.

23 Ada Ignazzi,
Marianna Farnararo, contessa De Fusco

At the age of 16, Marianna Farnararo married the Count Albenzio De Fusco, a young landowner of Lettere (Naples), and their marriage was enlivened by the birth of five children: Giovanna, Francesco, Biagio, Vincenzo, Enrico.

Become Countess De Fusco, Marianna entered in the Neapolitan nobility, frequenting assiduously the worldly society of the capital; thanks to her husband Albenzio, she was able to establish friendships and important social relations which she later skillfully exploited for the realization of the Pompeian works. After twelve years of marriage, Count Albert De Fusco, barely forty, died, leaving Marianna, a 28-year-old widow, with five young children. The first years of widowhood were very hard for the young Marianna, who found herself alone to raise and educate the five children, as well as administering the land assets received in inheritance by her dead husband.

Therefore, in 1870, Marianna returned to the Volpicelli palace, where she devoted herself to religious practices. Catherine Volpicelli, in fact, had become the apostle of the Sacro Cuore di Gesù, starting the Pia Unione delle Ancelle e Oblate del Sacro Cuore, to then reach the foundation of the religious institute of the “Ancelle del Sacro Cuore”. The Countess Marianna, whose first seeds of spirituality had matured in the religious confraternities of her native Monopoly, was always close to her and was among the first to consecrate herself to the Terz’Ordine del Sacro Cuore.

Between 1867 and 1868, during the recitation of the Rosario in prayer groups, she met the lawyer Bartolo Longo, a native of Latiano (Brindisi), who have been moved to Naples to complete the law studies undertaken in Lecce.

In his first years in Naples, Bartolo Longo, conquered by the anticlerical spirit of the time, had distanced himself from the Church and had been involved in demonstrations against the clergy and the Pope. Some friends, however, helped him to return to the Catholic Church: he was invited to spread devotion to the Sacro Cuore di Gesù and, for this reason, addressed to Catherine Volpicelli and Countess De Fusco.

The cohabitation of Marianna and Bartolo in Palazzo Volpicelli lasted a year; in 1871 they left that residence to move to a building in Largo Salvator Rosa. The reasons for this transfer are attributed to the diversification of the apostolate action with respect to Caterina Volpicelli and to the Countess’s need to ease the pain suffered by her 8-year-old son Enrico, drowned in the well under construction in the palace.

Bartolo Longo Marianna De Fusco was entrusted with the administration of her land properties in Lettere, Gragnano and Valle di Pompei, attempting to make them fruitful. In Valle di Pompei Bartolo Longo also wanted to spread the recitation of the Rosario. *“When Bartolo Longo began his apostolate among the abandoned people of Pompeii, he found in Marianna a skilled, intelligent and precious collaborator. Together they began a journey of life and faith which saw them united and with only one intent: the care of the souls of the peasants of the Valle and the promulgation of the Marian cult with the recitation of the Rosario. Pursued in different ways only one objective: to do good for other people”*[24].

In 1875, the lawyer brought to Pompeii the painting of Madonna del Rosario, received as a gift by a nun of Naples; on 8 May 1876 the first stone of the Sanctuary was laid by the two founders. However, this communion of activities and the utilization of the proceeds of the patrimony for apostolate and voluntary purposes was not well seen. Pope Leone XIII, advised them to marry to put an end to the rumours, dispensing them from the previous vows. The wedding was celebrated on 1° April 1885, in the private chapel of the General Vicar of Naples, in the parish church of Santa Maria delle Vergini; Marianna Farnararo was 48 years old and Bartolo Longo 44.

In 1887 Pope Leone XIII blessed the crown and the other precious decorations of the now very venerated painting of Madonna del Rosario. In 1896 the couple ceded to the Santa Sede the Sanctuary and the other works of Pompeii. Pope Leone XIII declared Sanctuary as Pontificio, separating it from the jurisdiction of the diocese of Nola. In 1901 the Pope himself elevated the Sanctuary of Valle di Pompei to the role of Pontifical Basilica, a privilege enjoyed only by a few other sanctuaries in Italy. In September 1906 the couple, who had remained curators and administrators of the Sanctuary’s affairs, definitively ceded the administration to Pope Pio X (the two disposals are depicted in two frescoed medallions, placed at the base of the dome).

The Countess De Fusco died in Pompei in 1924 at the age of 88, ahead of her husband Bartolo of just over two years (1926 at the age of 85 years). The funeral was solemn; the body was initially buried in the Chapel of the Congregation of the Rosario of the cemetery of Naples, for its disposition, considering not to be worthy to rest in the Sanctuary but six years later, was again taken to Pompeii and buried near the bronze monument, which was dedicated to her in the Basilica. In 1938 his mortal remains were definitively moved to the

24 Ada Ignazzi,
Marianna Farnararo, contessa De Fusco

crypt of the Sanctuary, next to those of Bartolo Longo; the relics of this latter, proclaimed Blessed on October 26, 1980, were then placed in a special chapel of the Sanctuary.

The Sanctuary was built in different times. The original plant, erected between 1876 and 1891 on a design by Antonio Cua, was set on a Latin cross plan with a single nave and extended on an area of about 400 m^2 (Fig. 3.25).

Fig. 3.25 – The Sanctuary before the enlargement and works on the facade.

In the 1930's, the need to host many faithful led to the extension of the building on the same structure with a Latin cross, basing on the design by the architect Monsignor Spirito Maria Chiappetta. As a result of the enlargement, the Basilica has extended over an internal surface of 2000 m^2.

Functional destination _ The Basilica has always performed the function of a cult building. In detail the installation of CNT devices was carried out inside the Crypt below the high altar. The room hosts the celebration of Mass weekly and on religious celebrations but is not subject to large crowds.

Materials and construction techniques[25] _ The building has a bear-loads walls structure made with stone of Vesuvius; the aisles are instead marked by vaults on marble columns. The facade of the Basilica was erected in 1893 according to the plan drawn up by the architect Giovanni Rispoli on the model of the Roman basilicas, with a double order of columns and portico on three arches; in 1901 it was inaugurated as a monument to the Universal Peace. The decorative apparatus is made with the same travertine of the mountain Tifata that was previously used by Masuccio Secondo for the Tower of the church of Santa

25 www.santuario.it

Chiara and by Luigi Vanvitelli for the Royal Palace of Caserta. Between the two orders of columns in pink granite is placed the inscription in bronze “Virgini SS: Rosarii Dicatum” while, on the sides of the papal loggia there are pairs of columns binate in granite of Finland.

Numerous details and decorative elements in bronze enrich the entire facade that culminates with the statue of the Vergine del Rosario, made by Gaetano Chiaromonte with a single block of Carrara marble. A characteristic feature of the external façade is also the 80-metre-high bell tower, built between 1912 and 1925 by the architect Aristide Leonori. The supporting structure in red bricks is covered on the outside by five orders in grey granite and white marble and culminates with a dome 6 meters high. As a result of the stress caused by the earthquake which struck Irpinia in 1980, the A characteristic feature of the external façade is also the 80-metre-high bell tower, built between 1912 and 1925 by the architect Aristide Leonori. The supporting structure in red bricks is covered on the outside by five orders in grey granite and white marble and culminates with a dome 6 meters high. As a result of the stress caused by the earthquake which struck Irpinia in 1980, the bell tower had to undergo some consolidation and restoration work.

Inside the Basilica is divided into a central aisle and two lateral minors, all richly decorated with marbles, frescoes and precious vessels of worship (like the four wooden confessionals) made by the Neapolitan cabinetmakers Vincenzo Trudi and Luigi Bellavita (Fig. 3.26).

Fig. 3.26 – The Sanctuary from the outside (left) and from the central aisle (right)

At the intersection between the central nave and the transept the dome rises, high about 57 meters, on two drums: the lower one ends in a ciborium while the upper is pierced by windows and covered by a lantern with a dome. The fresco of the dome is the work of the painter Angelo Landi of Salò and represents the “vision or dream of St Domenico”.

To the left of the main altar there is a door carved by Vincenzo Trudi on a design by architect Giovanni Rispoli that leads, through a staircase, to the Crypt realized during the enlargement of the Basilica of the 30's. Here, along with others, the remains of Countess Marianna De Fusco are preserved, alongside a bust made by sculptor Domenico Paduano.

The installation of the CNT device system was carried out just in front of the altar of the Crypt, on the wall near to a passage closed by a dark marble (Fig. 3.27).

Fig. 3.27 – The Crypt altar (left) – The installation wall (right)

Presence of moisture from capillary rise _ The diagnosis of the presence of rising damp had to consider immediately the location of the room. The Crypt, in fact, is located at a low altitude; in particular, the environment immediately behind the wall investigated, which showed the greatest signs of humidity, seems to be walled and not accessible. Therefore, it was considered that the phenomena encountered could be partly affected by the contribution of other water supplies coming, for example, from any filling behind the masonry (Fig. 3.28).

Moreover, it has been verified that the environment, beyond being able to take advantage of the beneficial contribution of the external sunlight, which would have facilitated the disposal of the wet contents by evaporation towards the external, does not receive even a sufficient natural ventilation; the few openings present, in fact, fail to allow the circulation of the air due to the physical obstacle caused by the body of the central altar. Although there is a mechanical ventilation inside the room, the age of the plant and poor maintenance have not allowed it to be used in order to improve indoor conditions.

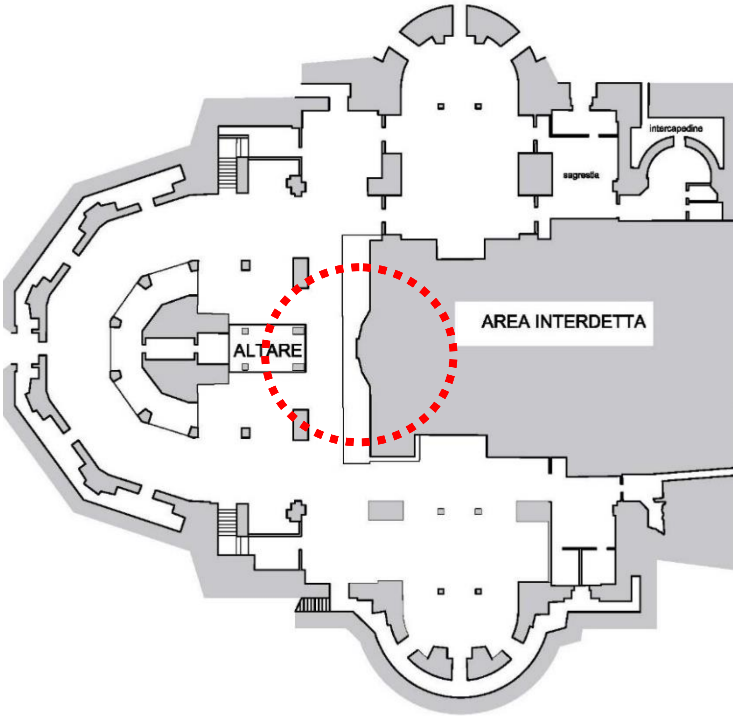


Fig. 3.28 – Identification of the area of intervention

Accessibility and availability_ Throughout the trial period the Crypt remained totally accessible to the faithful both for the visit, which sometimes took place without any interference even during the monitoring operations, and for the religious celebrations.

The survey within the three sites was carried out by installing the CNT device system, IDROSCAN probes and probes for monitoring the environmental parameters of relative humidity and internal temperature. Each installation was equipped with a modem that provided the connection of the devices to the company, so that it could check the operation remotely and report the anomalies.

In the sites of the Conde Duque and Escuela de Minas the installation was carried out in spring 2018 and the monitoring was carried out every six months (autumn 2018 – spring 2019 – autumn 2019). The recovery work of the Escuela de Minas laboratory, which was unpredictable, did not allow the last monitoring of autumn 2019.

In the Basilica of Pompeii the survey began in July 2017. In this case, pending the frequency with which these places of worship are visited, monitoring has been carried out annually (July 2017– July 2019).

4. TESTING ON MATERIALS

Chapter 2 deals with the effects of the presence of water within the porous structure of the building materials, the consequent reduction in mechanical and thermal performance and the dimensional alteration of the elements, the phenomena of superficial decay and the detachment and pulverization of the material.

It has been observed that the lesser or greater aptitude of a material to absorb water and to allow its movement depends on its physical characteristics (porosity), on the chemical nature (the silica composition) and the electrostatic attraction that takes place between the water and the walls of the capillary pores.

Experimental surveys carried out by various researchers have shown that the mechanical resistances of a material, natural or artificial (in the case studies have been analyzed the experiments on tuff[1] and bricks[2]) are strongly reduced in complete and semi-saturation conditions (S = 100% and S = 50%).

Other studies, however, have shown that the presence of moisture inside a building material leads to an overall reduction in the degree of thermal insulation of the entire wall and, consequently, in the energy performance of the building envelope.

Both results highlight a very important aspect: the mechanical and thermal behaviour of materials changes over time, in relation to the natural ageing and external conditions. The parameters used in the modelling of buildings, therefore, cannot prescind from this change.

The diagnostic phase, prior to the choice of structural consolidation or energy efficiency measures, must consider the specifications (and not theoretical) performance of the material in its conditions of use. Even in the simplest case of interventions for the conservation,

1 R. Ceroni, M. Pece, G. Manfredi, G. Marcari, S. Voto
Analisi e caratterizzazione meccanica di murature di tufo

2 E. Franzoni, C. Gentilini, G. Graziani and S. Bandini
Compressive behaviour of brick masonry triplets in wet and dry conditions

knowing the real state of the wall according to the degree of saturation of materials can guide the choice of method and technologies to be adopted. The intervention may be more or less light depending on the results provided by the diagnosis: from the adoption of evaporative interventions to the substitution of portions of masonry, through the method of replacement of bricks suggested when the material has lost its mechanical performances.

Unlike the many tests carried out for the evaluation of mechanical resistance of wet materials, no studies have been found in bibliography on the measurement of the percentage variation of thermal conductivity of building materials in relation to their degree of saturation.

Therefore, in order to outline the true behaviour of masonries under operating conditions and to correct the calculation values used in the structural or energy simulation of the building, the research has promoted the development of two distinct experimental campaigns to **quantify the variation in performance of traditional building materials** subjected to different degrees of imbibition. The test has also given the opportunity to make some interesting remarks on the data obtained from previous research made by other scholars.

Downstream of the bibliographic studies aimed at identifying the typical materials of the Madrilenian and Neapolitan building tradition, it was decided to develop the tests on the Madrilenian bricks and the Neapolitan yellow tuff.

METHODOLOGY FOR CONDITIONING SPECIMENS

The laboratory tests were carried out by imposing different saturation conditions on the specimens. The samples were divided into groups of 3, each with a given wet content. For each degree of saturation an average of the test values recorded on the three corresponding samples was considered.

The bibliographical references suggested testing the samples under dry (S = 0%), semi-saturated (S = 50%) and saturated conditions (S = 100%).

Therefore, the mechanical tests on the tuff have been carried out at these saturation levels, varying the method of conditioning the test pieces to evaluate the incidence of the drying and imbibing cycles (in air or in oven) on the mechanical behaviour of the stone. Due to the difficulty of finding the necessary instrumentation, it was not possible to perform thermal tests on this material.

On the other hand, for bricks, both mechanical resistance tests and measurements of the thermal conductivity change, as a function of the saturation degree of the samples, were carried out. In this case, considering that little quantities of moisture, including 15÷30%, can significantly affect the alteration of the thermal insulation of materials, causing in the building envelope a sudden increase in thermal conductivity and a lowering of the thermo-hygrometric comfort of the internal environments, it was decided to introduce an additional range of saturation S ≈ 25%. This class is certainly more representative of the normal operating situations of a masonry.

The conditioning of the samples was carried out according to the weight method described by UNI 11085[3], based on the principle of the loss of mass of a sample after drying by heating, and was applied using the following equipment:

- Balance with accuracy of 0,01 gr
- Electric laboratory heater capable of maintaining drying temperature with a stability and uniformity of 2°C
- Dryer containing silica gel with cobalt chloride indicator

It should be noted that the assessment of “saturated weight” of natural and artificial stone elements is not immediate and sometimes requires complex procedures, with application of vacuum, pressure or boiling to achieve total saturation of the blocks, which shorten the experimental time but require more control in the laboratory[4]. In this study, due to the high sensitivity of the moisture data, the total immersion method laid down by UNI EN 772-11[5] was adopted. However, for the sake of completeness, reference should be made to the simplified method proposed by Z. Zaretzky[6], which provides comparable results obtained by means of household instruments: a pressure cooker with a temperature of 110÷115°C and a pressure of 0,75 kp/cm^2, and a kitchen balance with a capacity not less than 2kg and a sensitivity of 0,5g.

After recording the initial weight of the samples under environmental conditions, they were all subjected to 4-hour drying cycles in the oven at 105°C and cooling in the dryer until the ambient temperature was reached. At the end of each step the samples were weighed. The

3 UNI 11085:2003
Materiali lapidei naturali ed artificiali. Determinazione del contenuto d’acqua: metodo ponderale

4 A. Garcia Verduch
Método para la determinación de agua de los ladrillos.

5 UNI EN 772-11:2011. Determinazione dell’assorbimento d’acqua per muratura

6 Z. Zaretzky
Porosidad aparente y otros datos - Control rápido en refractarios

test is completed when the difference between two successive weights was less than 0.1% by determining the dry weight of the samples (W_d).

Subsequently, the samples were completely immersed in water until the constant mass was reached, thus determining the wet weight (W_W) of each sample and, by difference with the dry weight, the percentage of the absorbed water content C_W, applying the relation (Eq. 4.1):

$$C_w = \frac{(W_w - W_d)}{W_d} x\ 100$$

Eq. 4.1

Some samples were tested in this condition of complete saturation with S = 100%. The others, on the other hand, were turned to the oven until the intermediate values of moisture were reached, determined according to the quantity of known water to be disposed of.

In order to ensure a uniform distribution of the wet content within the investigated elements, the samples were thermo-hygrometric balanced prior to each test; the bricks were left for one hour in the humid chamber (at a temperature of 20÷22°C and relative humidity of 40÷60%) while the tuff blocks have been properly sealed to allow the expansion of the moisture content inside the capillary system of the material hindering evaporation towards the external.

Finally, the last three test specimens were turned to the condition S=0% by drying in an oven at 105°C until the initial dry weight was reached and tested in this dry condition.

4.1 LABORATORY TESTING ON MADRILENIAN BRICKS

The experimental survey, made at the Polytechnic of Madrid, was developed using the solid bricks produced by the company “Ladrillos artesanos” located in the municipality of Navas de Oro of the Autonomous Community of Castilla y León. The company is specialized in the production of bricks handmade “in the ancient way” which are used in the restoration of historical architectures to replace the damaged parts of the building.

