Methodology for diagnosis of rendering anomalies due to moisture in walls

Metodologia de diagnóstico de anomalias de rebocos exteriores devidas à humidade

Ana Cristian Magalhães
Civil Engineer/ Laboratório Nacional de Engenharia Civil, Portugal,
acristian@lnec.pt

Maria do Rosário Veiga
Civil Engineer/Laboratório Nacional de Engenharia Civil, Portugal,
rveiga@lnec.pt

C. Pina Santos
Civil Engineer/Laboratório Nacional de Engenharia Civil, Portugal,
pina.santos@lnec.pt

Luís Matias
Physicist/Laboratório Nacional de Engenharia Civil, Portugal,
lmatias@lnec.pt

António Vilhena
Civil Engineer/Laboratório Nacional de Engenharia Civil, Portugal,
avilhena@lnec.pt

Abstract
Moisture is one of the most powerful causes of decay of historic buildings. A lack of understanding concerning the action of moisture and the resulting degradation mechanisms are often preventing efficient repair of ancient walls. Thus, there is a need to develop and systematise a methodology of diagnosis of defects due to moisture, taking into account the characteristics and properties of materials used on those walls. The use of in situ test methods, especially non-*destructive*invasive methods, is an important tool, but those methods must be adapted to this particular use, calibrated and interrelated in a global approach. As a result of a Research Project developed at LNEC a methodology involving several phases is proposed, based on tests applied to several case studies and on the analysis of their results. This work synthesises the proposed methodology presenting examples of data combinations for the suggested techniques and its interpretation in order to characterise the state of conservation of renderings and to estimate their performance.

Keywords
Renderings; ancient walls; anomalies; diagnosis; moisture.

Resumo
A humidade é uma das mais poderosas causas de degradação de edifícios históricos. O desconhecimento da acção da humidade e dos mecanismos de degradação dela resultantes impedem frequentemente uma reparação eficaz de paredes antigas. Assim, é necessário desenvolver e sistematizar uma metodologia de diagnóstico das anomalias devidas à humidade, tendo em conta as características e propriedades dos materiais usados nessas paredes. O uso de ensaios in situ, especialmente de métodos não-destrutivosinvasivos, é uma ferramenta importante, mas tais métodos devem ser adaptados a esta utilização, calibrados e inter-relacionados numa abordagem global. Como resultado de um Projecto de Investigação desenvolvido no LNEC, propõe-se uma metodologia envolvendo várias fases, baseada em ensaios aplicados a vários casos de estudo e na análise dos respectivos resultados. Este trabalho sintetiza a metodologia proposta, apresentando exemplos de combinações de resultados para as técnicas sugeridas e para a sua interpretação, de forma caracterizar o estado de conservação dos revestimentos e a avaliar o seu desempenho.

Palavras-chave
Rebocos; paredes antigas; anomalias; diagnóstico; humidade

Introduction

Exterior renderings of ancient buildings often present several defects which have moisture as main origin. In fact, water is a primary cause of many anomalies and secondary cause of many others. Moisture in walls of ancient buildings can have diversified causes: groundwater, rain, inner condensation, presence of soluble hygroscopic salts, rupture of piping, obstruction of gutters or of fall pipes, etc.

The knowledge of the origin of anomalies due to moisture and of the resulting mechanisms of degradation of affected renders is essential to provide a correct diagnosis. In this sense, the detection and the quantification of anomalies resulting from moisture in walls of ancient buildings must be carried out using a set of different techniques, whose results, considered together, supply important data regarding the state of conservation of renderings [1, 2].

The characterization of walls' materials is essential to understand the degradation mechanisms. The literature has presented several studies in this field [3-9].

A study aiming to systematize and to apply a set of available characterization techniques of materials was developed in order to integrate them on a reliable methodology for diagnosis of damage of ancient walls, in particular those defects directly associated with moisture [10].

The objective of the diagnostic is the gathering of information allowing the elimination or minimization of the damage mechanisms and, in particular, the definition of a repair strategy for the wall renderings.

