

Methodologies for characterisation and repair of mortars of ancient buildings

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ABSTRACT: There is a clear need to develop and systematise a methodology to approach interventions on ancient renders. In fact inadequate interventions, with systematic resource to modern solutions, originated in Portugal a situation characterised by the disappearing of original lime renderings and finishings and caused several anomalies due to functional incompatibility between pre-existing elements and new materials.

The research project *Oldrenders*, accomplished by researchers from *LNEC* in collaboration with the construction enterprise *STAP - Reparação, Consolidação e Modificação de Estruturas, SA.*, and partially financed by *Agência de Inovação*, has as main objectives the definition of such a methodology and the preparation of criteria to support the selection of substitutive compatible mortars. This paper synthesises the aims and conclusions of the Project.

1. OBJECTIVES OF THE RESEARCH

Interventions on ancient buildings included for too long the systematic removal of the original renders, plasters and finishings and its substitution by renders and plasters based on Portland cement, painted with products based, first in oil paints and then in acrylic and vinylic resins.

In the meantime, the theory of conservation has more and more pointed out the historic and aesthetic importance of preservation of material evidences and their fundamental part in the definition of formal and material authenticity of historic artifacts.

Several studies recently developed at *LNEC*, or with *LNEC*'s direct support (Aguiar, J., 1999, Margalha, G., 1997, Tavares, M., 1998), contributed to modify the Portuguese idea about the architectural value and meaning of renders and finishings in the nation's historic heritage. From a restrictive perspective - today considered as false and related to fascist paradigms - affirming the primacy of the simplicity of white lime on South of the country and of the solid expression of faced stone masonry, on the North, there was a quick evolution to the re-discover of an enormous richness of chromatic, textural and decorative expression. Indeed, external solutions completely unknown by architectural and urbanistic history till recently, were finally rediscovered, such as paintings, *grafitti and sgrafitti, trompe-l'oeil, scagliole, intonachini*, etc. This long oblivion originated a dramatic incapacity of "seeing" this kind of techniques, with hard consequences in the quality of our urban rehabilitation interventions.

The enormous quantity of inadequate interventions in historic buildings, with systematic resource to modern solutions, created a situation characterised by the disappearing of original lime renderings and finishings. As a consequence, the surviving original decorations acquired a new patrimonial value, which obliges new intervention attitudes.

Actually, substitutive practices, which are still the great majority in Portuguese building restoration and urban rehabilitation, originated several anomalies due to functional incompatibility between new renders and ancient masonry, besides affecting the patrimonial and

architectonic value of the building, by the substitution of original coats with high documental and aesthetic value by new materials, incapable of reproducing intentions and forms of historic presentation.

There is a clear need to develop a new methodology to approach this problem, which is the main objective of the Project *Oldrenders*, just accomplished by a team of researchers from LNEC, in collaboration with the enterprise STAP and partially financed by *Agência de Inovação*.

The application of more rigorous principles to the design and specification of repair solutions for renders, always considering functional and aesthetic compatibility, implies the resource to lime technologies, in a moment where there aren't enough prepared enterprises nor skilful workmanship to use them successfully. The high qualification required to reproduce solutions described in old construction manuals is only available nowadays for a few restorers specially formed in conservation techniques and mural painting.

Everywhere, the discrepancy between quality requirements for the execution of ancient technologies and the real available capacity, is obliging the development of alternative and more pragmatic ways to achieve compatible technologies. These approaches can lead to the definition of pre-dosed products, with selected binders and aggregates, ready to use in urban generic rehabilitation. Naturally, interventions in classified architectural heritage require knowledge, methodologies and technologies much more similar to the original and always demand a careful case study.

Anyway, the formulation and the selection of a pre-dosed product, or of a traditional lime mortar to prepare *in situ* for use in rehabilitation urban interventions, must be subjected to an evaluation based on technical rigorous criteria, which are not presently completely defined. The establishment of general requirements for this kind of products and for traditional lime renders, were a part of the Project *Oldrenders* and a synthesis will be exposed in chapter 4.

Nevertheless, the conservation and repair of an ancient render is much more than a technical problem, because it requires a great critical capacity in the approach. It implies decisions about the final architectural presentation concept, based on information about the characteristics of pre-existing materials and on the knowledge of technological capacities to practise the interventions.

Sometimes, there is an idea that, to acquire the necessary science to take fundamental decisions, it is enough to ask for chemical and mineralogical characterisation of the original mortars, but the truth is that sometimes the results obtained in those analyses are not even taken into account.