The company produces two types of bricks composed of the same solid matrix, obtained from the mixture of local clay with water; the difference between the two products consists in the way they are dried or cooked. Some of them, in fact, are air-dried, according to the traditional method, and for this reason have been coded in the test with the acronym T (traditional method); others, instead, are cooked in biomass ovens, according to a modern method, and for this they have been coded in the test with the acronym M (modern method). The shapes of the bricks and special elements are obtained by making each time special formworks to reproduce faithfully the elements of the building to be replaced in the restoration (Fig. 4.1).

Fig. 4.1 - Brick construction and air-drying phases

Each brick has been cut to obtain two prismatic elements of size 4x4x16cm; a total of 24 samples, 12 of type T and 12 of type M have been tested. On the two types, as a preliminary step, a phase of physical characterization by observation in microscopy at 225x (Fig. 4.2).

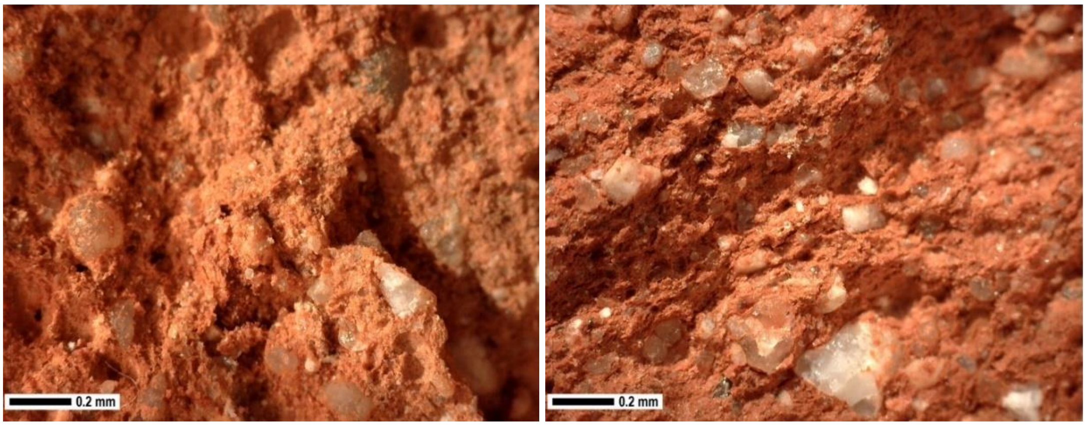


Fig. 4.2 – Microscopic images of T–samples (on the left) and M-samples (on the right)

The analysis shows that the solid matrix of air-dried bricks T has less compactness than the solid matrix of those dried in furnace M.

To verify the observed data, the physical characteristics of the two specimens were measured: by the ratio between the volume of the solid part and the volume of the voids, obtained by calculating the volume occupied by water under conditions of complete saturation, it is noted that the average porosity of the T samples is greater than the average porosity of the M samples (Tab. 4.1).

Tab. 4.1: Physical properties of the investigated material

	V_S [cm³] volume of the sample	**V_v** [cm³] volume of voids	**V_s** [cm³] V_p-V_{mv} volume of the solid	**n** V_v/V_s porosity	**e** V_v/V_s porosity index
T 1-12	256,00	60,42	195,58	0,24	0,31
M 1-12	256,00	51,02	204,95	0,20	0,25

For both types of samples, the water absorption coefficient has been calculated, applying the ratio (Eq. 4.2) provided by UNI EN 772-11[7]:

$$C_{wa} = \frac{p_{sat} - p_{dry}}{S_s \sqrt{t_{so}}} \; x \; 10^6 \qquad \left[\frac{g}{m^2 \cdot s^{0,5}}\right]$$

Eq. 4.2

p_{dry} weight of dry material
p_{sat} weight of water saturated material
S_s side surface of the blocks immersed in water
t_{sat} total time of saturation

The measurement results are given in Tabb. 4.2 and 4.3:

Tab. 4.2: Absorption coefficient of samples T

	t = 24h	**t = 44h**		
	W_{dry} [gr] Dry weight	**W_{wet}** [gr] Wet weight	**C_{aw}** $\left[\frac{g}{m^2 \cdot s^{0,5}}\right]$ Absorption coefficient	**Δ C_{awa}** Average absorption coefficient
T1	506,21	562,04	7,22	**7,19**
T2	475,20	532,05	7,36	
T3	508,20	568,11	7,75	
T4	473,70	529,78	7,26	
T5	469,48	526,07	7,32	
T6	414,81	464,17	6,39	
T7	507,35	564,69	7,42	
T8	467,91	523,18	7,15	
T9	455,69	507,34	6,68	
T10	479,58	533,89	7,03	
T11	471,71	527,86	7,27	
T12	480,92	538,23	7,42	

7 UNI EN 772-11:2011
Metodi di prova per elementi per muratura - Parte 11: Determinazione dell'assorbimento d'acqua per muratura...

Tab. 4.3: Absorption coefficient of samples M

	t = 24h	t = 44h		
	W_{dry} [gr] Dry weight	**W_{wet}** [gr] Wet weight	**C_{aw}** $\left[\frac{g}{m^2 \cdot s^{0,5}}\right]$ Absorption coefficient	**Δ C_{awa}** Average absorption coefficient
M1	556,99	604,76	6,18	**6,09**
M2	531,22	575,71	5,76	
M3	553,96	603,25	6,38	
M4	530,15	577,28	6,10	
M5	518,78	566,14	6,13	
M6	530,56	579,44	6,33	
M7	558,48	606,09	6,16	
M8	515,89	559,41	5,63	
M9	524,26	573,74	6,40	
M10	530,55	579,61	6,35	
M11	526,20	570,22	5,70	
M12	548,65	594,64	5,95	

The report confirms that there is a 15% higher absorption in the T-samples produced with air drying than in the M-samples oven dried.

Following the conditioning methodology of the samples, the terns corresponding to each degree of saturation have been identified (Tab. 4.3):

Tab. 4.4: Grouping of test pieces to conditioning

Degree of saturation	**Air dried bricks (T)**		**Oven cooked bricks (M)**	
	tern	**elements**	**tern**	**elements**
S = 100%	T_{1-3}	$T_1 - T_2 - T_3$	M_{1-3}	$M_1 - M_2 - M_3$
S ≈ 50%	T_{4-6}	$T_4 - T_5 - T_6$	M_{4-6}	$M_4 - M_5 - M_6$
S ≈ 25%	T_{7-9}	$T_7 - T_8 - T_9$	M_{7-9}	$M_7 - M_8 - M_9$
S = 0%	T_{10-12}	$T_{10} - T_{11} - T_{12}$	M_{10-12}	$M_{10} - M_{11} - M_{12}$

The dry weight (S=0%) and the saturated weight (S=100%) were identified for each sample using the conditioning method. The difference between the two values corresponds to the maximum quantity of water that can be contained by each sample in relation to its size and porous structure (absorption index). Therefore, weights for intermediate saturation conditions could be identified. Each drying cycle in the oven was stopped when the ideal weight was reached, that is the wet content that must be investigated.

VARIATION IN THERMAL PROPERTIES AS SATURATION CHANGES

Each tern of samples in each saturation condition has been subjected to a direct and non-invasive measurement of thermal conductivity. The instrument used, C-Therm TCi system, applies the MTPS (modified transient plane Source) technology, standardized by

ASTM D7984[8]. The technique uses a sensor that produces a heat reflectance with a spiral plate placed at its summit, in contact with the material sample. (Fig. 4.3)

Fig. 4.3 – Equipment used for measuring thermophysical properties

The temperature increase between the samples and the sensor results in a change in the voltage of the sensor inversely proportional to the thermal conductivity of the material: the voltage increase is faster for thermally insulating materials.

In this case, in order to limit the contact resistance between the samples and the sensor, a thin layer of Wakefield 120 paste has been placed, a contact agent with known thermal resistance that eliminates the influence of the layer of air created by the roughness of the samples and thus corrects the measurement recorded.

For each sample tested, four measurements were made on opposite faces. In the final analysis, an average of the values recorded for each element and an average of the values recorded for each group under the same saturation conditions were considered. The calculated averages of effusivity values **E** and conductivity values **K** and their standard deviations shall be reported for each tern.

In order to assess the variation in the thermal performance of material with different water contents compared to that in working conditions, the test was also carried out on samples under thermo-hygrometric environmental conditions, which represents the condition of bricks after their production. For these specimens, indicated in the table with the acronym **EC,** a value of physiological moisture is calculated close to 4% (Tab. 4.5).

8 ASTM D7984 – 16.
Standard Test Method for Measurement of Thermal Effusivity of Fabrics Using a MTPS Instrument

Tab. 4.5: Thermal measurements at different saturation degrees

	Saturation [%]	**E** [Ws½/m²K]	**Standard deviation** [%]	**K** [W/mK]	**Standard deviation** [%]
T_{1-3}	S=100%	1921,25	2,3	1,90	4,5
T_{4-6}	S≈50%	1562,63	4,1	1,30	6,4
T_{7-9}	S≈25%	1203,05	14,8	0,87	21,2
T_{10-12}	S=0%	1225,98	5,8	0,89	9,2
M_{1-3}	S=100%	1981,96	0,6	2,02	1,1
M_{4-6}	S≈50%	1695,39	6,1	1,47	13,1
M_{7-9}	S≈25%	1263,72	2,2	0,93	3,5
M_{10-12}	S=0%	1121,76	9,0	0,77	14,1
EC	S≈4%	1156,25	-	0,81	-

For air-dried samples T an increase in thermal conductivity equal to 46% from dry to semi-saturated condition (S ≈ 50%) and 113% from dry to saturated condition (S = 100%) was found (Fig. 4.4)

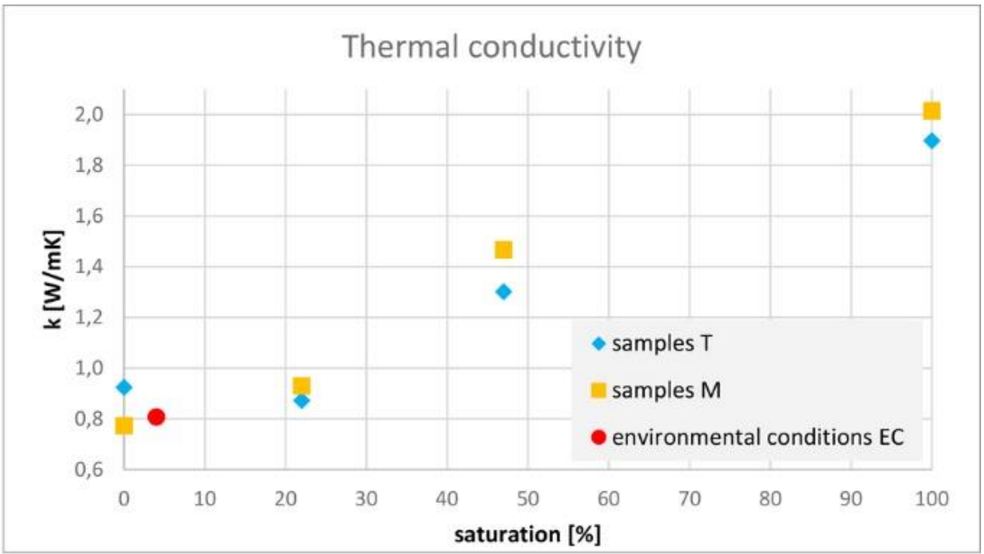


Fig. 4.4 – Thermal conductivity values at different saturation degrees

This performance decay is even more evident in specimens cooked in the oven M for which there is an increase in thermal conductivity of 90% from dry to semi-saturated condition (S ≈ 50%) and 160% from dry to saturated condition (S = 100%).

At the same degree of saturation there is a difference in the data recorded for the two types of samples: the increase in thermal conductivity related to the the increase of the water content is much greater in samples cooked in the oven M.

Similar studies made on other materials had shown analogous results: some experiments carried out on wood-based materials have shown that thermal conductivity increases almost linearly with the moisture content at a given temperature and greatly with the increase in temperatures[9]; a similar study made to measure the thermal conductivity value of autoclave aerated concrete at 0-45°C temperatures and 0- 41,5% humidity content, showed a significant change in the thermal conductivity of the analysed material in relation to the variation in humidity and temperature[10].

On the contrary, no previous experiments have been carried out to assess the variation in the effusivity and thermal conductivity of bricks, depending on their saturation degree and the way they are packaged. As an example, the value of the thermal conductivity of solid masonry bricks extracted from the database of a software commonly used for numerical simulations of the behaviour of masonry in presence of moisture, equal to 0,6 W/m K is compared with the calculated values of 0,87 W/m K (for T samples) and 0,93 W/m K (for M samples) at the lowest saturation range of 25%.

A standard reference that addresses the problem of the variation of the thermal performances in presence of humidity is supplied by the UNI EN ISO 10456[11]; the standard supplies the corrective coefficients to be applied to the values of thermal conductivity relating to the saturation degree. However, Table 4 of that standard specifies that these coefficients are only applicable for wet content ranges between 0 and 25 m^3/m^3, while there are no indications for higher saturation levels.

CHANGES IN MECHANICAL PROPERTIES AS SATURATION CHANGES

The sample terns were subjected to mechanical strength tests by imposing bending rupture according to UNI EN 12372[12]. Each half of the samples obtained from the bending rupture was subjected to uniaxial compression tests with a load application speed of 0,05 $(N/mm^2)/s$, carried out in accordance with UNI EN 772-1[13] (Fig. 4.5).

9 E. Troppova, M. Svehlık, J. Tippner and R. Wimmer
Influence of temperature and moisture content on the thermal conductivity of wood-based fibreboards

10 Z. Pehlivanli, R. Calin and I. Uzun
Effect of Moisture and Temperature on Thermal Conductivity of G2/04 Class Autoclaved Aerated Concrete

11 UNI EN ISO 10456:2008
Materiali e prodotti per edilizia. Proprietà igrometriche

12 UNI EN 12372:200
Metodi di prova per pietre naturali. Determinazione della resistenza a flessione sotto carico concentrato

13 UNI EN 772-1:2015
Metodi di prova per elementi per muratura - Parte 1: Determinazione della resistenza a compressione

Fig. 4.5 – Equipment used for bending and compression mechanical strength tests

The mean value of the tests carried out for each saturation degree was still compared with that obtained on samples under environmental thermo-hygrometric conditions (Tab. 4.6).

Tab. 4.6: Mechanical measurements at different saturation degrees

	Saturation [%]	f_{btm} [MPa]	**Standard deviation** [%]	f_{bm} [MPa]	**Standard deviation** [%]
$\mathbf{T}_{1-3}$	S=100%	2,30	51,1	8,80	21,4
$\mathbf{T}_{4-6}$	S≈50%	2,22	31,3	6,48	43,6
$\mathbf{T}_{7-9}$	S≈25%	2,90	16,1	8,68	11,7
$\mathbf{T}_{10-12}$	S=0%	2,62	10,0	9,15	13,4
$\mathbf{M}_{1-3}$	S=100%	4,67	16,7	13,75	13,9
$\mathbf{M}_{4-6}$	S≈50%	3,97	26,6	12,46	8,5
$\mathbf{M}_{7-9}$	S≈25%	4,51	20,2	12,94	2,9
$\mathbf{M}_{10-12}$	S=0%	4,79	22,8	14,41	23,2
EC	S≈4%	2,36	-	11,33	-

Although with a lower impact, also the mechanical resistance tests have shown a performance decay of the material when they are wetted.

For air-dried T-samples, a 29% reduction in compressive resistance from dry to semi-saturated condition (S ≈ 50%) and 4% from dry to saturated condition (S = 100%) was found.

For cooked in oven M-samples this reduction is 14% from dry to semi-saturated (S ≈ 50%) and 5% from dry to saturated condition (S = 100%) (Fig. 4.6 and 4.7).

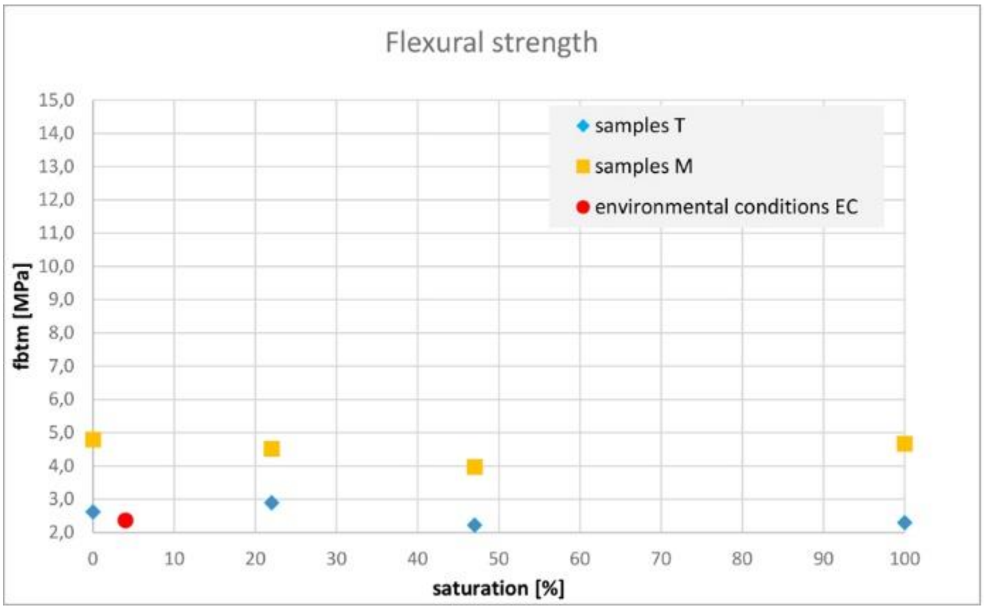


Fig. 4.6 – Flexural strength values at different saturation degrees

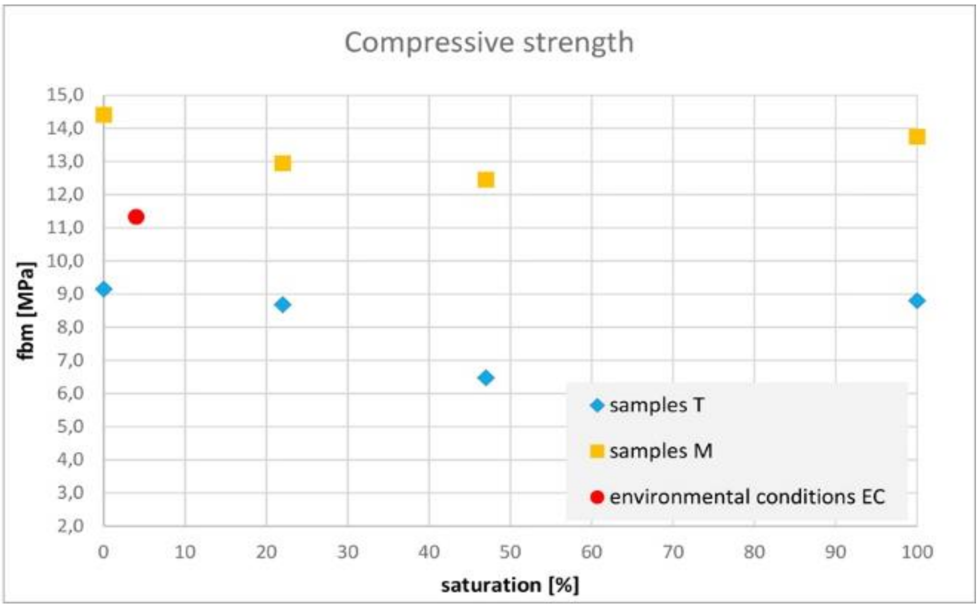


Fig. 4.7 – Compressive strength values at different saturation degrees

It is interesting to note that the performance drop in terms of mechanical strength is greater in intermediate saturation conditions than the condition of complete saturation. This evidence is probably linked to the way the specimens were conditioned to reach the required water content: after an initial drying phase in the oven at 105°C for the determination of the dry weight, all the samples were completely immersed in water until the saturated weight was reached. Subsequently, some test pieces were tested with maximum saturation, while the others were conducted at intermediate saturation levels by further drying cycles in the oven and achieving thermo-hygrometric equilibrium in the humid chamber. Therefore, it is reasonable to assume that this second cycle of forced drying has led to a further decay of the mechanical performance of the material.