The techniques were selected based on the analysis of results obtained on several case studies (Santa Marta Fortess, Oitavos Fortress, Évora Cathedral, Inglesinhos Convent, described in previous work [4, 10-15]), taking into account criteria related with complementarity – evaluation as complete as possible of mechanical, physical and chemical aspects – limitation of destruction – and practicality – easy and quick application, low cost, low specialization of operators (as much as feasible).

The proposed methodology involves the following phases:

- general observation of the building and registration of the main anomalies;
- detection of problematic zones using non-destructive *in situ* test methods of global analysis;
- quantification of damage of mechanical, physical and chemical nature, using non-destructive test methods of localized application;
- whenever necessary use of destructive test methods to complement the quantification of degradation;
- classification of the state of conservation of renderings;
- establishment of a diagnosis;
- definition of a repair strategy.

Methodology

The methodology, synthesized on figure 1, concerns a set of available techniques and their interpretation and correlation of results.

General observation of the building and its renderings

A general observation of the building and its renderings, carried out by an expert observer, allows to identify and to register the symptoms and their severity, establishing a map of anomalies with a classification by type.

The visual observation must always be complemented by photographic records. It is important to include data concerning extrinsic conditions to the building (orientation, solar radiation incidence, predominant wind, rain intensity, medium and extreme values of temperature and relative humidity) in order to predict how they affect the materials and how they contribute to the degradation process.

The type of rendering must be identified in this process, as well as its composition and technique of production and application – coats, thickness, texture and colour – implying a first selection of low deteriorated zones for this observation. Rendering from high degraded zones must also be observed in order to collect information for the evaluation of the degradation mechanisms. In subsequent phases, those zones, identified as low deterioration and high deterioration zones, can be used for the application of *in situ* tests and, if necessary, to collect samples for laboratory analysis, allowing for characterisation of the material – low deterioration zone – and for deterioration study – high deterioration zone.

A preliminary damage diagnosis based only on the observed symptoms may be possible at the first phase. If