Laboratorial analysis is indeed valuable when we know what to look for, but, to the definition of repair or restore solution, there are several sources of equally precious information, that need a direct contact with the surface to study: percussion with fingers, *in situ* tests, stratigraphic analysis *in situ* and in laboratory.

The correlation between the information obtained and the proposed solution is, anyway, indispensable.

Essentially, the first aim of the Project *Oldrenders* is to provide and to systematise a methodology of intervention, using techniques of observation and analysis, in laboratory and *in situ*, capable of guiding the identification of the different coats, of types of solutions and of methods of execution.

As a second (but equally important) objective, a series of criteria were developed to support design decisions for presentation of façades, considering the performance of new and old renders together.

2. PROPOSED METHODOLOGY FOR INTERVENTIONS ON ANCIENT RENDERS

The first option to consider in an intervention on ancient renders must be the conservation of old solutions, their maintenance and repair, because that's what dictates the respect for the principles of authenticity.

When, nevertheless, it is necessary to renovate mortars, their formulation can be selected by two logical procedure:

- Trying to reproduce the formulation of the old mortar.
 - Formulating a compatible mortar, with an adequate performance and an aesthetic appearance that preserves the image of the building (Válek, 2000; Papayianni, 1998)
- The first procedure is theoretically perfect, but practically impossible to adopt by itself. As a matter of fact, even if the analytical techniques for old mortar characterisation are nowadays very rigorous in what concerns the material as it is presently, several and very important lacuna persist about the complex dynamic processes of mortar evolution, with crystallisation and re-crystallisation cycles and with continuous reactions between the constituents, the background and the environment. More relevant than that, it seems impossible to trace completely the execution techniques, the skills of workmanship, the cure, the climatic conditions in the period subsequent to the application and we all know how determinant these factors are for the render performance.

This means that, when trying to reproduce the composition of an old mortar based only on analytical characterisation, there is a risk to obtain a mortar with a completely different performance, and possibly not capable of fulfilling the functions they are expected to accomplish in the building.

So, it is considered more effective to adopt a methodology where the two procedures pointed out can be complementary, considering, namely, the following criteria:

- To use a mortar with a composition similar to the old one, with the same type of binder and aggregates of similar nature and shape; the use of additives (pozzolan, ceramic powder, animal hair, etc.) must be checked and the possibility to use similar ones or substitutes with identical functions must be evaluated.
- The main functional characteristics of pre-existing mortars must be reproduced, as long as possible.
- The new material must be compatible with the pre-existing materials in contact, in a mechanical, chemical, physical and aesthetic way (Válek et al., 2000).

This methodology implies, naturally, an important double investment:

- On the improvement of the analytical techniques for old mortar characterisation.
- On the identification of the functions to accomplish by the render and of the mortar characteristics needed to fulfil those functions. This phase is extremely sensible and assumes an effort to understand the behaviour of each ancient building and of the part that concerns each element of construction.

3. ANALYTICAL TECHNIQUES FOR OLD MORTARS CHARACTERISATION

There are a great number of physico-chemical techniques that can be applied for old mortars characterisation. This chapter presents a previous reference to some important sampling issues to be kept and a short description of the most important techniques with their benefits and limitations to maximise the objectives of the characterisation itself. Taking into consideration the aspects that will be presented, and also our experience, has led us to advise a system of characterisation based on the application of the diagram presented on figure 1.

A careful and correct sampling is indispensable to assure the success of the entire characterisation study. Some procedures advised by recognised specialists in conservation (Chiari et al., 1992 and 1996; Berlucci, 1995) refer the importance of the initial and careful inspection for the choice of the locals to be sampled. The extraction localisation must be well documented and registered before and after taking the sample, with a complete description of the aspects that governed the selection of that sample.

The size of the extracted sample should be adequate to assure the objectives of the characterisation (40 g is a good quantity) and to allow confirmation of some analysis or - and this is very important - to keep a “reserve” for the future.

In the laboratory, the sample is carefully observed under a stereomicroscope at low magnification to detect special features, such as fibre materials, and to separate the different layers of the sample, for subsequent analysis, if necessary, of each one. In the next step, the sample is gently broken down and lightly ground in a porcelain mortar, removing by sieving the larger aggregate particles (> 4.75 mm); then the remaining material is ground until a fine powder is obtained (< 105 μm) and dried.