In both cases, there is a decrease in the uni-axial compressive strengths of 75% of the samples in the semi-saturated condition (S ≈ 50%) and 29% of the samples in the saturated condition (S = 100%) compared to the resistance of a sample tested under environmental thermo-hygrometric conditions (shown in red on the graph).

The results obtained from the experiment offer the opportunity to carry out different evaluations: on the one hand, the change of the performance, especially thermal, of the samples belonging to the same class (packaged with the same procedure)according to the variation of the saturation degree; on the other hand, with the same moisture content, there was a different behaviour of the air-dried samples compared to those cooked in the oven. This last feature shows how even the packaging process affects the accomplishment of the thermal and mechanical properties of the building materials.

Note

This research and related results are published in the paper

V. Vitiello, R. Castelluccio and M. Del Rio Merino (2020). Experimental research to evaluate the percentage change of thermal and mechanical performances of bricks in historical buildings due to moisture. *Construction and Building Materials*, ISSN 0950-0618, doi.org/10.1016/j.conbuildmat.2020.118107

4.2 LABORATORY TESTING ON NEAPOLITAN YELLOW TUFF

The experimental survey, conducted at the DICEA of the University of Naples Federico II, was developed using Neapolitan yellow tuff taken during the excavation works carried out for the construction of the S. Rocco gallery near Capodimonte. The material extracted on that occasion was kept for years in one of the courtyards of the Department. This condition of long exposure to atmospheric agents was particularly interesting to assimilate the degree of natural aging of the material, subjected to drying and bleaching cycles by rain, to that of the blocks constituting the walls of a historic building. The blocks have been cleared removing the first surface layers, affected by the formation of biological microorganisms, and cut into cubic samples of size 10 x 10 x 10 cm. A total of 15 samples were tested. (Fig. 4.8).

Fig. 4.8 – From left: material before cutting, dimensional check of samples, cataloguing of specimens

The first phase of material characterization included the measurement of its specific weight using the pycnometer, according to the methods prescribed by ASTM D854[14]. The test is based on the measurement of the volume of water contained in a pycnometer with known capacity, which is moved from the volume of material inserted into it. Knowing the density of the liquid and the initial weight of the material, which is dried before the test to remove the physiological moisture content, it is possible to determine the density of the investigated sample (Fig. 4.9).

14 ASTM D854
Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer

Fig. 4.9 – Test steps on a powder sample (left) and solid sample (right)

Considering that a piece of stone completely immersed in water preserves a very small percentage of not filled voids, relative to the pores not communicating with each other that cannot be passed through by the fluid, a second measurement was carried out using pulverized and screened material. Therefore, pycnometers with a different capacity of 100cc had to be used for the test with powder material and 250cc for the test with solid material.

The results of the measurement showed for the powdered samples a density 12% higher than the that one of the solid samples, attributable to the effect produced by the pulverization in the elimination of residual pores (Tab. 4.7).

Tab. 4.7: Specific Gravity measurement by Water Pycnometer Method

POWDERED MATERIAL			**SOLID MATERIAL**		
$\mathbf{W_{pyc}}$ [gr] pycnometer weight 100cc	$\mathbf{W_{mat}}$ [gr] material weight	$\mathbf{W_{mat} / V_{mat}}$ [gr/cm^3]	$\mathbf{W_{pyc}}$ [gr] pycnometer weight 250cc	$\mathbf{W_{mat}}$ [gr] material weight	$\mathbf{W_{mat} / V_{mat}}$ [gr/cm^3]
59,77	16,93	**2,55**	189,94	20,27	**2,24**

In this test, not being able to perform the measurements of the thermal properties of the materials, it was chosen to operate in the conditioning classes corresponding to the dry (S = 0%), semi-saturated (S ≈ 50%) and saturated (S = 100%) conditions. Lower water content did not provide any interesting data on the change in mechanical performance. Therefore, by indicating the samples with the acronym TGN (Tufo Giallo Napoletano – Neapolitan Yellow Tuff) and following the conditioning method described in the previous paragraphs, the sample classes corresponding to each degree of saturation have been identified, each containing 5 samples tested (Tab. 4.8):

Tab. 4.8: Grouping of samples

Saturation degree	Neapolitan yellow tuff samples class	elements
S = 0%	TGN 1 - 5	$TGN_1 – TGN_2 – TGN_3 – TGN_4 – TGN_5$
S ≈ 50%	TGN 6 - 10	$TGN_6 – TGN_7 – TGN_8 – TGN_9 – TGN_{10}$
S = 100%	TGN 11 - 15	$TGN_{11} – TGN_{12} – TGN_{13} – TGN_{14} – TGN_{15}$

The dry weight (S = 0%) and the saturated weight (S = 100%) were identified for each sample using the conditioning method. The difference between the two values corresponds to the maximum amount of water that can be contained by each sample in relation to its size and porous structure. From this value the ideal sample weights for the saturation class corresponding to S = 50% were identified.

CHANGES IN MECHANICAL PROPERTIES AS SATURATION CHANGES

The first phase of the test was carried out by imposing the saturation degrees of the samples by soaking them through complete immersion and subsequent drying in the oven at 105°C until the ideal weight (the established wet content) was reached.

The five samples of each saturation range were subjected to mechanical uniaxial compression tests carried out in accordance with UNI 9724-3[15]. The test was made using a monotone load at a speed of 0,5 MPa/s. At the same time the values of axial deformations read from 4 measures (Fig. 4.10)

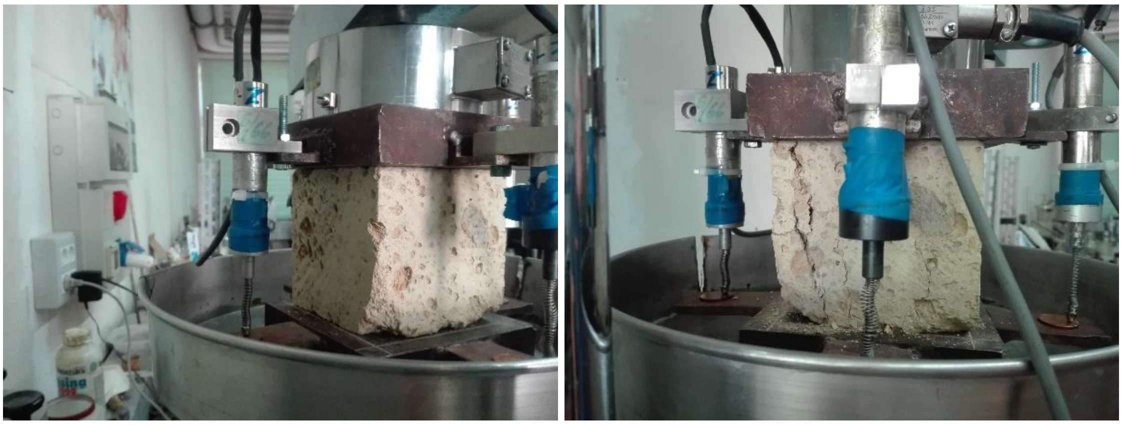


Fig. 4.10 – Test steps before breaking (left) and after (right)

Analysis of the data shows a reduction of the mechanical compressive strengths when the degree of saturation increases.

15 UNI 9724-3:199
Materiali lapidei. Determinazione della resistenza a compressione

In fact, for samples tested under dry conditions (S = 0) a mean of the five maximum diverting strain of 2.3 MPa was recorded; for samples tested in semi-saturated conditions (S ≈ 50%) an average of the five maximum diverting strain of 1,6 MPa was recorded; finally, for the samples tested under full saturation conditions (S = 100%), an average of the five maximum diverting strain of 1,3 MPa was recorded (Tab. 4.9).

Tab. 4.9: Mechanical measurements at different saturation degrees

sample	Saturation [%]	Maximum Compressive strength [MPa]	Medium Compressive strength [MPa]	Standard deviation [%]
TGN 1	S = 0	2,53	2,30	11,2%
TGN 2		2,02		
TGN 3		2,59		
TGN 4		2,07		
TGN 5		2,28		
TGN 6	S ≈ 50%	1,35	1,64	10,2%
TGN 7		1,56		
TGN 8		1,42		
TGN 9		1,33		
TGN 10		0,86		
TGN 11	S = 100%	1,37	1,30	20,4%
TGN 12		1,61		
TGN 13		1,69		
TGN 14		1,72		
TGN 15		1,80		

The diagram between the stresses and deformations is shown in the graph (Fig. 4.11).

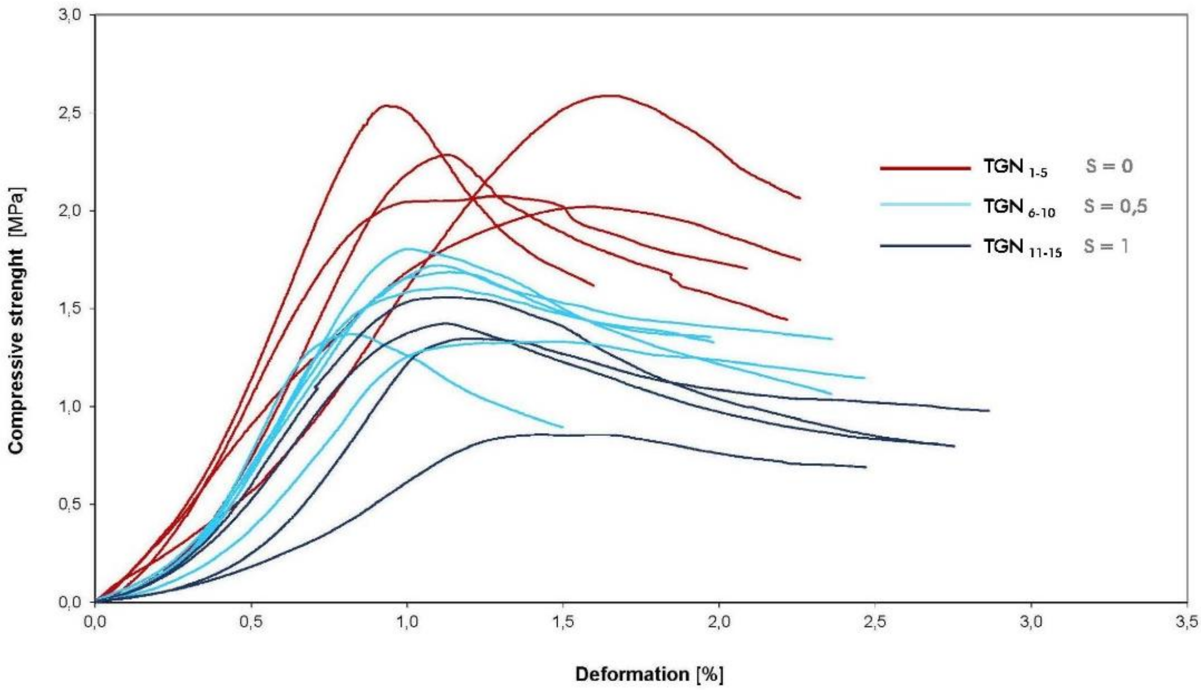


Fig. 4.11 – Compressive strength values at different saturation degrees

The test results showed a 37% reduction in mechanical resistance from the dry condition (S=0%) to the semi-saturated condition (S=50%) and 45% from the dry condition to the condition (S=100%).

The relationship between the degree of saturation of samples of Neapolitan yellow tuff and its moisture content was studied by Evangelista[16] who has shown that the mechanical behaviour of this material is influenced by its degree of saturation and also, that the variation of the water content causes not negligible deformations of the tufaceous mass. The results of the mono-axial compressive tests, in analogy with the results obtained in this study, had shown a reduction in the compressive strength of tests from dry to saturated conditions.

These reductions recorded in this study are greater than those shown in Evangelista's results, this can be attributed to the ageing effect of the material due to its long exposure to air and weather conditions.

Data from similar experiments carried out by other scholars and, on different materials, within this same research, had shown a reduction in the compressive strength of the samples greater in the semi-saturated condition than in the condition of complete saturation compared to the dry condition. The results of the test made on the samples of Neapolitan yellow tuff, on the contrary, have recorded a progressive reduction of the mechanical resistances when the saturation degree increases.

In order to interpret the different experimental responses, some hypotheses have been formulated about the influence of the conditioning process of the samples which, in the latter survey, had been modified. In the previous tests, in fact, the samples had been dried in an oven until they reached the dry mass; later they had been completely immersed in water until they reached the humid mass; finally, to reach intermediate degrees of conditioning, the samples had been dried again in an oven. In the last experiment, however, after conducting the samples from the dry to the saturated condition, it was decided that the semi-saturated condition was reached by natural evaporation with exposure to the air.

It was then assumed that in the first case the conditioning of the samples by drying in the oven resulted in their higher deterioration, thus recording a greater reduction of the mechanical resistances in the semi-saturated conditions. This additional component of

16 A. Evangelista
Influenza del contenuto d'acqua sul comportamento del tufo giallo napoletano

deterioration has been eliminated in the test on tuff, due to the way of drying (with natural and not forced evaporation).

In order to confirm this hypothesis, further comparative laboratory tests were carried on samples under saturated and dry conditions where the second condition (S = 0%) has been reached by drying in the oven for some samples and by natural evaporation to the air for others. The comparison between the two different conditions was evaluated.

CHANGES IN MECHANICAL PROPERTIES AS CONDITIONING CHANGES

The test was carried out on 9 samples divided into three terns; all samples were weighed under undisturbed environmental conditions the day after their cutting.

$TGN_{8\text{-}10}$ samples were conducted to the dry condition by air drying; reaching a moist content equal to the physiological moisture content of the material (S≈5%), recorded when the difference between two successive weights was less than 0.1%. In this condition, indicated by the acronym **S = EC**, they were subjected to a uniaxial compression test. The other samples were also brought to a minimum moist content condition following two different procedures:

- $TGN_{1\text{-}3}$ samples were air-dried until the value of the moist content equal to physiological moisture. Subsequently, they were completely immersed in water until the saturated condition (S=100%). In this condition, indicated by the acronym **S = 1a**, they were subjected to the uniaxial compression test;

- $TGN_{4\text{-}6}$ samples were dried in an oven at 105°C, reaching the value of saturation S=0%. Subsequently, they were completely immersed in water until the saturated condition (S=100%). In this condition, indicated by the acronym **S = 1o**, they were subjected to the uniaxial compression test.

Therefore the results of the test give the possibility to compare the stress-deformation diagrams between the samples under physiological humidity conditions **S=EC** and the samples with maximum saturation reached, for some samples, starting from the environmental conditions **S=1a**, and for others, imposing a passage of forced drying in the oven **S=1o** (Tab. 4.10).

Tab. 4.10: Mechanical measurements at different saturation degrees

sample	Saturation [%]	Maximum Compressive strength [MPa]	Medium Compressive strength [MPa]	Standard deviation [%]
TGN 1	S = 1 a	12,49	11,97	6,13%
TGN 2		11,46		
TGN 3		23,02		
TGN 4	S = 1 o	7,78	7,99	7,61%
TGN 5		8,68		
TGN 6		7,51		
TGN 7	S = EC	14,78	13,19	10,64%
TGN 8		12,66		
TGN 10		12,13		

An abnormal behaviour of the TGN_3 sample was observed during the test, which showed much higher resistance than the others. This can be easily explained by the presence of impurities inside the stone matrix that have conditioned its behaviour; even after having reached the break, the sample has kept its shape overall (Fig.4.12).

Fig. 4.12 – Sample TGN_3 before compression test (left) and after compression test (right)

In order to better interpret the comparative strength data under these three conditions, it was determined the value of the mean compressive strength in the condition **S=1a**, and the corresponding standard deviation, excluding the TGN_3 sample data.

The value of the mean compressive strength of the samples saturated starting from the air-dried condition **S=1a** is however much greater than the value recorded on the samples saturated starting from the oven-dried condition in the oven **S=1o**, with a difference between the two data of 33% (Fig. 4.13).