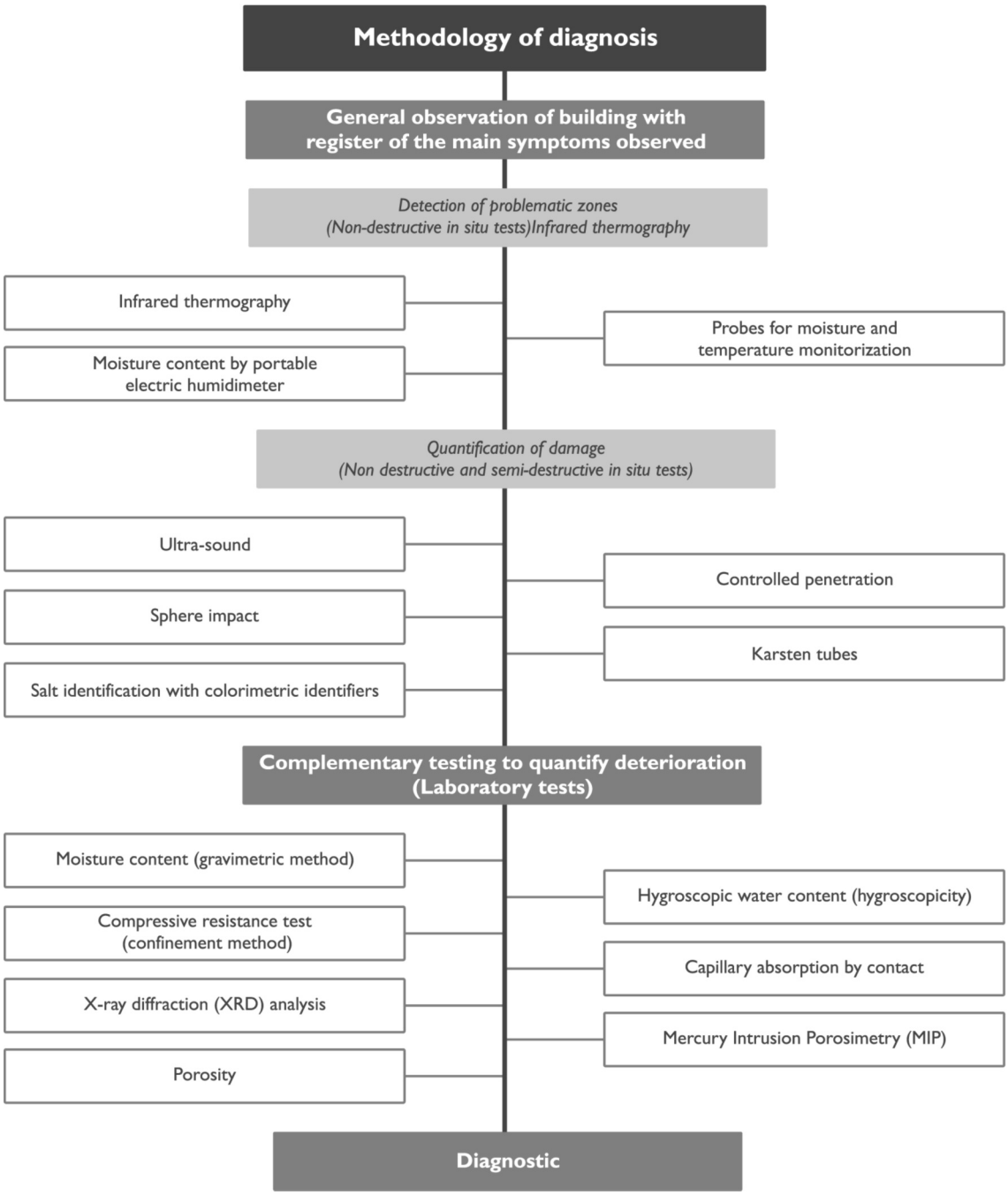


Fig. 1 Proposed methodology for diagnosis of wall renderings' defects due to moisture.

this is not possible, the diagnostic should be substantiated by an extended study, using experimental characterization techniques [16].

Detection of problematic zones using methods of global analysis

After the visual analysis, a study orientated for the location of problematic zones is carried out by resource to test methods allowing a global analysis of the wall. *In situ* wide spectre non-destructive techniques are used, aiming to detect anomalies and to trace the degradation symptoms.

The global analysis test methods referred in this paper – infrared thermography, monitorization of moisture and temperature with miniature probes and with a portable electric humidimeter – aim essentially at the identification and the quantification of areas with high water content, the assessment of the distribution of water inside the wall and the follow up of the evolution of water content along time.

Quantification of damage using methods of localized application

The detected anomalies of mechanical, physical or chemical origin can be quantified through methods of local application, which supply information concerning intensity and level of degradation.

In general, previously to the tests, it is advisable to systematize information concerning renderings characteristics and their degradation level based on visual analysis, in order to improve the interpretation of the results and their representativity. In fact, even if results are quantified, they are always comparative values and they must be evaluated considering the type of mortar.

As much as possible, test areas must be selected taking into account the diversity of characteristics and the existence of sufficiently regular areas to perform the tests in the best possible conditions.

The most relevant anomalies of the renderings must be selected in each zone and classified according to the degree of degradation produced. Loss of adhesion to the support or loss of cohesion are often the predominant anomalies, because they are particularly difficult to repair. Tests should be carried out in zones with different degradation types and levels in order to compare results.

For the quantified evaluation of damage related to mechanical characteristics some *in situ* tests can be used: ultrasounds, sphere impact and controlled penetration. For the evaluation of the water behaviour the Karsten tubes method is proposed. Colorimetric identifiers can be used for the detection of soluble salts.

Complementary quantification of degradation

For clarification of some aspects concerning characterisation of materials, study of degradation products and quantification of damage, the use of complementary techniques of diagnosis can be necessary, requiring the extraction of samples of ancient renderings. In general, these techniques are carried out in laboratory, allowing rigorous determinations.

The set of proposed techniques are: moisture content by gravimetric method, hygroscopic water content (hygroscopicity), compressive resistance test (confinement method), capillary absorption by contact, mercury intrusion porosimetry (MIP), porosity (hydrostatic pressure method), X-ray diffraction (XRD) analysis.