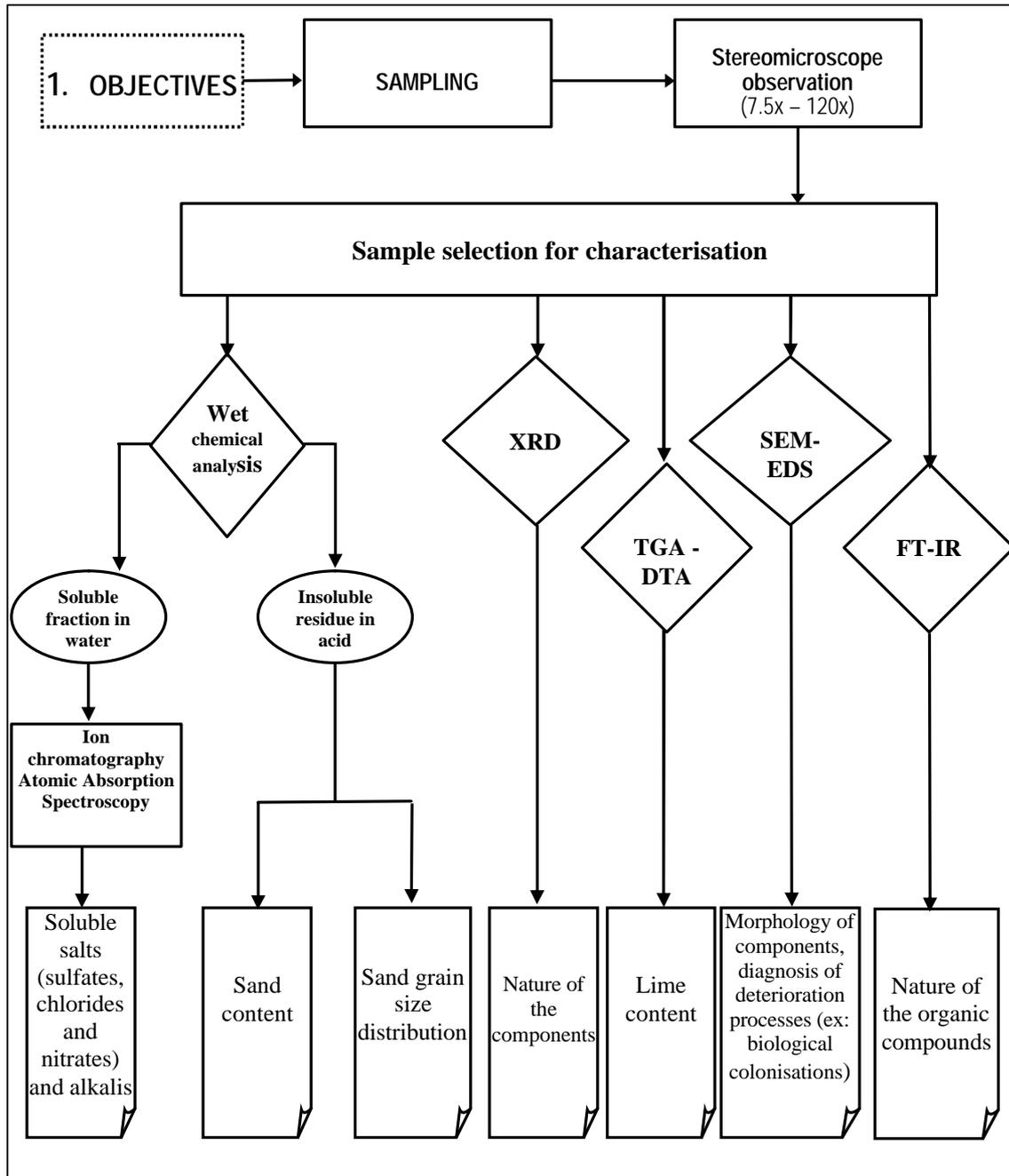


Figure 1: Scheme of the sequence of tests to identify the composition of ancient mortars

The dried samples are attacked by a warm acid chloride solution (1:3) and then filtered using vacuum. The residue obtained (insoluble residue) after drying is weighted and gives the actual content of sand in the sample. If we have a reasonable initial sample quantity, this procedure is slightly altered in order to obtain the grain size distribution of the sand in the sample. The main difference is that the sample is not finely ground but only gently broken with a rubber hammer.