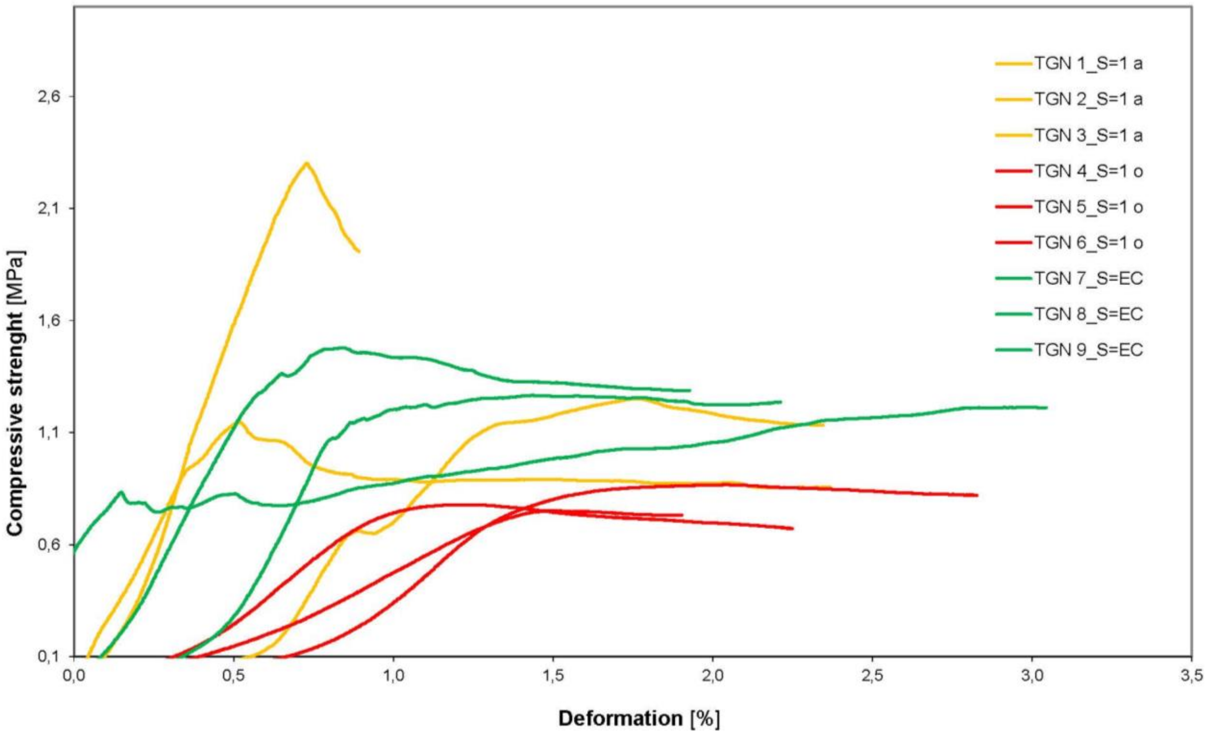


Fig. 4.13 – Compressive strength values corresponding to different processes for conditioning

The tests results confirmed the influence of the sample conditioning method on their mechanical performance, highlighting the contribution of the drying cycle in the oven on the material decay.

4.2 DISCUSSION OF RESULTS AND COMPARISON WITH PREVIOUS STUDIES

The results of the tests showed the extreme variability of the thermal and mechanical characteristics of a building material corresponding to their saturation degree.

In the first survey, carried out on bricks, it has been shown that the thermal performance of the material undergoes a strong reduction already in correspondence of relatively low levels of imbibition. This variation results in a factor of great uncertainty as to the true behaviour of masonry under operating conditions, which is even more evident if the experimental data are compared with the tabulated values introduced by the simulation models for structural calculation or energy verification. In addition, an interesting aspect has emerged regarding the variability of the same performance, at the same wet content, varying the process of drying/baking the bricks.

Experiments on the Neapolitan yellow tuff have also provided interesting data on the variation of the mechanical performance of a stone according to its imbibition degree and the level of natural aging, which was simulated in the test by imposing different conditioning procedures (natural or forced).

As a result of this evidence it is necessary to consider the importance of a preliminary phase of characterization of the material constituting the masonry, in order to identify, as a preliminary step, their real state of conservation. It is important that the survey is conducted both on existing materials in the building, in order to define a complete diagnostic picture, and on new materials to be introduced for replacement or repair of small portions, in order to ensure a thermo-Hygrometric balance of the wall in favour of the maintenance of the building's health conditions and the prevention of localized phenomena of degradation related to physical and material discrepancies.

This second survey is certainly easier to carry out, because it can be developed in the factory before the supply of the material. More complex is the characterization on-site of the conservation status of the masonry, which would require invasive investigations taking samples for laboratory testing.

With this in mind, the research aimed to test an innovative method for a non-invasive characterization of the damp content of the masonry, diagnosing their "health status", that is better described in chapter 5.

5. IDROSCAN METHOD: TESTING AND IMPLEMENTATION

The second **goal** of the research project was to **test new methods for diagnosing** the phenomenon of rising damp aimed at classifying the conservation status of wet masonries and the ongoing monitoring of the recovery systems adopted.

In Chapter 2 the methods used to diagnose the presence of water in masonry were presented, dividing them between qualitative (thermography) and quantitative (weight method and calcium carbide method). For both types the critical issues related to the insufficiency of the data provided by the first and the invasiveness of the second have been identified and, therefore, they have been considered not applicable in the Cultural Heritage.

At the same time, the study of the integrated system of CNT devices has shown the possibility to implement the functionality of the probe IDROSCAN® in order to transform it into an instantaneous and non-invasive measuring instrument of the humid content.

The device, that has dimensions of 170 x 140 x 30 mm, can measure, simply touching the inspected wall, the value of an electrical parameter variable according to the moisture content inside the material (Fig. 5.1).

Fig. 5.1 –IDROSCAN® probe

It is known, in fact, that each body has its own aptitude to oppose the passage of electric current, which can be expressed in terms of **electrical resistance R (inverse of the electrical conductance G)**. This property does not depend on the geometry of the object but only on the material of which the body is composed, or on its **specific resistivity ρ** which can be measured in [Ω/m].

The electrical properties of a porous material depend on the combination of the specific resistivity of the solid matrix, the still air contained in the voids and the water present. Therefore, depending on the degree of saturation, the response of the material to the passage of a weak electric current is modified. While the values of the electrical resistivity of many materials, including that of the air, are known and tabulated, the electrical resistivity of the water is variable due to the concentration of dissolved salts contained in it that affects the passage of electric current (higher in solutions with higher saline content).

This principle is the basis for the operation of the Idroscan probe which, through two plates arranged in parallel, is able to emit and receive a weak electric current, on a surface of 10x10cm for a depth varying between 0 and 10cm, that crosses the material with a semielliptical wave. From the comparative assessment of the data collected at the same point in different times, it is noted that the value measured and expressed in **idroscan units u.i.** is a function of the average volumetric water content of the masonry. Therefore, the probe allows to know the variation of the parameter detected.

In order to relate the parameter read by the instrument with the amount of water present, a system of curves has been constructed (Fig. 5.2) correlating the idroscan units, the measured electrical parameter and the content of moisture.

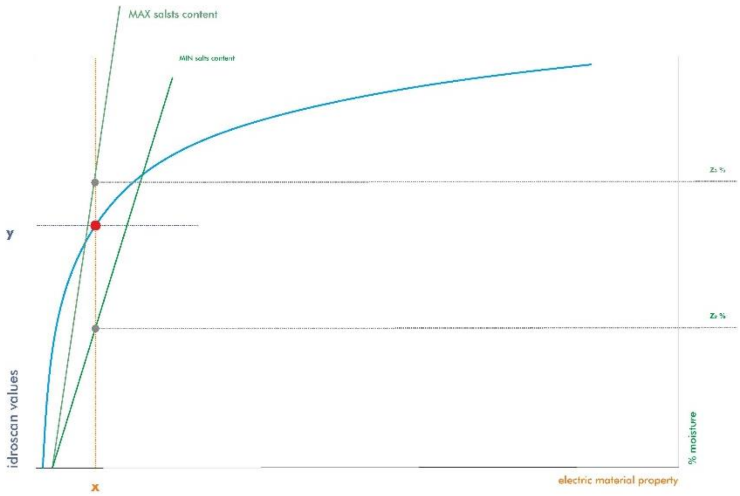


Fig. 5.2 – IDROSCAN® curves

The blue curve in the graph shows the relationship between the measurements made by the instrument on different materials, in terms of u.i. (left axis of the ordinates), with the values of the investigated electrical property (axis of the abscissa) provided by the bibliography.

The green lines in the graph represent the variation of the electrical property investigated on an ideal material in relation to its moisture content and the different salt concentration.

The ideal material considered is 75% solid and 25% empty. The measurement with the probe will give a value **y** in terms of u.i. to which, through the blue curve, corresponds a value of its electrical property **x** (Fig. 5.2). To relate this value to the amount of moisture in the sample, the salinity curves of the liquid should be intercepted.

The value of x corresponds to a range of values of the wet content between $\mathbf{z_1}$ and $\mathbf{z_2}$, where $\mathbf{z_1}$ corresponds to the degree of salinity of zero and $\mathbf{z_2}$ corresponds to a maximum degree of salinity.

The operating principle of the probe IDROSCAN® is covered by industrial patents owned by Leonardo Solutions Srl:

- UIBM No. 0001391106 (Ufficio Italiano Brevetti e Marchi);
- EPO n°2157491 (European Patent Office)

The probe was designed as an instrument for evaluating changes in the water content of a masonry subjected to the action of CNT devices. The data collected do not provide a unique and determined measurement of the wet content but allow to evaluate the variation between the initial condition (before the neutralization) and the intermediate and final conditions of the wall drying process.

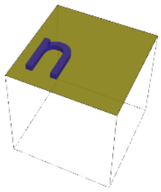
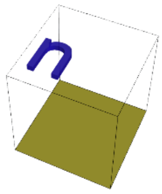
It is used to identify the trend in the drying time of the masonry subject to a remedial action.

Therefore, considering the possibility of correlating the idroscan parameter with the water content of the masonry, an experimental campaign has been developed aimed at applying the **IDROSCAN Method** as an approach for non-invasive diagnosis of the conservation status of masonry affected by rising damp.

5.1 LABORATORY TESTING

In order to achieve the stated goal, a programme of laboratory tests on blocks of Neapolitan yellow tuff has been developed. Starting from a single block, two samples have been obtained, identified with the letters A and B, with dimensions 20x20x15 cm (Tab. 5.1).

Tab. 5.1: Physical properties of the investigated material

Sample dimensions [cm - cm^2 - cm^3]							
							
	b	h	A Area	b'	h'	A' Area	V Volume
A	19,8	20,1	398,0	19,7	20,0	394,0	5939,9
B	20,3	19,9	404,0	20,2	20,0	404,0	5979,0

Direct measurements were carried out at the same time on each sample either by weight test or by the Idroscan method. The idroscan data acquisition was made by placing the probe at the centre of the faces with a size of 20x20cm, in order to limit the boundary effect of the sample in relation to the measuring range of the instrument. (Fig. 5.3).

Fig. 5.3 – Application of the probe IDROSCAN® on the two samples

Considering that the electric reading reaches a depth of about 10cm, the measurements were made on both sides of each sample, considering an average value in order to interpret the behaviour of the material and to homogenise the data with respect to the distribution of the wet content in the whole thickness.

The test was carried out using the following procedure:

- **Step 1:** after cutting, the samples were dried at open air until the physiological moisture condition was reached;
- **Step 2:** The samples have been slowly wetted to reach the maximum saturation condition. Samples A and B were saturated following two different procedures which influenced the electrical response recorded by the probe *[omissis]* (Fig. 5.4).
- **Step 3:** The difference between wet weight and dry weight determined the maximum quantity absorbed by each sample. This allowed to establish the intermediate wet contents achieved in the following stages.

Fig. 5.4 – Conditioning of the A test piece for capillary ascent

The samples were weighed in regular intervals; every tome four measurements were made on each side using the Idroscan probe; the mean values were related with the water content per unit volume recorded at each corresponding weight.

Subsequently, the blocks were dried by natural evaporation at the air, placing them in a sufficiently ventilated environment, shielded from solar radiation.

The data were recorded using two drying and soaking cycles on both sample A and sample B for a total of 480 measurements (Tab. 5.2).

Tab. 5.2: Recorded data on sample A *[omissis]*

SAMPLE A												
ui n - ui' n = side measurements ui = mean value of idroscan												
W [gr]	**Cw/V** [gr/dm^3]	**%**	**ui $_1$**	**ui $_2$**	**ui $_3$**	**ui $_4$**	**ui' $_1$**	**ui' $_2$**	**ui' $_3$**	**ui' $_4$**	**ui**	
…	…..	…..	…	…	…	..	…	…	…	…	…	…

For each data group the trend curves representing the **instrument response curves** of the Idroscan method have been identified (Fig. 5.5).

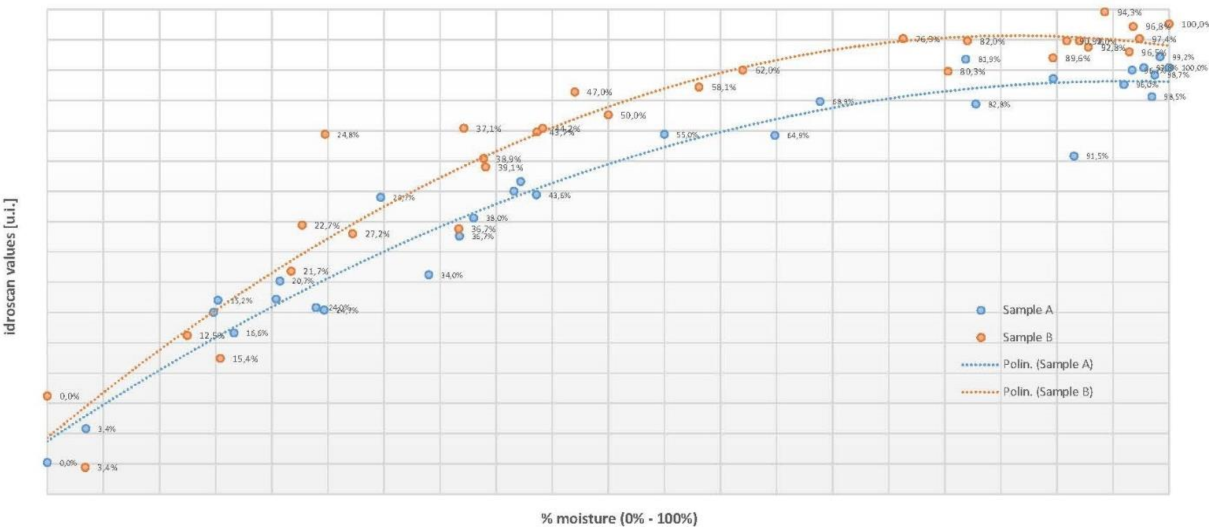


Fig. 5.5 – Instrumental response curve for samples A (in blue) and B (in orange)

All data are within the measurement range between *[omissis]* u.i. and *[omissis]* u.i., which can be considered the instrument response range of the method applied to this specific investigated material.

5.2 IDROSCAN METHOD: FROM DATA COMPARISON TO INSTANTANEOUS MEASUREMENT

The interpretation of the data provided by the measurements and the course of the instrument response curve highlighted three main sections:

- A first section, rather "long", is included between the dry condition (S=0) and a saturation value close to 35%; in this range the correspondence between the electrical properties of the material, expressed in u.i., and the amount of water absorbed by the sample varies with an almost linear course.
- A second parabolic section is included between the saturation values of 35% and 65%; in this range the variation of the electrical measurement expressed in u.i. is slower than the corresponding increase of the moisture content (the tangency angle of the instrument response curve decreases with respect to the first linear section);
- In the third section, included between the saturation values of 65% and 100%, the electrical measurements of the instrument are very close.

The ranges identified are close to the ranges in which the variation in the thermal and mechanical performance of wetted construction materials had been assessed. Bibliographic studies had shown a very strong reduction in mechanical performance in semi-saturation conditions (S=50%). These data have been confirmed by the results of measurements carried out on bricks. In addition, in this latest experiment, a significant alteration of the thermal properties of the material was also found, in terms of increased conductivity at levels of moisture close to 25%.

These values can be taken as a reference for the evaluation of the performance of a masonry in relation to its wet content and for the evaluation of its "health" status.

By intersecting these data with the instrument response curves it is possible to identify three **ranges of diagnosis** about the conservation status of the masonry (Fig. 5.6):

Fig. 5.6 – Ranges of diagnosis of a wall made with Neapolitan yellow tuff

- For saturation levels between S=0% and S=35%, which for Neapolitan yellow tuff masonries correspond to an electrical measurement range between *[omissis]* u.i. and *[omissis]* u.i., a condition of **healthy masonry** can be diagnosed, for which no intervention is necessary;
- For saturation levels between S=35% and S=65%, corresponding for this material to an electrical measurement range between *[omissis]* u.i. and *[omissis]* u.i., a condition of **masonry to recover** can be diagnosed. The damp content of the material, in fact, suggests an important alteration of its thermal performance and, probably, the

triggering of degradation phenomena. In this case it will be necessary to plan a recovery intervention that will be more or less light depending on the position of the data measured by the probe in the diagnostic range;

- Finally, the third diagnostic range, corresponding to a saturation range between 65% and 100% and an electrical measurement range between *[omissis]* u.i. and *[omissis]* u.i., a condition of **masonry to replace** can be diagnosed, because the constitutive material has undergone a strong reduction in mechanical resistance that affects the static of the masonry structures. Therefore, for measurements included in this last diagnostic interval, the designer should consider taking important intervention methods which also include the replacement of the damaged masonry portions.

5.3 DISCUSSION OF THE RESULTS

The construction of **ranges of diagnosis** provides the great advantage of applying the **Idroscan method** as a procedure for diagnosing the conservation status of historic masonries affected by rising damp. Compared to traditional methods of investigation, the idroscan method has several elements of originality.

First of all, it provides a quantitative measurement of the wet content and, therefore, of the conservation status of the masonry investigated, which is displayed in the diagnostic range. The description of the progress of the pathology is extremely interesting in order to guide the selection of the most correct recovery intervention.

This assessment is carried out in a completely non-invasive manner, in the same way as with infrared thermography IRT. Compared to the latter, however, the method offers the great advantage of regardless of the many factors, related to the thermo-hygrometric conditions of the environment, which may alter the thermographic reading or which, however, require further processing of the data collected for their correct interpretation.

These aspects make interesting the use of the method for non-invasive monitoring of masonries subjected to a recovery intervention and, therefore, for the performance verification and testing of materials and technologies adopted.

The non-invasive character of the Idroscan method, which makes it particularly applicable in the context of Cultural Heritage, lies in the test procedure, which can be carried out by simple contact with the masonry. The data is instantly readable on the instrument monitor. Conversion, however, must go through the instrument response curve.

Therefore, there are some future research developments aimed at:

- determining the uniqueness of the curve, constructed for the Neapolitan yellow tuff, by extending the survey plan to various building materials;
- in the event that different responses for different materials should be highlighted, it is planned to build a database of instrument response curves related to the most recurrent materials in the construction tradition;
- patenting a new instrument by affecting the electrical operation of the probe from the scope of improvement observed in the survey.

The instrument, thus implemented, can be able to perform quantitative, instantaneous and non-invasive measurements of the wet masonry to be used for the diagnosis of the disease and the monitoring and testing of the remediation interventions.

Note:

Details *[omissis]* relating to the testing, operation of the instrument and observations made to implement the method have been omitted as they are covered by non-disclosure industrial agreements.