The majority of these tests is currently applied in characterisation or in damage diagnosis of ancient buildings, so their description is available in the literature. However, some of the tests were specially developed or adapted at LNEC to be used with mortar samples extracted from old buildings; they were calibrated and described in previous works [6, 7, 11].

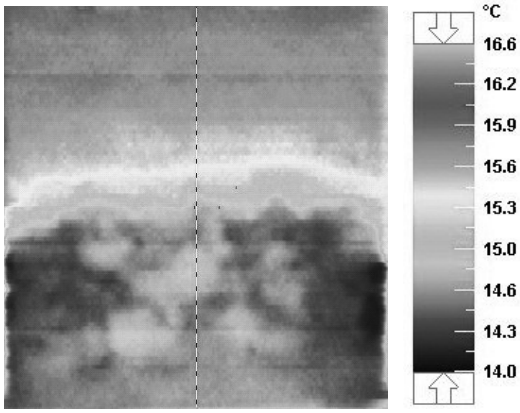
Evaluation of test results

In general the application of the referred techniques to ancient mortars is relatively complex due to different factors like typology and heterogeneity of the materials. Therefore the data obtained in each test must be used as comparative and not absolute values.

Some tests used in the methodology are illustrated on figures 2 to 4.

In table 1 the main limitations and advantages of the techniques are presented.

The interpretation of the results of the described test program, applied in a systematic way, by a specialized team, enables a safe classification of the state of conservation of ancient renderings, supporting eventual interventions to be carried out.



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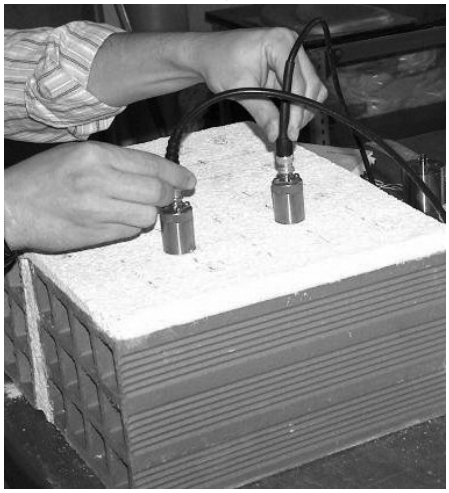

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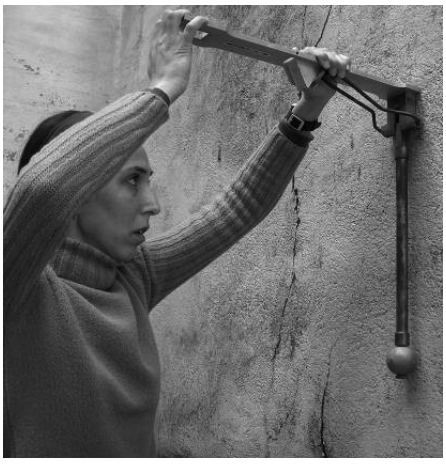

c)

Fig. 2 a) infrared thermography; b) ultra-sound; c) sphere impact.

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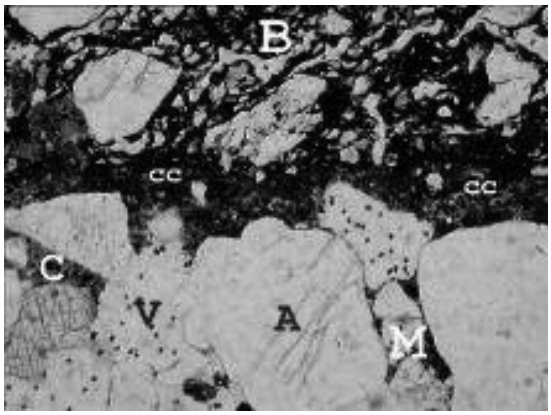
Fig. 3 a) controlled penetration; b) Karsten tubes; c) Salt identification with colorimetric identifiers.