In the soluble fraction of the sample we can apply different analytical techniques, such as ion chromatography (IC) or atomic absorption spectroscopy (AAS), to obtain some chemical data, namely the content of soluble salts and alkalis in the sample. The presence of carbonate aggregate is the main disadvantage of wet chemical analysis. In such case the content of aggregate cannot be analysed by this method because all the carbonates are dissolved by the acid attack (Jedrzejewska, H. 1960; Groot, C. et al., 2000; Teutonico, J.M., 1998).

This limitation can be overtaken by the use of the optical microscopy (in transmitted polarised light) in which we have the possibility to identify the type of aggregate, binder, additives, porosity and cracking and secondary mineral formation. With an image analysis system linked to the microscope we have the possibility to obtain the binder/aggregate ratio and porosity (air voids). Besides the poor resolution, this technique is limited also by the need of experienced personnel and by the high price of the equipment (González M.L.G., 1994; Schouenborg, B. et al., 1993).

One of the most important techniques in materials characterisation is the x-ray diffraction analysis (XRD). This technique, based on the diffraction of the x-rays by crystals, is used to know the mineralogical components or crystalline phases in the sample (Braga Reis, M.O., 1994). XRD provides valuable support to other types of analysis and namely in combination with thermal analysis may solve a great number of questions, such as binder type, presence of some pozzolanic materials and alteration products. The XRD is limited by being a bulk material analysis method and it can give no information on the spatial interrelationships of mortars components (Groot, et al., 2000).

The x-ray patterns, in our case, are obtained with a Philips diffractometer with cobalt radiation. We perform the identification of the pattern using the JCPDS database of standard x-ray powder patterns with the search/match procedure PC-APD provided by Philips.

Other important technique that complements the XRD is thermal analysis (TA). TA is the term applied to a group of techniques in which a physical property of a substance is measured as a function of temperature, while the substance is subjected to a controlled temperature program. In this context, the most important methods are thermogravimetry (TG) and differential thermal analysis (DTA), which actually appear associated in the same instrument (simultaneous TG-DTA) (Santos, Silva, A., 1994).

The TG is a method that measures the weight change taking place in a sample when it is heated (or cooled) with a constant heating rate. In addition to the TG measurement, a differential TG curve may be obtained, in which the TG weight loss steps are transformed into peaks establishing the temperature where the weight loss shows a maximum rate. At the same time, the instrument measure the energy changes in a sample (DTA curve), that could be represented by endothermic (heat consumption) or exothermic (heat liberation) effects in the DTA curve. Quantitative analysis is based on the TG curve while DTA provide information for the qualitative identification of the components that undergo the weight losses (Chiari, G. et al., 1992 and 1996). The main limitation of this group of techniques is in the identification of unknown constituents in the samples.

A thermal analyser system SETARAM TG-DTA was used for our analysis, using a heating rate between 10° and 20° C/min from room temperature to 1000° C and argon as inert gas (3 l/h).

In our rapidly expanding technology, the scientist is required to observe, analyse, and correctly explain phenomena occurring on a micrometer or submicrometer scale. The scanning electron microscope (SEM) with an energy-dispersive x-ray spectrometer (EDS) coupled with a computer-based multichannel analyser provides to the SEM-EDS a powerful analytical facility in the observation and characterisation of heterogeneous organic and inorganic materials. With the SEM-EDS the area to be examined, or the microvolume to be analysed, is irradiated with a finely focused electron beam, which may be static or swept in a raster across the surface of the sample. This radiation gives origin to different signals, such as secondary electrons, backscattered electrons, characteristic x-rays, etc., which can be used to examine many characteristics of the sample (morphologies, textural interrelationships of the components,

composition). The great limitation of the SEM-EDS is the equipment's price, which influences also the analysis' price (Groot, et al., 2000; Santos Silva, A., 1994; Leslie, B., 2000).

The samples are fractured and, before being observed with SEM, are coated with a thin film of carbon in a vacuum evaporation system. This coating is necessary to eliminate the electric charge, which builds up rapidly in a non-conducting sample like a mortar. We use in our work a JEOL 6400 SEM and a NORAN EDS system, working in the range between 10-20 KeV.

One of the techniques widely used for the characterisation of organic materials is the infrared spectrometry. The infrared (IR) region is an invisible portion of the electromagnetic spectrum; the common unit of wavelength in the IR region is the micron. The IR area is of particular interest to the scientist because this is the primary region in which frequencies of radiation correspond to those of molecular vibrations and rotations.