6. PERFORMANCE TESTS OF CNT

Paragraph 2.5 describes how the Charge Neutralization Technology CNT® works and the advantages provided by the method especially for its application in the context of Cultural Heritage, which can be summarized as follows:

- this technology is able to act directly on the behaviour of water regardless of the type of building material or masonry structure;
- the method promotes the neutralization of the electrostatic attraction that is naturally generated between the walls of the capillary pores of a building material and the water molecule, thus eliminating the cause of the disease;
- the application of the technology is totally reversible and non-invasive, since it only provides for the installation of a CNT device connected to the electric charge which can also be placed in a hidden position inside the operating environment, succeeding in carrying out its function on a spherical range of action up to 15m;
- the installation of the integrated system of CNT devices, including probes for the acquisition of the relative humidity and environmental temperature parameters (Hr-T probe) and the variation of the moisture content inside the masonry (IDROSCAN probe) allows to monitor in real time the progress of the rehabilitation process ensuring that the masonry enters the new thermo-hygrometric equilibrium of dry condition with time compatible with the physical and chemical nature of the constituent materials (without causing sudden stress on the surface finishing layers).

In order to verify these characteristics, the research has pursued a third goal related to the **verification of the performance effectiveness of the Charge Neutralization Technology** in stopping the dynamics of the capillary rise in a definitive and non-invasive way. The survey was developed in two stages:

Phase 1 provides for the cataloguing of data on installations throughout the national territory. The *case history* containing the cases considered most interesting, for the type of the building and the installation site, was represented in a **performance check sheet**, containing parameters for the verification of any remediation for masonry affected by rising damp;

In **Phase 2**, on the other hand, the on-site testing of the integrated CNT system was promoted by carrying out the installation of the devices and sensors in three historical buildings and monitoring the intervention during the next 18 months with quality tests and direct measurements of the moisture content inside the walls investigated.

6.1 DATA COLLECTION: THE PERFORMANCE CHECK SHEET[1]

The effectiveness of the CNT has been verified in the context of numerous installations carried out throughout the country, in private and public buildings, many of which have been conducted in partnership with Universities and research centres.

The course of the drying process of the masonry was always checked with qualitative and non-invasive investigation by comparing thermographic images during installation, intermediate checks and final verification. Whenever possible, the survey has been extended to areas outside the intervention field, in order to obtain "control points" of the dynamics of the flows inside the walls not subjected to the action of the CNT.

Intermediate monitoring has been carried out on an annual or half-yearly basis, trying to respect the seasonal variations in order to make easily comparable the chromatic palettes detected, that vary according to the environmental thermo-hygrometric parameters.

Some experimental cases have been followed within the interdepartmental research project CNT-Apps, of which the DICEA of the University of Naples is partner, represented by prof. Roberto Castelluccio. In these cases, the quality checks were supplemented by wet content measurements carried out by weighting tests according to the procedure specified in standard UNI 11085.

Finally, in cases where intermediate or final thermographic tests have shown thermal anomalies in correspondence of the moist front, which are reasonably attributable to hygroscopic salt deposition, Ionic chromatography tests were also carried out to determine their type and concentration.

[1] V. Vitiello and R. Castelluccio
Il risanamento delle murature affette da umidità da risalita capillare. Il metodo CNT

From the company's extensive database, a case history of interventions has been extracted, in significant numbers to understand the effectiveness of the method in very different operating conditions, in relation to the geographical and climatic range in which the buildings are located and to the materials and construction techniques used.

During the research, a performance check sheet has been designed to identify the essential data for each intervention. The sheets attached to the text *Il risanamento delle murature affette da umidità da risalita capillare. Il metodo CNT* (V. Vitiello and R. Castelluccio, 2019), group the cases analysed in three families:

- **completed interventions**, for which it is possible to appreciate the results obtained in terms of drying the walls and its maintenance over time;
- **extreme cases**, relating to operating conditions which are particularly unfavourable to the disposal of damp contents in masonry;
- **cases in progress**, for which an initial assessment has been made of the progress of the drying process.

In order to make the reading of the data homogeneous, the parameters necessary to describe each installation and to provide the elements useful for the performance test of the intervention were identified.

Given that, to date, there are no certification and testing protocols for the restoration of wet masonry, the **PERFORMANCE CHECK SHEET** thus developed is an innovative and strategic instrument for the development of good design practices, monitoring and testing of these interventions.

Each sheet is made up of two pages: the first contains general information about the building under intervention, while the second contains technical data about the installation (Fig. 6.1).

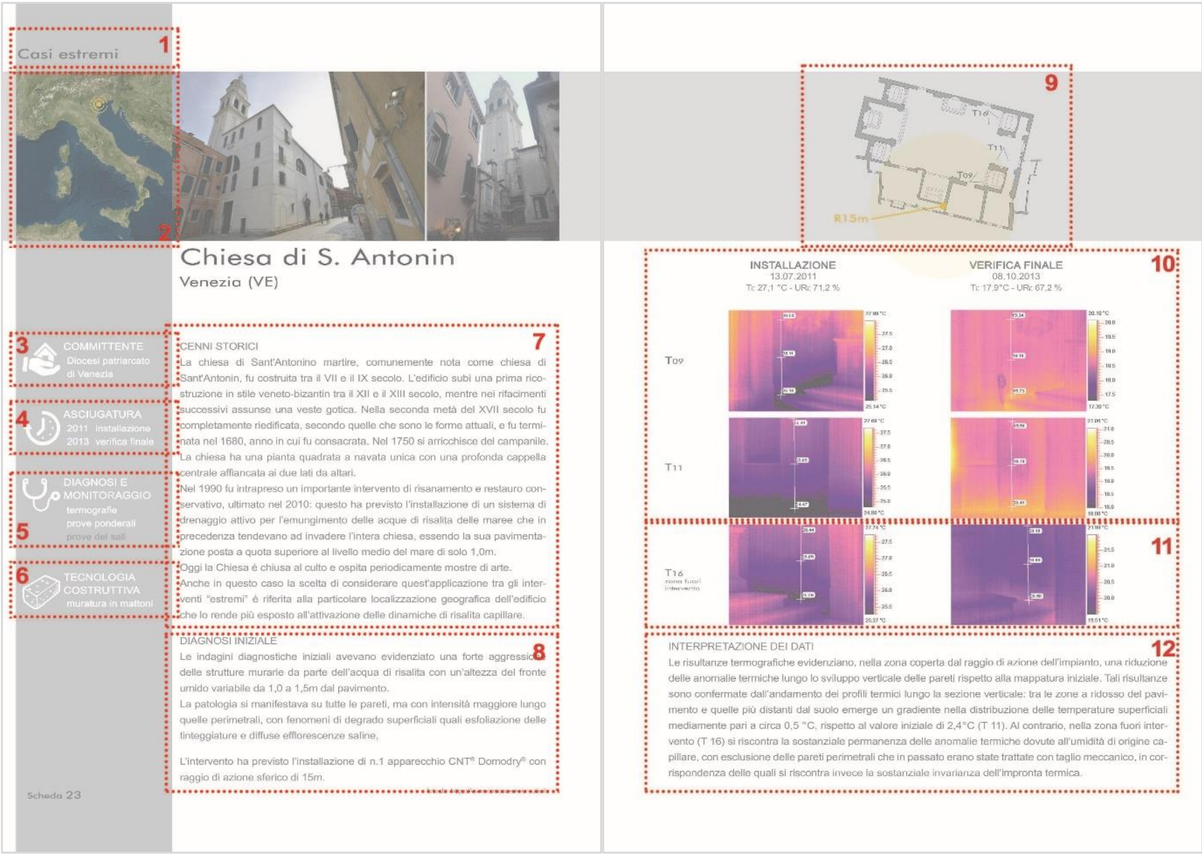


Fig. 6.1 – The performance check sheet

For each installation the sheet shows:

1. **Family of the case analysed**
2. **Geographic location of the building**
3. **Client (whether public or private)**
4. **Time from installation to final verification (or intermediate for current cases)**
5. **Diagnostic investigations (thermographs, weight tests, salt tests)**
6. **Technology and construction material**
7. **Historical background on the building**
8. **Initial diagnostic phases; number and model of CNT device installed**
9. **Location of the device and of the points where the thermographic images were acquired**
10. **Qualitative test of the intervention by comparison of thermographic images**
11. **Possible acquisition of thermographs "outside the range of the device"**
12. **Interpretation of results and, where available, discussion**

6.2 ON-SITE TESTS: INSTALLATION, MONITORING AND FINAL CHECK

Following the same procedure described, the performance verification of the CNT made in this research has been developed in the three historical buildings tested.

EL CUARTEL DE CONDE DUQUE

Reference cases _ Thit survey can be included among the "completed interventions" because, at the end of the research it was necessary to remove the devices to allow the Office of General Administration to carry out the maintenance work in the investigated environments, in order to expand the close archive area.

Geographic location of the building _ The building is in the Malasaña district, close to the city centre of Madrid, positioned in a flat area with the main front overlooking a rather urbanized area and the opposite front overlooking a large green area (Fig. 6.2).

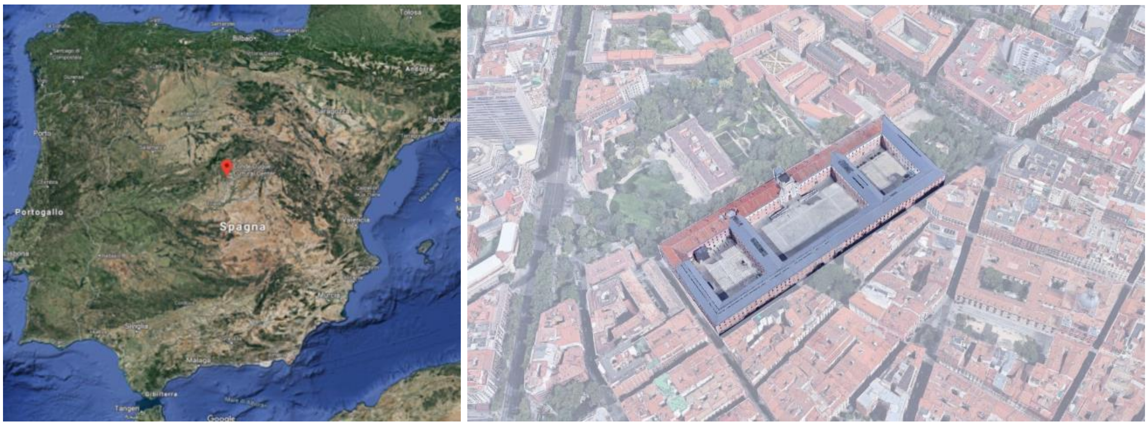


Fig. 6.2 – El Cuartel de Conde Duque in its urban context

Client _ The Cuartel is a property of the Ayuntamiento de Madrid since 1969. The survey, therefore, was conducted in collaboration with a public contractor represented by the Historical Heritage Office of the city.

Time from installation to final verification _ The installation of the devices was carried out in April 2018. After 18 months of monitoring, in November 2019, the final verification of the intervention was carried out.

Diagnostic investigations _ The monitoring of the survey was carried out either by acquisition of thermographic images or by weighting tests.

Technology and building material _ The building is made up of a brick-bearing structure, sometimes reinforced with chaotic textures in limestone.

Historical background on the building _ Recalling briefly what already described in paragraph 3.6, the building was built at the behest of Filippo V of Borbone in the first thirty years of the eighteenth century, designed by the baroque architect Pedro de Ribera. Born as a barracks of the guards of the Royal Corps, the building has changed several destinations to become, as part of the restoration and conversion project wanted by the Ayuntamiento of Madrid, one of the largest cultural centers in the city

Phases of initial diagnosis _ In the first phase of diagnosis no signs of rising damp were apparent, above all because of the presence of counter-walls and counter-vaults and cement plasters with great thickness that did not allow to evaluate the state of conservation of the underlying structures. Therefore, as a preliminary to the installation of the devices, the plasters of the wall chosen for the intervention has been removed (Fig. 6.3).

The experiment included the installation of a **CNT** device with a radius of 15m; on the same wall were also installed two probes IDROSCAN, **ID1** and **ID2**, and a probe **Hr-T** while, a second probe **Hr-T** was installed on the opposite wall.

Fig. 6.3 – The wall before and after the removal of the plaster

Location of the device and of the points where the thermographic images were acquired _ 18 thermographic images have been acquired in both the internal and external zones of the devices range during the installation and monitoring phases (Fig. 6.4).

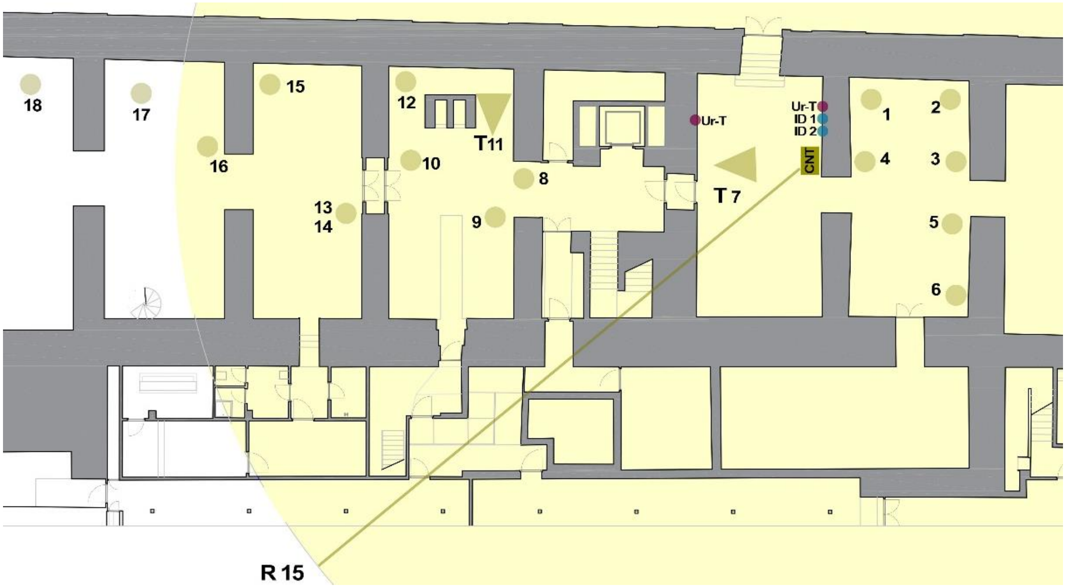


Fig. 6.4 – Location of the device and of the points where the thermographic images were acquired

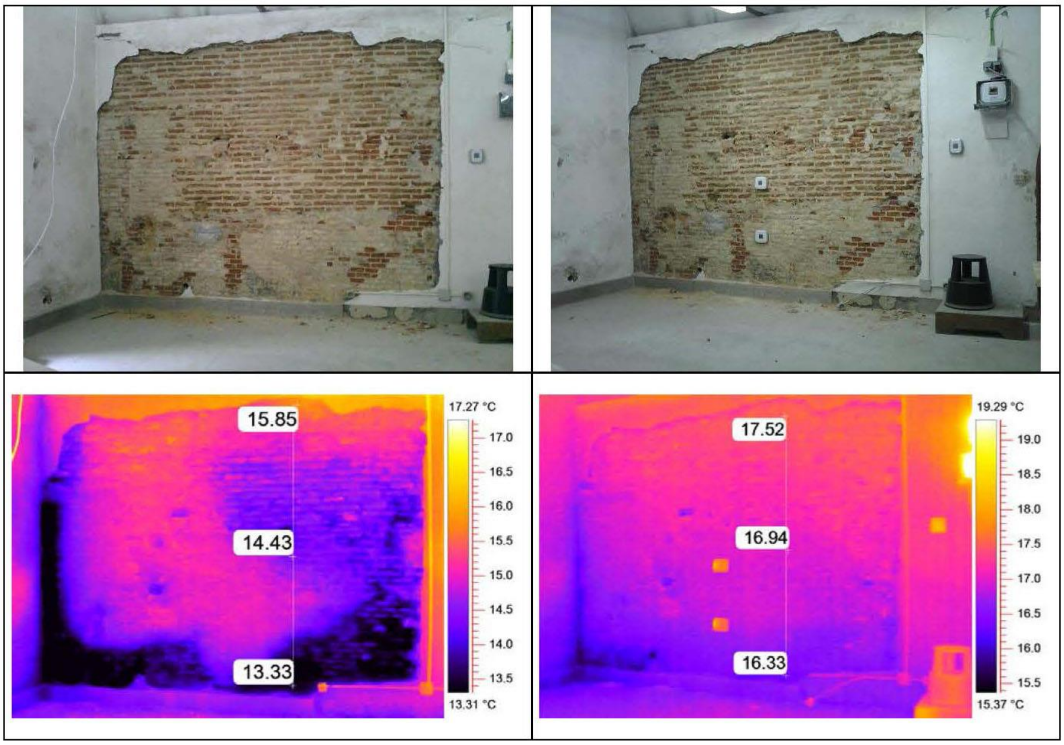
Qualitative verification of the intervention _ For the purpose of the performance check of the intervention it is considered useful to compare the $\mathbf{T_7}$ thermographs (Fig. 6.5), which frame the wall on which the device was installed, and the $\mathbf{T_{11}}$ thermographs (Fig. 6.6) which frame a wall still inside the range of action but in a position particularly disadvantageous for the evaporation of the damp content, overlooking a massive lift in an environment occupied by several shelves.

To allow an exhaustive interpretation of thermal images, the environmental parameters detected during the four monitoring phases have been recorded: installation, 1° monitoring, 2° monitoring, final verification (Tab. 6.1).

Tab. 6.1: Environmental parameters of monitoring days

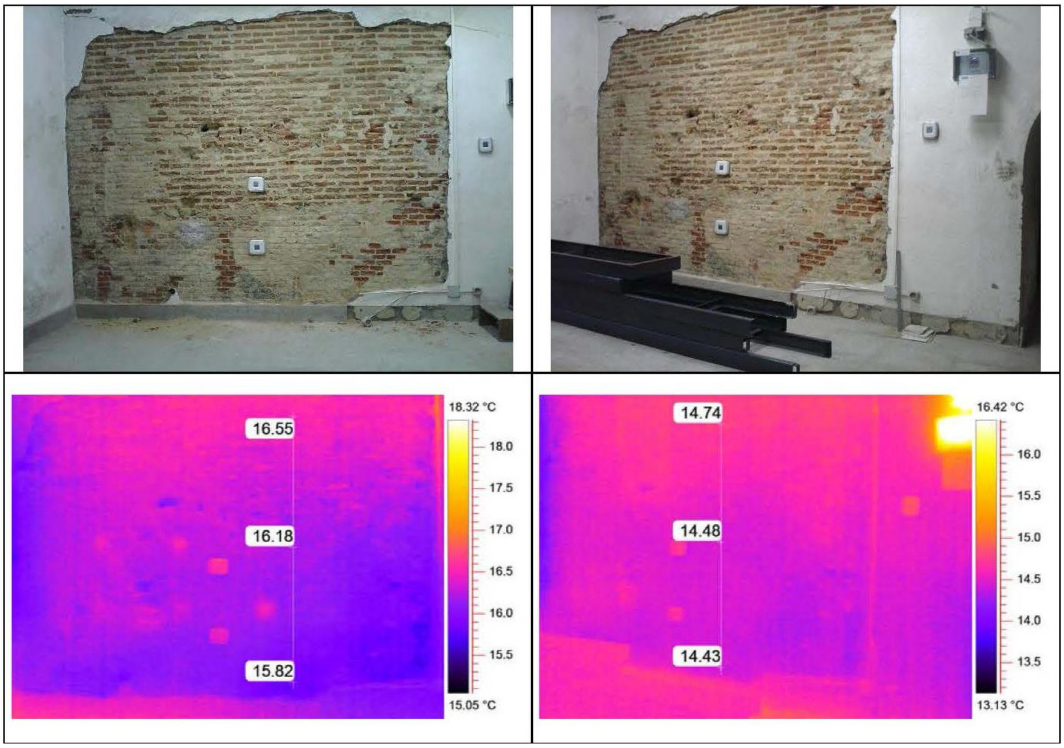
day		**inside**		**outside**	
		Hr [%]	**T** [°C]	**Hr** [%]	**T** [°C]
24/04/2018	Installation	52,9	18,2	43,1	19,8
14/11/2018	1° monitoring	58,3	17,1	73,7	13,5
22/05/2019	2° monitoring	40,2	19,8	25,3	29,5
27/11/2019	Final verification	59,7	16,1	72,4	12,0

The images were compared according to the same seasonal periods, with similar thermo-hygrometric parameters: spring 2018 – 2019 (installation – 2° monitoring) and autumn 2018 – 2019 (1° monitoring – final verification).