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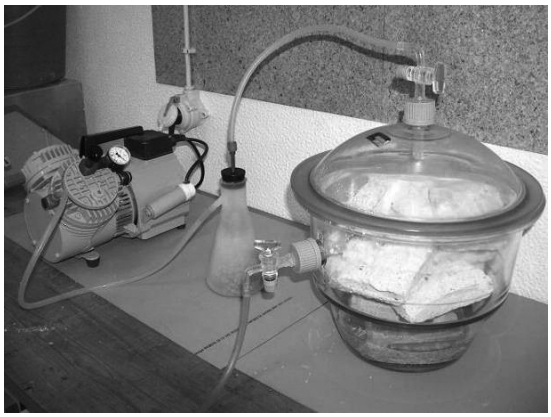

c)

Fig. 4 a) compressive resistance test (confinement method); b) capillary absorption by contact; c) determination of open porosity.

Establishment of a diagnosis

The location of damaged zones and the identification and quantification of zones with high water contents by non-destructive techniques of wide spectre - infrared thermography or techniques of moisture monitorization - allow to detect and to follow the evolution of water presence in the interior of the walls during long periods. It also permits to identify with some confidence the water's origin.

Very wet zones of renderings can present high levels of degradation, namely with loss of cohesion and adhesion and increase of the porosity. The tests of sphere impact, controlled penetration, ultra-sounds and Karsten tubes allow to establish a classification of the state of conservation, related with reduction of mechanical characteristics and increment of porosity. The existence of soluble salts such as sulphates is a cause of expansions in the renderings, producing powdering, loss of adhesion or detachment. The colorimetric identifiers (strips) allow to detect the presence of ions in the mortar and to determine their concentration in a semi-quantitative way. Through the correlation of the test results it is possible to confirm if there is a real correspondence between renderings with high water content and high degradation level (generalized loss of cohesion, bad adhesion, significant increase of water permeability, very low strength, etc.).

In the next phase, constituted by laboratory tests, the rendering materials characteristics are carefully quantified and the reaction products are identified in order to make possible the understanding of the degradation mechanisms.

The gravimetric method for moisture content determination complements the portable electric humidimeter measurements, allowing to quantify moisture inside the mortar and making possible the establishment of moisture profiles.

The values of hygroscopic moisture can reveal the existence of contents of soluble hygroscopic salts inside the mortar, and to check if these salts are the main cause of the moisture levels. Reduced values of the hygroscopic moisture are not due to the presence of hygroscopic salts, and point out to moisture originated by infiltration through the roof, through wall cracks or by rising capillarity through the interior of the wall.

Table 1 Main advantages and limitations of techniques.

Technique	Objective(s)	Advantages	Limitations
Infrared thermography	Detection of wet surface and internal zones through the evaluation of the distribution of temperatures in the wall surface	Non-invasive *in situ* test; evaluation of the states of wetness and of conservation of large areas of rendering; quick use; possibility of use in places of difficult access	Need of water evaporation or imposed heating to produce temperature differentiation, therefore, in practice the technique gives best results in dry, or sunny periods and in walls with solar significant exposition; alternatively, it needs artificial heating; method is sensitive to the presence of soluble salts, which can influence evaporation and the capacity of moisture detection [17]
Moisture and temperature monitorization with probes	Continuous measurement of moisture and of temperature near the surface or in the interior of the wall (probes inserted in drilled holes)	Possibility of assessment of evolution of the rendering hygrotermal state; complementary to thermography	Invasive test; imprecise measurements when the holes' air is saturated
Moisture content measurements with portable electric humidimeter	Evaluation of water contents on the mortars' surface	Non-invasive *in situ* test; quick and practical use for the detection of zones with high and medium moisture content	Need of a great number of careful and systematized measurements; sensitive to the presence of salts in the mortar, which can modify the results
Ultra-sonic velocity measurements	Location of possible damaged zones through reduction of ultra-sound waves velocity; complementary to other data concerning the materials mechanical resistance and stiffness	Non-invasive *in situ* test; quick and practical use; useful for assessment of the state of conservation and also for the evaluation of compatibility of substitution renderings	Interpretation of the results requires particular care and experience; the technique requires previous calibration for each type of mortar
Sphere impact	Information regarding rendering's deformability and mechanical resistance	Quick *in situ* tests of easy interpretation; no demand of specialized technicians	Invasive tests; the obtained information is localized, requiring a series of measurements in different zones
Controlled penetration	Evaluation of mechanical resistance of internal coats		
Karsten tubes	Evaluation of water permeability. Qualitative information of the rendering's state of conservation	Non-invasive *in situ* test; quick technique, of use *in situ* and in laboratory	Possible limitations of representativeness of *in situ* test due to the presence of paintings or thin organic finishing or due to high water content of the mortar, preventing further water absorption.
Salt identification with colorimetric identifiers	Identification of a specific ion	Non-invasive *in situ* test; very simple test, of easy and quick use both *in situ* or in laboratory	Very localized test; need of several determinations in the same zone
Moisture content by gravimetric method	Determination of the mortar water content	Possible use of samples of any shape and dimensions	Destructive laboratory test; it requires special care in gathering and storage of sample in order to avoid losing moisture before the first weighing