Fourier transform infrared (FT-IR) spectroscopy is one of the equipments used to obtain IR spectra. Fourier FT-IR spectrometers record the interaction of IR radiation with experimental samples, measuring the frequencies at which the sample absorbs the radiation and the intensities of the absorptions. Determining these frequencies allows identification of the samples chemical makeup, since chemical functional groups are known to absorb light at specific frequencies. FT-IR experiments generally can be classified into the following two categories: qualitative analysis - where the aim is to identify the sample; and quantitative analysis - where the intensity of absorption (or, more commonly, of absorptions) is related to the concentration of the component. Our measurements are made with a Fourier Nicolet Magna 550 in the spectral region approximately between 500-4000 cm^{-1} , using both the potassium bromide disc and the Nujol mull techniques.

Apart this considerations about each technique, there exists a consensus in scientific community that the most effective way to characterise a mortar sample is to use a combination of physico-chemical techniques, like the methodology presented schematically in the diagram at the beginning of this chapter.

4. REQUIREMENTS FOR SUBSTITUTION MORTARS

The identification of requirements to establish and methods to evaluate renders concerning those requirements, is a task that demands a deep knowledge of the wall behaviour. It is possible, in a general way, to relate several mortar characteristics to each render requirement, but there are contradictions among the characteristics needed to accomplish the different requirements. The attempt to make them compatible leads to the relations summarised on table 1.

The selection of the test methods to measure the relevant characteristics is also determinant to get significant results. As long as possible, we use methods based on European standards, sometimes with adaptations to make them suitable for lime renders. To assess particularly important requirements, we established and tested specific test methods (Gonçalves, T., 1997; Veiga, R. 2000; Veiga, R. and Carvalho, F. 2000).

Taking into account the specificity of Portuguese construction and considering the results of a great number of tests made at LNEC on several types of mortars, such as their performance after application, the minimal requirements were established, which are synthesised at table 2.

Naturally, there is a need to verify the specific requirements to accomplish, besides the listed set, taking into account all the factors of the methodology referred in chapter 2. In fact, only the rendering and repointing mortars to use in current ancient buildings, with walls made of stone, bricks or mixed masonry, without a particularly high patrimonial value, could be evaluated just with a basis in these general requirements.

Table 1 – Synthesis of requirements, characteristics and tests

New Render Requirements	New Mortar Characteristics	Evaluation Methods
Not to contribute for the degradation of pre-existing elements it is supposed to protect and preserve, such as masonry and ancient mortars.	Moderate mechanical resistance	Flexural and compressive resistance tests (EN 1015-11). Tensile resistance test after restrained shrinkage (Veiga, R., 1997 and 2000).
	Moderate elasticity modulus	Dynamic elasticity modulus test (NF B 10-511).
	Moderate adhesion	Pull-out test (EN 1015-12).
	Low forces induced in the mortar or in the background by restrained shrinkage or by differential deformations	Restrained shrinkage test (Veiga, R., 1997 and 2000).
To protect and to preserve effectively those elements.	Thermal coefficient similar to the pre-existing mortars	Determination of thermal coefficient.
	Good performance concerning salts: resistance to salts existing within the wall and low content of soluble salts	Determination of salt resistance and salt content.
To keep a compatible image of the building.	Good performance concerning water: moderate water absorption, some resistance to water penetration, easy drying	Determination of capillarity coefficient (EN 1015-18). Evaluation of the protection capacity to water (Gonçalves, T., 1997, Veiga, R., 2000).
To protect, to preserve and to keep the image for a reasonable period of time: durability.	Porous structure with predominance of small pores.	Determination of porosity and of porosimetric distribution
To be reversible (to permit the correction of errors and substitution for maintenance).	Resistance to ageing due to climatic actions: resistance to cycles heat/cold, heat/water, and freeze/thaw	Accelerated artificial ageing test (Veiga, R. and Carvalho, F., 1998)
To be repairable.	Compatible appearance: colour, texture, flatness and brightness similar to pre-existing mortars.	Visual analysis; composition analysis; research of application technology; Munsell system or NCS system to measure colour.
Functional identity		
Material and technological identity	Structure and composition similar to pre-existing mortars.	Identification tests: chemical, physical and mineralogical characterisation (vd. 2); mercury porosimetry.
	Performance after application similar to pre-existing renders.	“In situ” performance tests (Veiga, R. and Carvalho, F., 2000): sphere shock, cut shock, controlled penetration, scratch, abrasion.
	Similarity of application technology	Registration consultations; “in situ” observations