T_7 in 25-04-2018

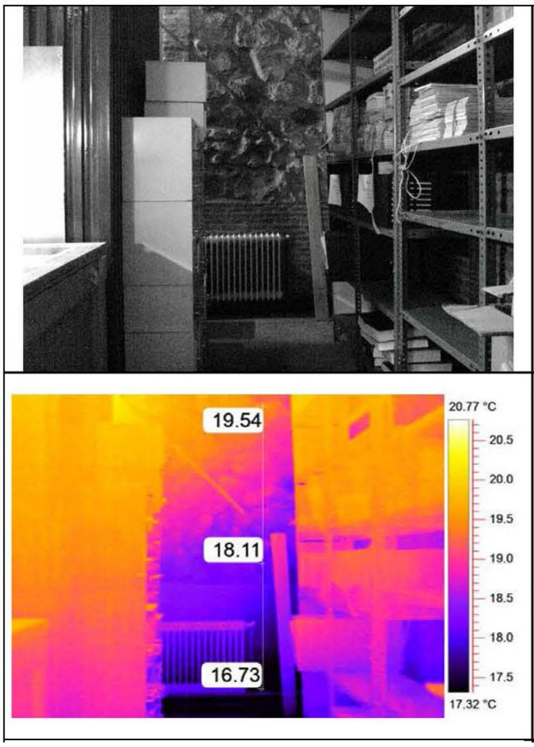
T_7 in 22-05-2019



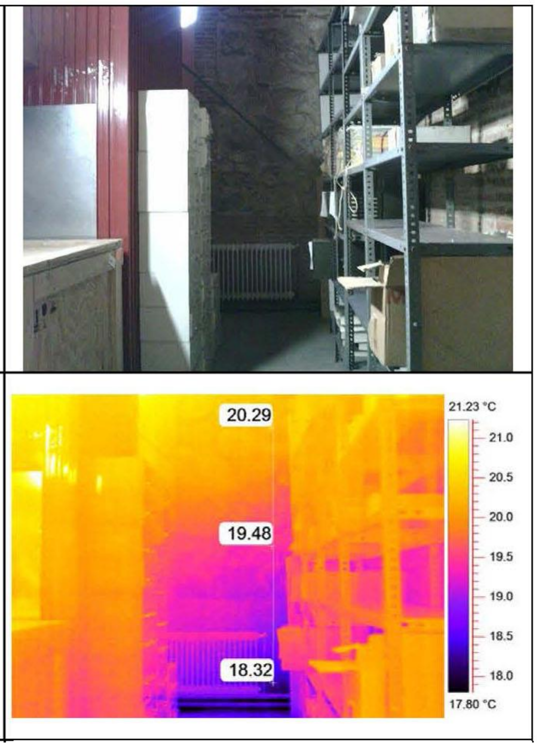
T_7 in 14-11-2018

T_7 in 27-11-2019

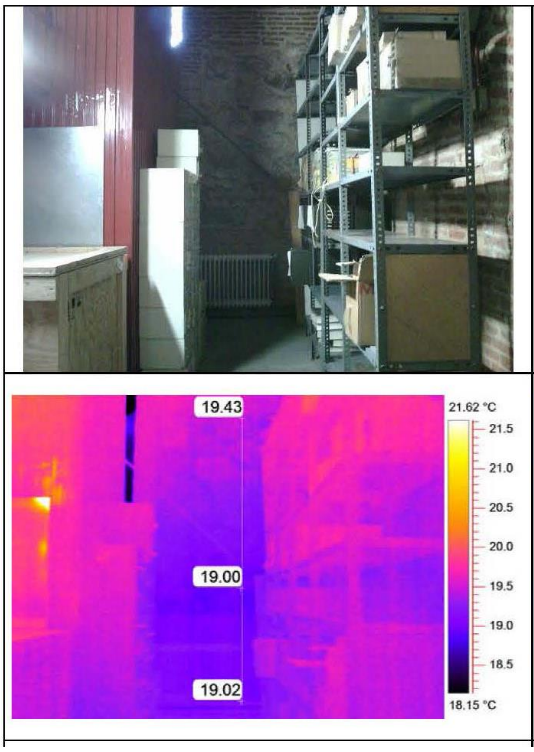
Fig. 6.5 – Comparison between IRT images T_7



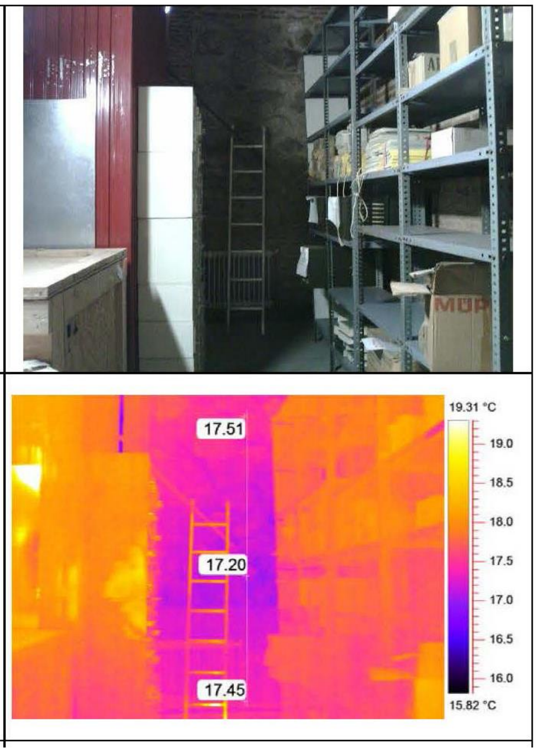
T_{11} in 25-04-2018



T_{11} in 22-05-2019



T_{11} in 14-11-2018



T_{11} in 27-11-2019

Fig. 6.6 – Comparison between IRT images T_{11}

Interpretation of data and discussion of weighted data

The comparison between the thermographic images showed a reduction in the range of variation of surface temperatures:

- The image T_7 shows a reduction from ΔT=**2,52**°C to ΔT=**1,19**°C during the spring and from ΔT=**0,73**°C to ΔT=**0,31**°C during the autumn;

- The image T_{11} shows a reduction from ΔT=**2,81**°C to ΔT=**1,97**°C during the spring and from ΔT=**0,41**°C to ΔT=**0,06**°C during the autumn.

The operating of CNT was not constant throughout the survey. In the summer months of 2018, in fact, there was the interruption of the electricity throughout the level corresponding to sotano -2. The fault has been recorded by the devices, indicating a lower operating time than the forecast of about 3000 hours.

Samples for the measurement of wet contents were also taken during monitoring. Following the indications supplied by the norm UNI 11085, a survey wall has been chosen and 12 points of withdrawal have been identified on it (Fig. 6.7).

Fig. 6.7 – Sampling points for weighting tests

For each point a sample of material was taken at depths of 0-10 cm. Laboratory tests provided values of the quantity of water present in the masonry. Below are the data collected within the four carried out monitoring (Tab. 6.2).

Tab. 6.2: Measurements of weights taken

			INSTALLATION 25 APRIL 2018	1° MONITORING 14 NOVEMBER 2018	2° MONITORING 22 MAY 2019	FINAL VERIFICATION 27 NOVEMBER 2019
n° sample.	**x**	**y**	C_w [%] $((w_w - w_d)/w_d)x100$	C_w [%] $((w_w - w_d)/w_d)x100$	C_w [%] $((w_w - w_d)/w_d)x100$	C_w [%] $((w_w - w_d)/w_d)x100$
	cm	**cm**	Water content	Water content	Water content	Water content
1	0	0	3,35%	8,88%	1,49%	1,46%
2	70		2,77%	1,50%	1,55%	2,00%
3	140		2,29%	1,48%	1,26%	5,77%
4	210		1,20%	0,22%	0,14%	0,26%
5	0	90	2,76%	2,52%	2,48%	3,24%
6	70		1,76%	1,40%	1,56%	0,94%
7	140		5,38%	3,82%	2,07%	4,81%
8	210		1,40%	0,47%	0,75%	0,47%
9	0	1501	1,35%	1,89%	2,35%	3,72%
10	70		4,46%	3,97%	3,86%	3,98%
11	140		3,42%	3,09%	2,99%	2,80%
12	210		2,90%	2,68%	2,64%	2,64%

The measured values have been averaged for each withdrawal quota. At the date of final verification of the intervention a reduction of the wet content has been recorded with respect to the value measured during installation of **2%** at the altitude of 150cm, **39%** at the altitude of 90cm and **54%** at the altitude of 40cm (Fig. 6.8).

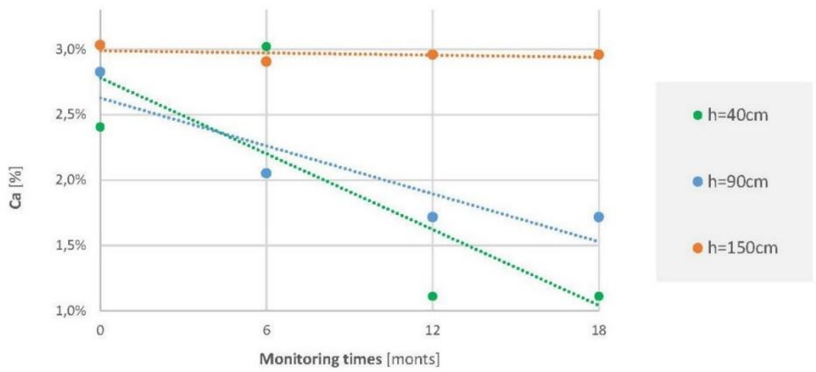


Fig. 6.8 – Variation of moist content corresponding to the sample's heights

The results confirm the findings of the non-invasive investigations.

THE ESCUELA TÉCNICA SUPERIOR DE INGENIEROS DE MINAS Y ENERGÍA

Reference cases _ Also in this case the test can be included between the "completed interventions" because, before the research finished, it was necessary to remove the devices to allow the maintenance of the investigated environments in order to restore the Chemistry Laboratory. Therefore, only non-invasive investigations were carried out during the final control verification and the direct weight measurement had to be dispensed with.

Geographic location of the building _ The building is in the area of Chamberì, north of the district Malasaña, in a flat area and strongly urbanized (Fig. 6.9).

Fig. 6.9 – The Escuela de Minas its urban context

Client _ Having to work on one of the locations of the Polytechnic University of Madrid, the experiment provided for collaboration with a public commissioner represented by the Director of the School.

Time from installation to final verification _ The installation of the devices was carried out in April 2018. After 18 months of monitoring, the final verification of the intervention was carried out in November 2019.

Diagnostic investigations _ Monitoring has been carried out either by comparison of thermographic images or by carrying out weight tests (except for final verification).

Technology and building materials _ The building consists of a structure in supporting masonry made of bricks, which rests on a massive base of natural stone.

Historical background on the building _ Recalling briefly what already described in section 3.6, the building was built at the end of the 19th century on a project of the architect Velàzquez Bosco and represents one of the oldest offices of the Polytechnic of Madrid. The architecture is very reminiscent of the author's historicist eclecticism, recurrent in his other works known and highlighted in the volumetric distribution, in the use of different building materials and in the ceramic decorations on the facades.

Phases of initial diagnosis _ The diagnosis of rising damp inside the investigated environment was not immediate. It was necessary to carry out a preliminary investigation to rule out other causes related to the water supply on the wall in direct contact with the ground and possible infiltration from the lateral cavedium. Both components could be excluded from the results of these investigations.

However, there was a low ventilation of the room, the presence of cement finishes and ceramic coatings that do not favour the disposal of the damp contents inside the walls. As a result of the combination of all the described parameters, a height of the damp front of about 2.20 m was highlighted. Again, as a preliminary to the installation of the devices, the plasters of a portion of the wall has been removed (Fig. 6.10).

The test included the installation of a **CNT** device with a radius of action of 10m on the wall opposite that investigated, together with an **Hr-T** probe while an IDROSCAN probe, **ID1**, was installed directly on the measuring wall.

Fig. 6.10 – The wall before and after the removal of the plaster

Location of the device and of the points where the thermographic images were acquired _ During the installation and monitoring phases of the device, 11 thermographic images have been acquired in both internal and external zones (Fig. 6.11).

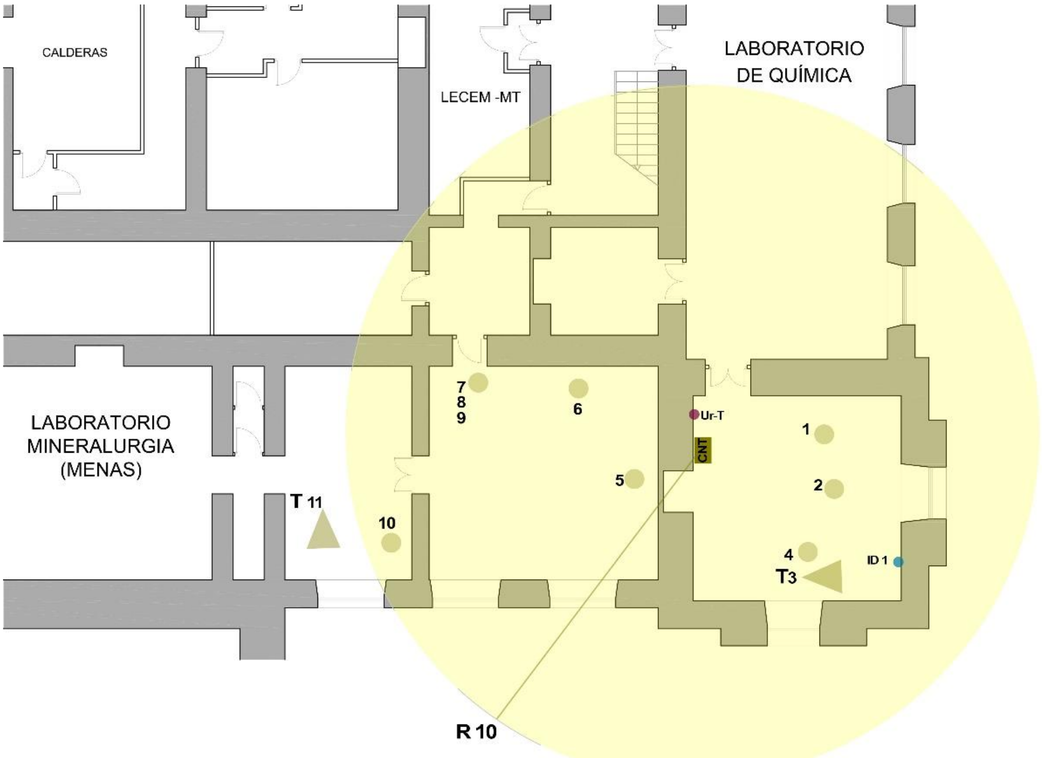


Fig. 6.11 – Location of the device and of the points where the thermographic images were acquired

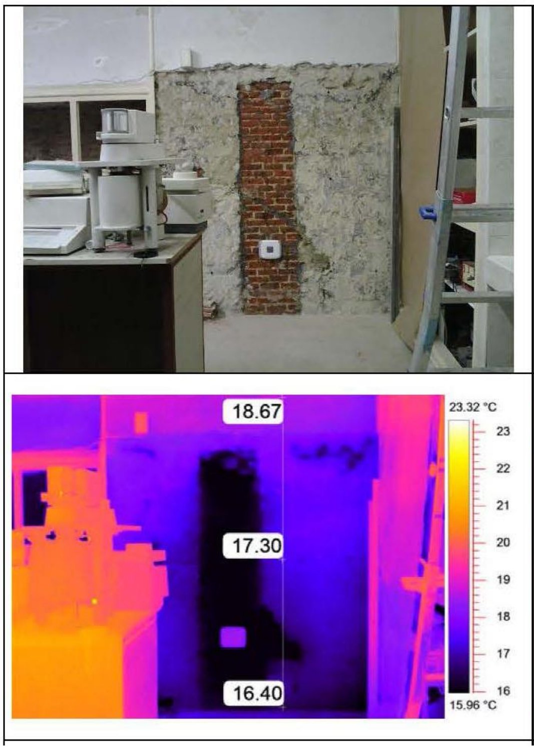
Qualitative verification of the intervention _ For the purpose of the performance check of the intervention it is considered useful to compare the $\mathbf{T_3}$ thermographs (Fig. 6.12), which frame the wall where the device has been installed, and the $\mathbf{T_{11}}$ thermographs (Fig. 6.13) that frame a wall outside the range of action.

To allow an exhaustive interpretation of thermal images, the environmental parameters recorded during the investigation are reported (Tab. 6.3).