Technique	Objective(s)	Advantages	Limitations
Hygroscopic water content	Determination of the hygroscopic mortar water content and estimation of hygroscopic soluble salts content	Possible use of samples of any shape and dimensions	Destructive laboratory test; the method requires a systematized gathering of samples, from different heights and depths of the wall; results can be masked by the impossibility of complete extraction of the finishing coats
Compressive resistance test (confinement method)	Information concerning the mechanical resistance of mortars	Possible use of small irregular samples	Destructive laboratory test; the confinement mortar must be stronger than the sample to test in order to obtain rupture by sample but nevertheless there is a possibility of some influence of the confinement mortar on the results
Capillary absorption by contact	Determination of the coefficient of capillarity by contact (Ccc)	Possible use of irregular samples	Destructive laboratory test; the test requires relatively large quantity of sample; the results can be affected by the shape of the sample, especially in the case of very thin specimens
Porosity	Information about open porosity of the mortar	Possible use of small samples without special shape demands	Destructive laboratory test; porosity value does not characterize by itself the material porous system; it requires to be complemented by other techniques, such as MIP
Mercury intrusion porosimetry (MIP)	Estimated quantification of the size distribution and the volume of pores	Possible use of small irregular samples	Destructive laboratory test; high cost of the equipment; demand of specialized technicians; health risk for operators due to the possibility of contamination with mercury; interpretation requires knowledge concerning porous structure
X-ray diffraction analysis (XRD)	Information regarding the type of binder. Detection of the presence of pozzolanic constituents and of alteration products	Possibility to carry out qualitative and crystallographic analyses of any crystalline components; requires a small quantity of sample reduced to powder or in rough state.	The technique does not allow to observe the inter-space relation of the mortars components; quantitative information is of limited precision; the equipment is expensive and requires a specialized operator

The analysis of the results of compressive resistance tests using the method adapted for irregular mortar samples (confinement method) allows to compare the strength of ancient samples to mortars of known behaviour; low resistance points out to poor cohesion but it may be a characteristic of the type of mortar or a symptom of a degradation process.

Coefficients of capillarity determined by the test of capillary absorption by contact allow to compare the speed of absorption of the existent mortars to new mortars of known behaviour. Together with the values of mechanical resistance they allow a picture of the state of conservation: reduced coefficients of capillarity and relatively high mechanical resistance indicate mortars in good condition, cohesion and adhesion. On the other side, absorption and drying curves allow an analysis of how the absorption and drying of water take place in the interior of the mortar, complementing the water permeability data obtained with the Karsten tubes.

The application of XRD on mortars allows the identification of main mortar constituents and supplies information on the presence of products related with the development of mechanisms of degradation [14]. This information, combined with the results of compressive resistance and of capillary absorption, contributes to the identification of degradation mechanisms, complementing the data regarding the state of conservation of renderings.