Table 2 – Minimal requirements for rendering and repointing substitution mortars for ancient buildings

Mechanical characteristics at 90 d (MPa)		Performance to stresses induced by restrained shrinkage, at 90 d *					Performance to water						
Mortar	Tensile resistance	Compressive resistance	Dynamic Elastic Modulus	Adhesion at 90 d (MPa)	Fr max (N)	G (N.mm)	CSAF	CREFF (mm)	Permeance (equivalent thickness of air) (m)	Capillarity coefficient at 24 h (kg/m ² .h ^{1/2})	Tests with humidimeter **		
											M (h)	S (h)	H (mv.h)
Render	0.2 – 0.7	0.4 – 2.5	2000-5000	0.1 – 0.3	< 70	> 40	> 1.5	> 0.7	< 0.08	< 12; > 8	> 0.1	< 120	< 16 000
					or cohesive rupture by the render								
Plaster	0.2 – 0.7	0.4 – 2.5	2000-5000	0.1 – 0.3 or cohesive rupture by the render	< 70	> 40	> 1.5	> 0.7	< 0.10	-	-	< 120	-
Repointing	0.4 - 0.8	0.6 – 3	3000-6000	0.1 – 0.5 or cohesive rupture by the mortar	< 70	> 40	> 1.5	> 0.7	< 0.10	< 12; > 8	> 0.1	< 120	< 16 000
Additional requirements to establish if characteristics of pre-existing mortars and of the background are known													
Render	Mechanical characteristics similar to pre-existing mortars and lower than those of the background.				No cohesive rupture by the background.				Lower than to tensile resistance of the background.		Capillarity and water vapour permeability similar to pre-existing mortars and higher than those of the background.		

* Values from test of restrained shrinkage (FEE Pa 37; Veiga, R., 1997 and 2000): Fr max: maximal force induced by shrinkage; G: tensile rupture energy; CSAF: safety coefficient for the opening of the first crack; CREFF: resistance coefficient to cracking evolution.

** Results from test of performance to water with humidimeter (FEE Pa 38; Gonçalves, T., 1997; Veiga, R., 2000): M: wetting delay; S: wetting period; H: wetting intensity.

The selection of substitution mortars for rendering and repointing, must, ideally, satisfy to an iterative procedure:

- a) Determination of the approximated composition and of the physical and mechanical characteristics of the pre-existing mortars.
- b) Preparation of a lime based mortar with constitution and appearance similar to the pre-existing.
- c) Execution of tests to verify the minimal requirements and the similarity of the main characteristics.
- d) Corrections to the tested formulation, to approximate the characteristics.
- e) Repetition of the stages b) to d), till a reasonable similarity of the fundamental characteristics is attained and so an adequate performance is expectable.
- f) Execution of experimental applications *in situ*.
- g) If necessary, new corrections to the tested formulation.
- h) If necessary, corrections to the application specifications.

For buildings less interesting from the monumental and historic point of view, when it is not possible to accomplish all the stages, a minimal program must be kept:

- Preparation of a mortar with a similar composition to a previously tested mortar, successfully used on a building with construction characteristics similar to the building to study.
- Stages c), d), f), g)

In these cases it's also possible to use a pre-dosed mortar with well known characteristics, as long as the minimal requirements are verified, by tests made by a suitable laboratory. This option permits, in the limit, to reduce the selection process to a single step:

- Preparation of a pre-dosed mortar with well-known suitable characteristics.

5. CONCLUSIONS

The methodology for interventions on ancient renders and repointing mortars proposed by the Project *Oldrenders* and synthesised in this paper includes a set of theoretical considerations about the need of preservation and repair of ancient mortars and a definition of the conditions to substitute them, totally or partially.

It is assumed that the substitution mortars must be, as long as possible, similar to the original, both materially and functionally, at least for monuments. This option implies a double investment on the improvement of the analytical techniques for old mortars characterisation and on the definition of the functions to be performed by the new mortars and of the requirements for them to verify.

The selection of substitution mortars according to the advocated methodology, implies an iterative procedure to verify the defined conditions. Nevertheless, for less valuable buildings from the historic and architectonic point of view the procedure can be simplified, specially if there is a decision to use a pre-dosed mortar previously tested for the same kind of construction and environment.

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