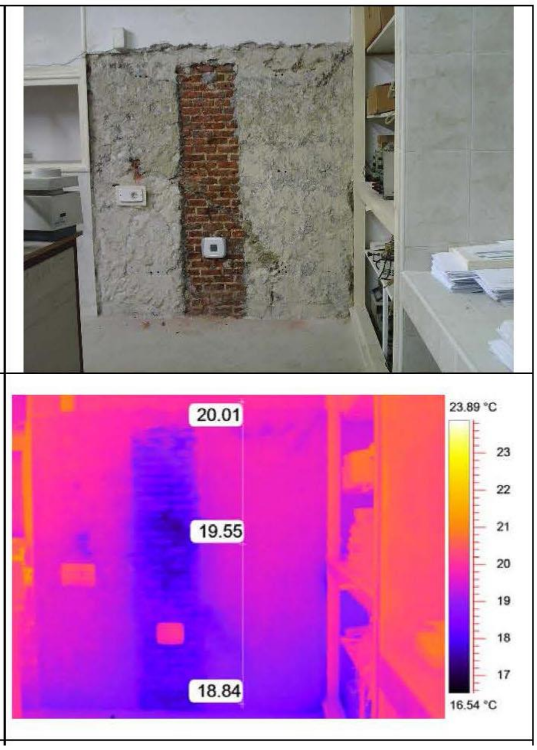
Tab. 6.3: Environmental parameters of monitoring days

day		inside		outside	
		Hr [%]	**T** [°C]	**Hr** [%]	**T** [°C]
23/04/2018	Installation	45,1	21,2	51,1	21,2
13/11/2018	1° monitoring	47,1	21,8	63,3	18,1
23/05/2019	2° monitoring	31,8	22,6	30,1	23,0
28/11/2019	Final verification	51,4	18,4	70,4	13,0

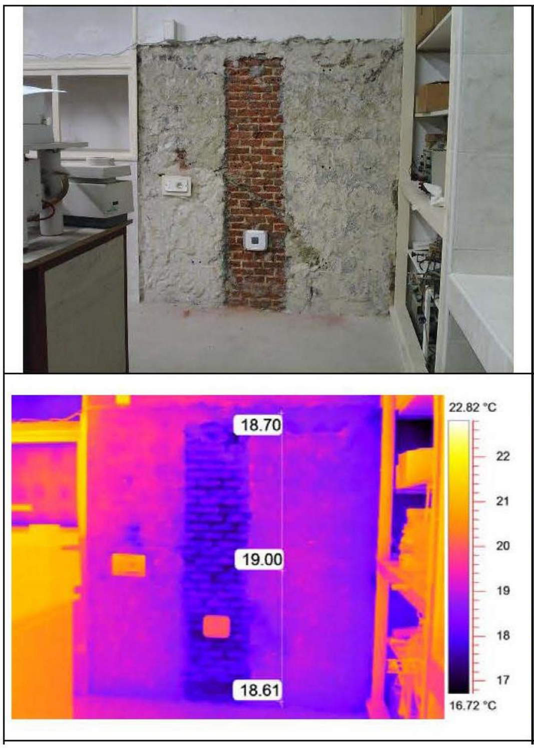
The images were compared according to the same seasonal periods, with similar thermo-hygrometric parameters: spring 2018 – 2019 (installation – 2° monitoring) and autumn 2018 – 2019 (1° monitoring – final verification).



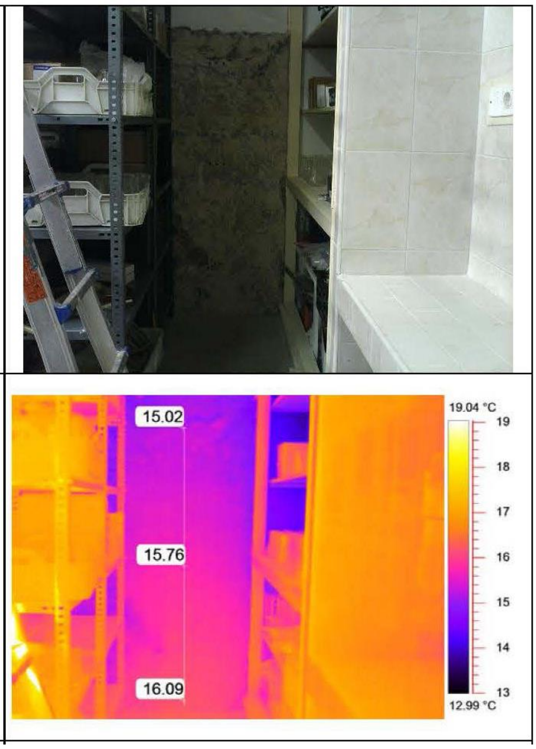
T_{03} in 24-04-2018



T_{03} in 23-05-2019

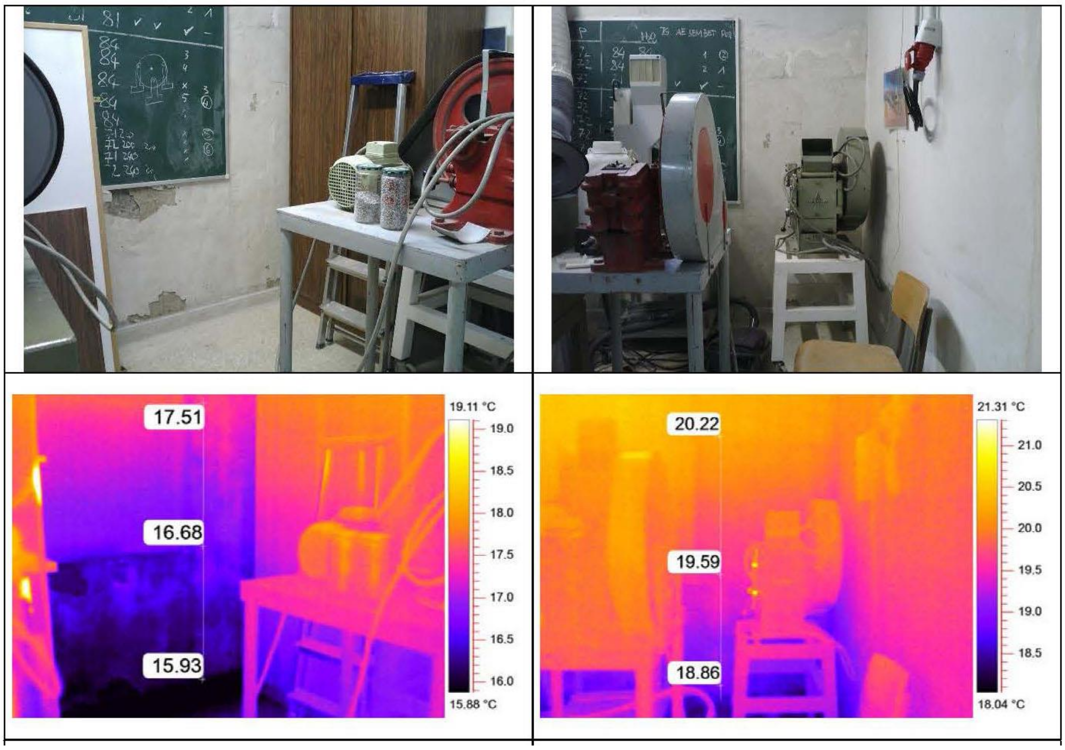


T_{03} in 13-11-2018

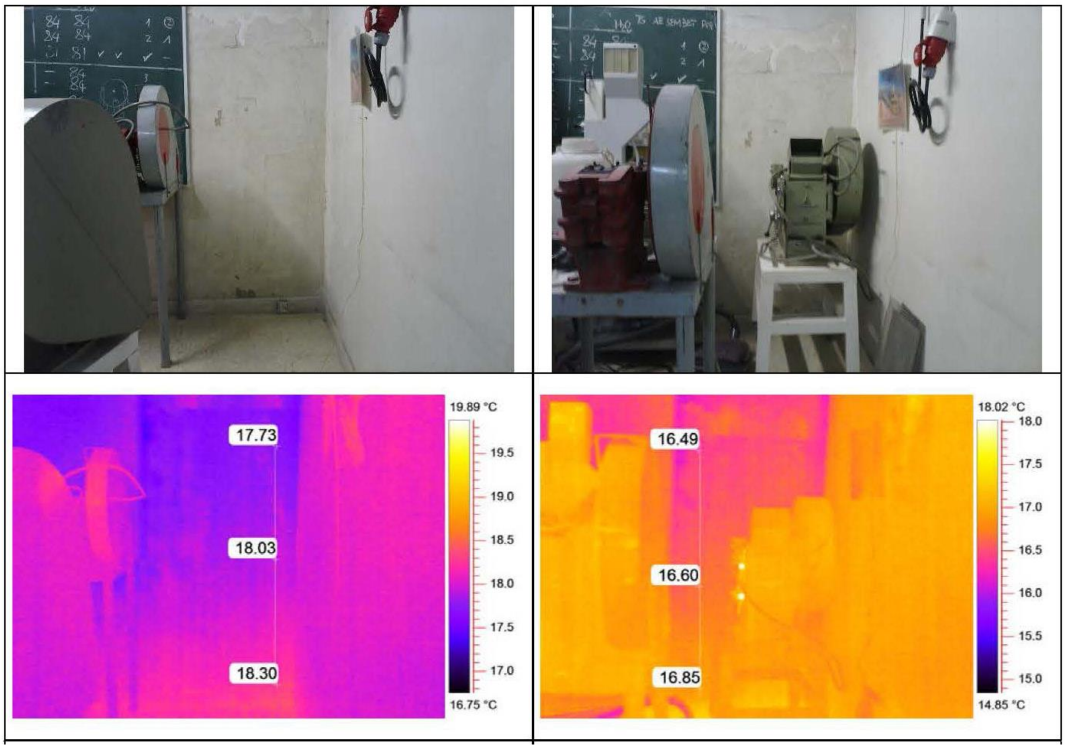


T_{03} in 28-11-2019

Fig. 6.12 – Comparison between IRT images T_3



T_{11} in 24-04-2018 **T_{11}** in 23-05-2019



T_{11} in 13-11-2018 **T_{11}** in 28-11-2019

Fig. 6.13 – Comparison between IRT images T_{11}

Interpretation of data and discussion of weighted data

The comparison between the thermographic images showed a reduction in the range of variation of the surface temperatures in the investigated area:

- The image T_3 shows a passage from ΔT=**2,27**°C to ΔT=**1,17**°C during the spring and from ΔT=**0,09**°C to ΔT=**1,07**°C during the autumn;

In the thermographic relief T_3 of November 2019 there is a reversal of the colour palette due to the interference of some furniture introduced later.

In this case it was also interesting to investigate the progress of the process at a point outside the range of the device. In particular, the thermographic images acquired in the context of the autumn survey of 2018 and 2019, in the area close to the mineralogy laboratory (T_{11}) they show a reversal of surface temperatures, which appear slightly higher in the lower part.

This condition can be caused by a passage of plants, that is by the difference in transmission of the heat flux between the two portions of the wall: the environment investigated is, in fact, under the access quota to the Escuela from calle Rio Rsas. The lower portion is in contact with the filling layers of the ground under the stairs while the upper portion, where the window opens, is free from both sides and corresponds to the base of the prospectus. In the autumn condition, the external ambient parameters of temperature (lower) and ventilation (greater), favour the thermal exchange through the exposed portion, resulting in the formation of a cold surface (blue colour gradations).

- The image T_{11} shows passage from ΔT=**1,58**°C to ΔT=**1,36**°C during the spring and from ΔT=**0,57**°C to ΔT=**0,36**°C during the autumn.

The variation read in both comparisons, spring and autumn, shows a substantial permanence of the same range of variation of surface temperatures, attributable to the fact that the investigated wall is just outside the range of action of the device and, therefore, its thermo-hygrometric response is not affected by CNT.

Samples for the measurement of wet contents were also taken during monitoring. Following the indications supplied by the standard UNI 11085, a survey wall has been chosen and 12 points of withdrawal have been identified on it (Fig. 6.14).

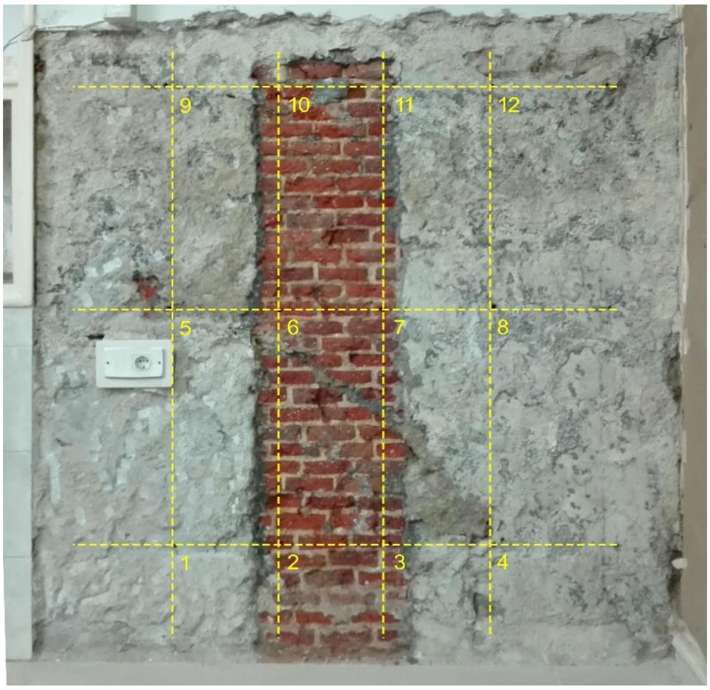


Fig. 6.14 – Sampling points for weighting tests

For each point a sample of material was taken at depths of 0-10 cm. Laboratory tests provided values of the quantity of water present in the masonry. Below are the data collected within the four carried out monitoring (Tab. 6.4).

Tab. 6.4: Measurements of weights taken

			INSTALLATION 23 APRIL 2018	**1° MONITORING 13 NOVEMBER 2018**	**2° MONITORING 23 MAY 2019**
n° sample.	**x**	**y**	**C_w** [%] $((w_w - w_d)/w_d)x100$	**C_w** [%] $((w_w - w_d)/w_d)x100$	**C_w** [%] $((w_w - w_d)/w_d)x100$
	cm	**cm**	Wet content	Wet content	Wet content
1	0	33	3,59%	3,52%	1,60%
2	30		10,20%	2,23%	2,48%
3	60		9,71%	0,93%	1,14%
4	90		11,59%	2,01%	2,24%
5	0	100	6,67%	2,25%	3,79%
6	30		10,05%	3,29%	2,12%
7	60		11,88%	2,66%	3,67%
8	90		13,96%	4,54%	6,67%
9	0	163	6,91%	5,77%	0,62%
10	30		9,20%	2,73%	1,67%
11	60		3,95%	0,66%	1,32%
12	90		4,10%	1,12%	0,92%

The measured values have been averaged for each withdrawal quota. At the date of final verification of the intervention a reduction of the wet content has been recorded with respect to the value measured during installation of **81%** at the height of 160cm, **62%** at the height of 100cm and **69%** at the height of 30cm (Fig. 6.15).

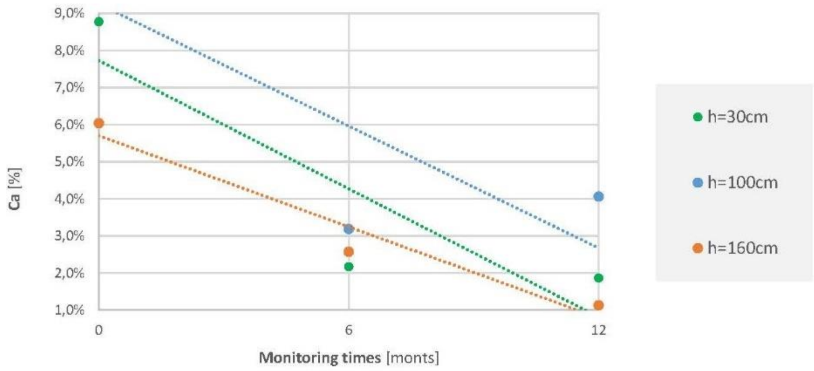


Fig. 6.15 – Variation of moist content corresponding to the sample's heights

The results confirm the findings of non-invasive investigations into a significant reduction in wet contents and their distribution. The results of direct measurements also demonstrate the influence of the larger surface area of evaporation of the masonry portion at the outer walkway (h=160cm) in terms of water disposal compared to the underlying masonry portion.

The Santuario of Beata Maria Vergine del S. Rosario

Reference cases _ The survey can be included between the "cases in progress" because, to the result of the tests carried out, the Sanctuary has decided to purchase the devices in order to maintain the achieved result during the time.

Geographic location of the building _ The building is in the city of Pompeii, on the edge of the Metropolitan City of Naples. The area, today rather urbanized, is close to the well-known archaeological site of Pompeii (Fig. 6.16).

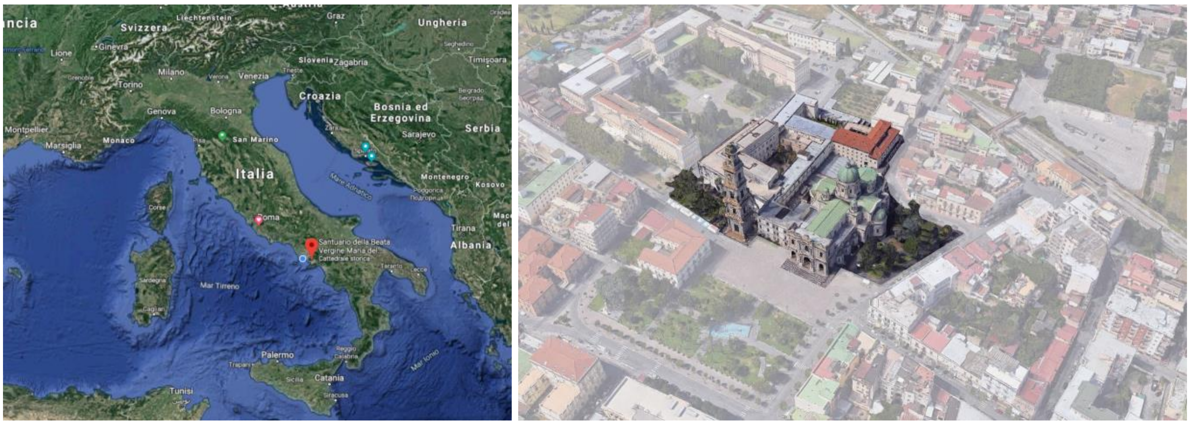


Fig. 6.16 – The Basilica in its urban context

Client _ The Basilica has been the property of the Papal State since 1896. The survey provided for collaboration with a public/private commissioner represented by the Sanctuary of Beata M. V. del S. Rosario.

Time from installation to final verification _ The device installation was carried out in July 2017 and, after two years, the application is still ongoing.

Diagnostic investigations _ The monitoring was carried out both by the acquisition of thermographic images and by carrying out weight tests, although in a small number to respect the decorative apparatus of the Crypt.

Technology and building materials _ The building consists of a mainly structure in supporting stone of Vesuvius; the naves, the smaller chapels and the same Crypt are richly decorated with marble, frescoes and mosaics.

Historical background on the building _ Recalling briefly what already described in paragraph 3.6, the first part of the building was founded at the end of the 19th century on a project by architect Antonio Cua, for the request of Countess Marianna De Fusco and Lower Bartolo Longo (Blessed Bartolo Longo today). After having been surrendered to the Holy See, Pope Leo XIII elevated her to the role of Pontifical Basilica. In the 30's the original plant was expanded according to the project of the architect Monsignor Spirito Maria Chiappetta, reaching the present surface.