The pore size distribution obtained through the mercury intrusion porosimetry and the values of open porosity, in combination with the results of compressive

strength, Karsten tubes, capillary absorption and hygroscopicity complement the evaluation of the mechanical behaviour and water behaviour of the mortar. The relation between the composition – determined by XRD analysis – and mercury intrusion porosimetry allows to appraise the degradation process of the mortars generated by the presence of salts. Higher porosity increases the total absorption and larger pore dimensions induce higher water absorption coefficients. However the degradation can be more significant in mortars with a larger volume of smaller pores, since higher pressures are produced in these pores during the process of salts crystallization, which takes place with volume increase. Smaller pores are also in the origin of higher rising capillarity. On the other hand, mortars with larger pores are weaker and they have higher total absorption. So, when repair mortars are formulated, a good balance between these characteristics is not easy to achieve.

Definition of a repair strategy

The strategy to adopt to solve problems related to moisture in renderings of ancient buildings with historical value must give priority to the preservation of the existent renderings (instead of removing and replacing them), with resource to conservation strategies supported by *maintenance plans*, *local repair* and *consolidation techniques*.

However, in the case of high severity anomalies, reduced value of the building and insufficient means, the strategy of intervention can pass by the option of partial or total *substitution of renderings*, imposing the previous elimination of the causes of anomalies, or at least their minimization, made possible by the first phase of the methodology of diagnosis applied: detection of problematic zones. Hence, the strategy of removal and replacement of historical mortars must be the last hypothesis to consider, only when the preservation strategies are not possible, and supported by the results of the applied methodology, namely by its second and, if necessary, third phases: quantification of degradation.

Maintenance includes the following operations: cleaning, treatment with biocides, correction of situations causing water infiltration, repair of finishing coats and *fulfilment* of superficial cracks.

Localized repair comprehends operations of treatment of cracks, salts elimination and filling out of lacunae, using materials similar to the existent ones.

Consolidation consists on the use of groutings in renderings with bad adhesion and cohesion consolidants when cohesion is insufficient.

Partial or total substitution of renderings implies the use of substitution materials compatible with the existent ones to avoid the risk of degradation increase.

The diagnosis of anomalies and the characterisation of the state of conservation of the renderings are important tools in the definition of strategies of intervention to adopt in ancient buildings with historical value.

Clear criteria must be defined to decide between i) repair of existent renderings, ii) partial or total substitution with compatible materials or iii) more onerous and complex options, involving consolidation (restitution of lost adhesion or of lost cohesion). The decision must be based on the following factors: value of the building and of the rendering; state of conservation of the rendering; availability of means in terms of technology, workmanship, time and budget allowances.

Conclusions

The described methodology proposes the evaluation of the renderings anomalies due to moisture in ancient walls by the simultaneous application of different techniques, whose connection of results supplies important data regarding the state of conservation of a rendering.

According to the proposed methodology, the investigation of the building must begin with a *general observation* and with the *register of the main anomalies and their severity*. After this first observation, a *global analysis* of the wall through *in situ* techniques of evaluation, allowing a more precise detection of the zones with problems, is proposed. Next, it is proposed a *localized analysis* of the anomalies using techniques of quantification and finally, for the establishment of the diagnosis, the use of laboratory techniques to explain some aspects and *complement the quantification* of the identified anomalies.

The experience shows that the systematized application of the proposed methodology makes possible the most rigorous determination of the qualitative and quantitative characterization of the renderings anomalies and their state of conservation.

The correlation of results obtained with the different techniques must lead to conclusions concerning the degradation mechanisms caused by moisture and their evolution allowing a classification of the state of conservation [4, 11, 18] of the rendering.

Considering the detection of causes and the identification, localization and quantification of anomalies, permitted by the methodology of diagnosis, an intervention methodology can be established based on conservation strategies including maintenance plans, techniques of localized repair and consolidation, preceded by the correction of causes and elimination of degradation mechanisms.

Repair and substitution materials must be selected fulfilling compatibility criteria with the pre-existent components, established taking into account both ethical conservation principles and the knowledge of composition, characteristics and behaviour of pre-existent materials provided by the described methodology.

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References

1 American Society for Non-Destructive Testing, *Nondestructive Testing Handbook. Infrared and Thermal Testing (Volume 3)*, American Society for Non-destructive Testing, Columbus (2001).