Phases of initial diagnosis _ The diagnosis of rising damp has taken into account the additional contribution of poor ventilation, hypogean position of the Crypt and the presence of contiguous walled areas, with probable filled with land.

The experiment included the installation of a **CNT** device with a radius of action of 15m on the wall opposite the altar, together with an Hr-T probe and an IDROSCAN probe, **ID1**.

Location of the device and of the points where the thermographic images were acquired _ During the installation and monitoring phases of the device, 9 thermographic images have been acquired in both internal and external zones (Fig. 6.17).

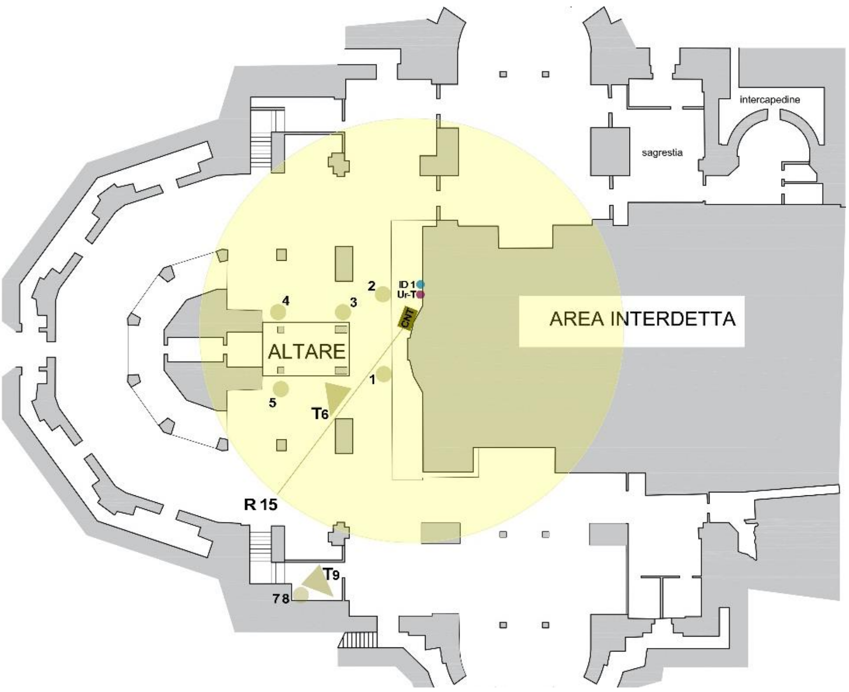


Fig. 6.17 – Location of the device and of the points where the thermographic images were acquired

Qualitative verification of the intervention _ For the purpose of the performance verification of the intervention it is considered useful to compare the thermographs T_6 (Fig.

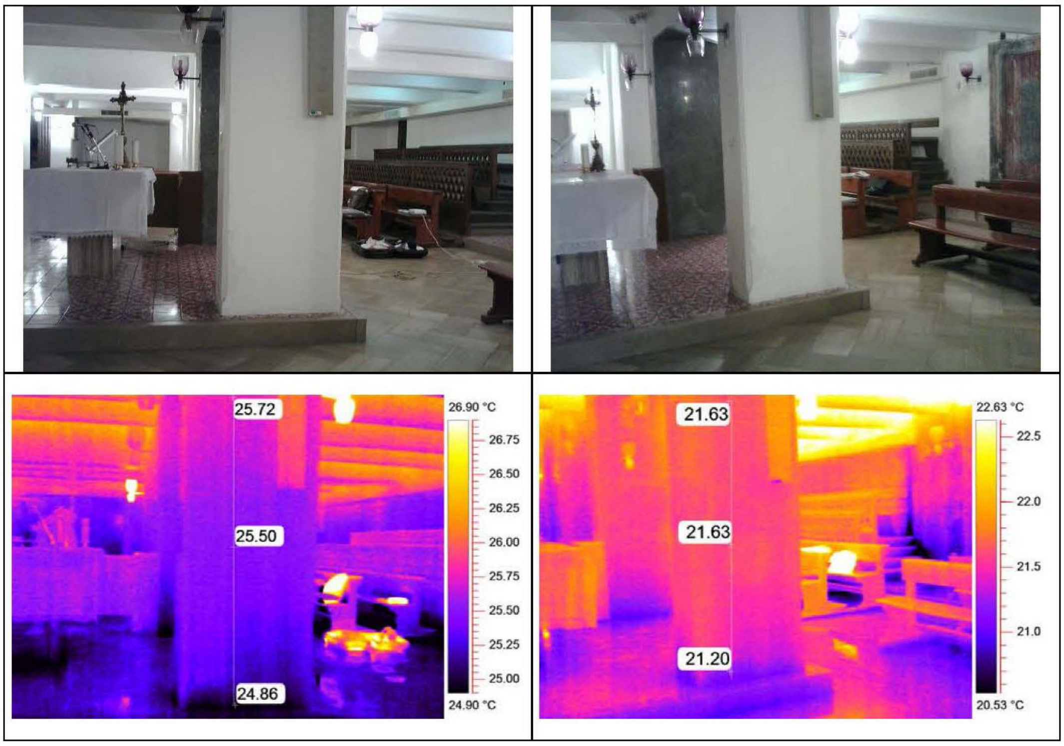
6.18), which frame an isolated column falling within the range of action of the device, and the thermographs T_9 (Fig. 6.19) that frame a wall outside the field of intervention at a small service area.

To allow an exhaustive interpretation of thermal images, the environmental parameters recorded during the investigation are reported (Tab. 6.5).

Tab. 6.5: Environmental parameters of monitoring days

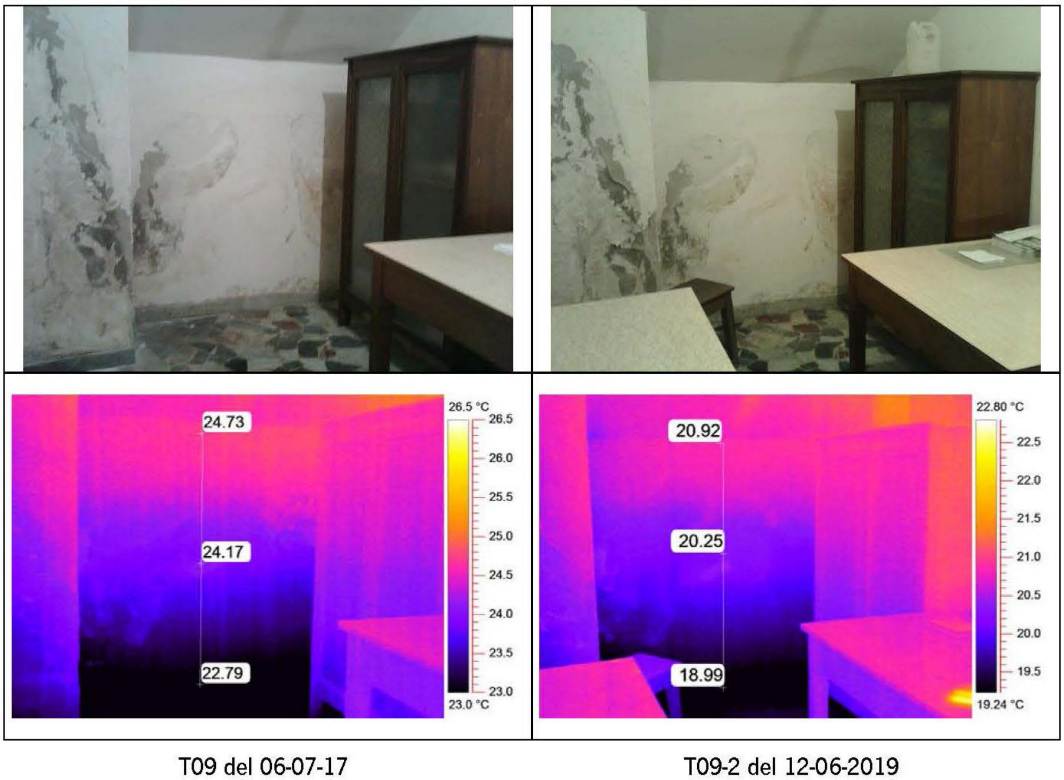
day		**inside**		**outside**	
		Hr [%]	**T** [°C]	**Hr** [%]	**T** [°C]
06/07/2017	Installation	66,2	26,7	70,0	29,0
18/07/2018	1° monitoring	81,1	26,2	42,7	29,8
12/06/2019	2° monitoring	65,1	25,3	54,2	31,4

Since the surveys were always carried out during the same seasonal period, it is possible to compare the data for the installation phase (summer 2017) with those for the second and most recent monitoring (summer 2019).



T_{06} in 06-07-2017 **T_{06}** in 12-06-2019

Fig. 6.18 – Comparison between IRT images T_6



T_{09} in 06-07-2017 **T_{09}** in 12-06-2019

Fig. 6.19 – Comparison between IRT images T_9

Interpretation of data and discussion of weighted data

The comparison of thermographic images has shown a general reduction in the range of variation of surface temperatures in the area of intervention:

- The image T_6 shows a reduction from ΔT=**0,86**°C to ΔT=**0,43**°C;

In this case it was also interesting to investigate the progress of the process at a point outside the range of the device. In particular, the T_9 thermographic images show a permanence of the phenomena of rising damp that settles with a maximum level of the humid front at the same altitude as the initial one.

- The image T_9 shows a quite constant range passing from ΔT=**1,94**°C to ΔT=**1,93**°C.

Samples for the measurement of wet contents were also taken during monitoring. Following the indications supplied by the norm UNI 11085, a survey wall has been chosen on which 3 points of withdrawal have been identified (Fig. 6.20).

Fig. 6.20 – Sampling points for weighting tests

For each sampling point a sample of material was taken at depths of 0-10 cm. Laboratory tests provided values of the quantity of water present in the masonry. The monitoring of July 2019 was not possible to carry out the sampling and, therefore, the data for the first year of installation (Tab. 6.6).

Tab. 6.6: Measurements of weights taken

			INSTALLATION 06 JULY 2017	**1° MONITORING 18 JULY 2018**
n° sample.	**x**	**y**	**C_w** [%] $((w_w - w_d)/w_d)x100$	**C_w** [%] $((w_w - w_d)/w_d)x100$
	cm	**cm**	contenuto di acqua	contenuto di acqua
S1 L	0	30	14,82%	15,75%
S1 M	0	80	14,00%	11,65%
S1 H	0	120	13,47%	9,26%
S1 HH	0	170	10,31%	7,86%

By comparing the values recorded in the July 2018 monitoring with the July 2017 installation values, we note an increase in the wet content of **6%** corresponding to the 30cm quota, while in the points at higher height there is a reduction of the humid content equal to **17%** at the altitude of 80cm, **31%** at the altitude of 120cm and **24%** at the height of 170cm (Fig. 6.21).

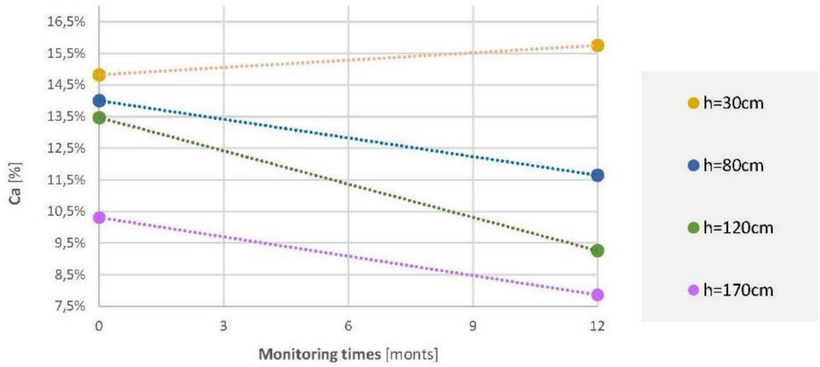


Fig. 6.21 – Variation of moist content corresponding to the sample's heights

The results confirm a general reduction in the initial wet contents highlighted by the non-invasive investigations. There is still a low "cold" area, at the attack with the marble flooring. The presence of this coating can justify the edge effect that can be read in the thermographic relief and give indications as to why the damp content of the wall continues to accumulate in this preferential zone (as shown by the weight values at 30cm).

6.3 DISCUSSION OF THE RESULTS

The performance check carried out for the recovery of the historic walls affected by rising damp through the application of CNT devices offers the opportunity to develop some interesting observations.

First, the Technology has verified the complete independence of its operation from the type of building material and technology of the buildings to recover.

In addition, the method has also been shown to be applicable for columns and pillars, unlike all other traditional interventions that fail to ensure the recovery of these isolated elements.

Very interesting was the comparison of the thermographic images obtained in the same monitoring in areas within and outside the range of action of the device. This comparison confirms that the disposal of the damp contents inside the walls, does not correspond to a random activation of the evaporative phenomenon in the investigated environments but represents just the result of the application of this Technology. The external walls to its field of action, in fact, even in the same conditions of evaporation, continue to absorb further water from the foundation soils keeping unchanged the height of the ascent.

Investigations have also demonstrated the effectiveness of IRT thermography as a tool for easy visualization of the disposal of wet contents and for the detection of the born of pathologies of second order related, for example, to the formation of surface condensation at hygroscopic salt deposits. On the other hand, the inadequacy of the method to provide specific (and not relative) values of the quantity of water present inside a masonry or part of it, or its conservation status, was also verified. The latter aspect fosters the interest in implementing the methods of quantitative and non-invasive diagnosis set out in Chapter 5.

Finally, the development of an instrumental diagnostic sheet aims to promote the development of tools for validation and certification of the many materials and techniques present on the market, which all too often propose remedies for the restoration of wet masonry detached from any scientific basis, generating confusion both in the audience of clients and in that of the professional technicians less experienced on this theme.

CONCLUSIONS AND FUTURE RESEARCH DEVELOPMENTS

The **specific results** discussed at the end of each insight presented in this thesis, at Chapter 4, 5 and 6, have demonstrated the achievement of the three goals of the project.

With respect to the first goal, about the **quantification of the variation in the performance of building materials subjected to different imbibition degrees**, the experiment described in Chapter 4 has implemented the scientific data obtained by other researchers on the alteration of the mechanical behaviour of building materials in the presence of moisture. In addition, the study provided original laboratory data for the quantification of the change in thermal properties of the same wetted materials.

The results of this study showed three ranges, defined as "diagnostic ranges" which represent the conservation status of materials and masonries according to the moisture content in them (0-35%, 35-65% and 65-100%).

These diagnostic ranges have been adopted as part of the surveys described in Chapter 5 for the **testing of new systems for diagnosing the phenomenon with a view to classifying the conservation status of wetted masonries**, which was the second goal of research. In fact, by inserting the measurements obtained by applying the Idroscan Method within the identified intervals, it was possible to make a quantitative diagnosis of the conservation status of the masonry investigated in an instantaneous and non-invasive way.

This result is undoubtedly an element of great originality that allows the application of the Idroscan Method both in the preliminary investigation phases and in the ongoing work for the monitoring and verification of the recovery interventions adopted.

Finally, with respect to the third goal, regarding the **verification of the effectiveness of the Charge Neutralization Technology in interrupting the dynamics of the rising damp in a definitive and especially non-invasive way**, the data obtained from the experimental survey described in Chapter 6 have attested the performance effectiveness of the method highlighting, in particular, its applicability in the context of Cultural Heritage and the characteristic of being able to act even on isolated elements such as pillars and columns.

Among the results of the experiment, emerges the elaboration of the diagnostic sheet, an original element aimed at the validation and certification of materials and techniques for the recovery of wet masonries.

TRANSVERSAL RESULTS OF PHD

In addition to the specific results reached with respect to the goals of the project, the development of the research has provided the opportunity to achieve further **transversal results** by configuring different moments of intersection between the disciplines involved, intercultural between the University and the company, and partnerships with Italian and foreign Universities.

In this perspective, an interesting first result is represented by the organization of the existing extensive bibliography on this theme, about the studies carried out so far in order to identify the findings of each of them and the salient points for the development of further research. From the study of the texts consulted, many references have been filtered through monographs, articles in journals and standards, reported in the chapter REFERENCES.

Deepening some research topics, it has been possible to give a personal contribution to the existing bibliography through the publication of:

- 8 papers in proceedings of conferences
- 1 paper in a scientific journal
- 1 monograph presented in Matera in April 2019 as part of an international conference organized on the topic of rising damp.

The related information about this publication are available in the paragraph PERSONAL BIBLIOGRAPHIC REFERENCES.

The conference held in Matera was a significant moment to strengthen the scientific network promoted by the project, configuring the opportunity for the union of common interests aimed at implementing research through a wide and transversal articulation that involves: Universities, Public Administrations responsible for the conservation of Cultural Heritage, companies and professionals involved in the sector and the professional Orders responsible for their training.

Finally, it should be noted that the development of the CNT system performance test has provided the inclusion in the CNT-Apps inter-departmental research group, which involves experienced researchers on the issue of the rehabilitation of wet masonries in the departments: D.I.C.E.A. of the University of Naples Federico II, TekneHub of the University of Ferrara, D.I.C.E.A. of the University of Padua, D.I.I. of the University of Salento, D.I.S.E.G. of the Polytechnic of Turin and Leonardo Solutions srl, industrial partner of the Department of Excellence DICEA of Federico II.

FUTURE DEVELOPMENT OF RESEARCH

The results of all bibliographic and experimental studies open the way to further and innovative research developments on the three points developed by the project.

The measurement of the variation in the performance of materials in the presence of moisture makes interesting the expand the survey on different building materials, with particular regard to the study of the alteration of the energetic properties of wetted materials and therefore of the alteration of the energetic performances of the building envelopes.

The test carried out for the application of the Idroscan method requires a deepening to determine the uniqueness of the response curve, built for the Neapolitan yellow tuff, and the relative instrumental diagnosis ranges, extending the investigation to various materials.

In addition, the data collected provide the elements needed to implement the operation of the probe in order to patent a new direct and non-invasive diagnostic tool to be used also for the monitoring of recovery interventions.

Finally, with reference to the diagnostic sheet developed as part of the CNT system performance test, the research will aim to develop good practices for the project of the recovery interventions on the wet masonries and the protocols to the validation and certification of the materials and the techniques present on the market.

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[28] UNI EN ISO 13788:2013. Prestazione igrometrica dei componenti e degli elementi per edilizia. Temperatura superficiale interna per evitare l'umidità superficiale critica e la condensazione interstiziale.

[29] Decreto interministeriale n.39 del 2015. Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici.

[30] Opuscolo Ministero della Salute: Umidità e muffe.