2 Henriques, F. M. A., *Humidade em paredes*, 2nd ed., LNEC, Lisbon (2001).

3 Santos, C. P.; Matias, L.; Magalhães, A. C.; Veiga, M. R., 'Application of thermography and ultra-sounds for wall anomalies diagnosis a laboratory research study', in *International Symposium. Non-Destructive Testing in Civil Engineering*, Berlin (2003), 16-19.

4 Magalhães, A. C.; Veiga, M. R., 'Comparison of in-situ mechanical tests on masonry mortars: sphere impact and controlled penetration test', in *Heritage, Weathering and Conservation Conference*, Madrid (2006), 561-567.

5 Borrelli, E., *Conservation of Architectural heritage, historic structures and materials salts*, ICCROM, Rome (1999).

6 Válek, J.; Veiga, M. R., 'Characterisation of mechanical properties of historic mortars – testing of irregular samples', in *Structural Studies, Repairs and Maintenance of Heritage Architecture IX*, ed. C. A. Brebbia, A. Torpiano, WIT Press, Southampton (2005), 1743-3509.

7 Veiga, M. R.; Magalhães, A. C.; Bosilikov, V. B., 'Capillary tests on historic mortar samples extracted from site. Methodology and compared results', in *13th International Brick and Block Masonry Conference*, Amsterdam (2004).

8 Veiga, M. R.; Aguiar, J.; Santos Silva A.; Carvalho, F., 'Methodologies for characterization and repair of mortars of ancient buildings', in *Historical Constructions*, ed. P. B. Lourenço, P. Roca, Universidade do Minho, Guimarães (2001) 353-362.

9 Groot, C.; Bartos, P.,;Hughes J., 'Characterisation of old mortars with respect to their repair', in *12th International Brick/Block Masonry Conference*, Madrid (2000) 815-827.

10 Magalhães, A. C.; Veiga, M. R., 'Metodologias de diagnóstico de anomalias devidas à humidade em paredes antigas', report 115/08-NRI, LNEC, Lisbon (2008).

11 Magalhães, A. C.; Veiga, M. R., 'Physical and mechanical characterisation of ancient mortars. Application to the evaluation of the state of conservation', *Materiales de Construcción* (accepted).

12 Magalhães, A. C.; Veiga, M. R., 'Avaliação da resistência de amostras de argamassas históricas recolhidas em obra. Metodologia e correlação de resultados', report 259/06-NRI, LNEC, Lisbon (2006).

13 Santos Silva, A.; Veiga, M. R., 'Degradation and repair of renders in ancient fortresses close to sea', in *Medachs – Construction Heritage in Coastal and Marine Environments: damage, diagnostics, maintenance and rehabilitation*, LNEC, Lisbon (2008).

14 Veiga, M. R.; Velosa, A.; Magalhães, A. C., 'Experimental Applications of mortars with pozzolanic additions. Characterization and performance evaluation', in *Construction and Building Materials* **23** (2009) 318-327.

15 Veiga, M. R.; Fragata, A.; Tavares, M.; Magalhães, A. C.; Ferreira, N., 'Revestimentos compatíveis para paredes antigas sujeitas a capilaridade ascendente. Aplicação a um caso de estudo', in *3.º Encontro sobre Patologia e Reabilitação de edifícios*, Porto (2009).

16 Onsiteformasonry Project Group, 'On-site investigation techniques for the structural evaluation of historic masonry buildings. Results and research methodologies of on-site for masonry', report, EC Project financed by the European Commission EVK4--CT-2001-00060 (2006).

17 Matias, L.; Vilhena, A.; Magalhães, A. C.; Santos, C. P.; Veiga, M. R., 'Performance of masonry specimens in contact with salt water. Absorption by capillary rise and evaporation phenomena', in *1st International Conference – Construction Heritage in Coastal and Marine Environments. Damage, Diagnosis, Maintenance and Rehabilitation*, LNEC, Lisbon (2008).

18 Veiga, M. R.; Aguiar, J., 'Definição de estratégias de intervenção em revestimentos de edifícios antigos', in *1.º Encontro Nacional sobre Patologia e Reabilitação de Edifícios*, FEUP, Porto (2003).