Abstract In an intervention on historic renders and plasters, the first step is to
decide upon the strategy: repair or substitution, based on an evaluation of the
cultural value of the render and of the building itself and on a careful diagnosis of
the typology of defects, their density and reparability. New renders or repaired
renders should fulfill the main functions they are required to, especially protection
and aesthetic functions. In any case, compatible materials should always be used.
Compatibility is needed for durability, not of the render, but of the wall as a
whole, and also for preserving the testimonial and symbolic value of the building
as well as its appearance. Compatibility is defined in relation with the substrate
and the pre-existent mortars, therefore tests are to be carried out on the old
materials and on possible solutions, to compare their characteristics and assist the
selection of the best one. It is adequate to begin by non-destructive or slightly
destructive in situ tests, because with them it is possible to collect useful
information without destruction of the historic renders and in a quick way. Simple
mechanical and physical tests can be carried out on the old mortars and a few
chemical tests can also be performed nowadays, with the appropriate portable
equipment. When more rigorous and complete tests are needed, some samples can
be collected and tested in laboratory, using methods adapted to non-regular,
possibly friable specimens. The characteristics of the mortars to use can be
established with a basis on the set of results obtained, in order to fulfill both
functionality and compatibility. However, sometimes it is not possible to get
enough data concerning the old materials, especially concerning masonry, which
is rather more difficult to test than mortars. For that situation, some general
requirements have been established, based on previous work carried out on
Portuguese masonry historic buildings, which can be used without risk of
damaging pre-existent materials. The decision concerning materials to use,
especially binder materials, should also take into account the climatic and
environmental conditions. Then, appropriate application technique, workmanship
and curing conditions are indispensable to achieve good results, from the
aesthetic, physical and mechanical points of view; therefore it is important to
know which conditions are available in the application phase.
1 Conservation strategy decision making

1.1 Strategy and factors

When facing an intervention on old renders, the first step – and probably the most important one - is deciding upon the strategy to implement. Two basic alternatives are possible:

- Preservation and repair with compatible materials
- Substitution by compatible new renders

Many factors should be taken into account, some of them of a subjective nature, others more technical and quantifiable:

1. Cultural value (for example combinations of historic value, artistic value, technical value and value associated with rarity).
2. State of conservation of the background and its capacity to be repaired (reparability).
4. Compatibility of the render with its current (or foreseen) use and the environmental conditions.
5. Available workmanship.

Factor 1 dominates. However, most cases fall in the category of “medium cultural value”. The technical team has essentially to deal with factors 2, 3 and 4, although an opinion on 1 and 5 is usually required. This decision requires a diagnosis and quantification of the wall’s anomalies (both masonry and render), as well as an evaluation of the future actions on the rendered surface that are foreseen.

1.2 Diagnostics

In many cases of planning interventions on renders and plasters quite simple and quick investigations and observations are enough to establish a diagnosis [1]:

1. Observation by a trained person:
   1.1. Presence of moisture.
   1.2. Type of defects: fungus, black crusts, detachments, lack of cohesion, cracks and micro-cracks, brown stains of corrosion products.
   1.3. Density and localisation of defects.
2. Moisture measurements: localisation and intensity of moisture, map of moisture distribution (Fig. 1).
3. Mechanical and physical in-situ and laboratory tests (Figs. 2-4).
These actions allow important questions to be answered:

- Is moisture a problem? Observations 1.1, 1.2, 1.3 and action 2 should provide an answer. Where does the moisture come from? Actions 1.3 and 2 will help to discover it.
- Apart from moisture, what other causes of defects are there? 1.1, 1.2, 1.3, 2 and possibly 3 will furnish the appropriate information. Structural problems – deformation? Salty fog? Pollution? Corrosion of metallic elements (Fig. 5)? Wrong interventions with incompatible materials?
- Are there defects with a low degree of reparability (Fig. 6)? Detachment and lack of cohesion are usually the most difficult defects to repair [2-4]. Observations 1.2 and 1.3 will generally allow the identification of these types of anomalies and action 3 will permit some quantification.
- Are renders and plasters globally affected, in a significant degree? Namely, are they globally too weak and permeable? Action 3 will help to get this answer [5-7].

The results of these simple diagnostic actions and their careful interpretation should provide significant information including: the identification of the main causes of defects and the way to control them; the identification of the defects of masonry and the possibility of evaluating the need to remove the render or plaster locally or globally; the classification of the state of conservation of the render or plaster itself, considering the intensity of defects and their reparability classed as high, medium or low levels of degradation.
1.3 **Foreseen actions**

Old buildings today can be subjected to different loads, due to change in use or diverse environmental conditions. It is necessary to verify if the current or future conditions of the building may suggest changes or enhancements to particular characteristics of renders and plasters. For example, for renders, higher pollution or traffic vibrations may now occur or for plasters, different uses such as museums, music or theatre rooms may require different physical characteristics.

1.4 **Decision making**

Based on the actions and observations mentioned above a decision about preservation and repair or substitution is possible. Table 1 gives an idea of the systematisation of decision processes for the case of “medium cultural value”.
Table 1 Support for intervention strategy decision making

<table>
<thead>
<tr>
<th>Cultural value</th>
<th>State of conservation of the substrate</th>
<th>State of conservation of the render/plaster</th>
<th>Compatibility with use and actions</th>
<th>Recommended strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Bad</td>
<td>Protect or reinforce the render/plaster in a compatible way (ex. silicate based painting)</td>
</tr>
<tr>
<td>Good</td>
<td>Bad</td>
<td>Good</td>
<td></td>
<td>Repair and consolidation of the render/plaster</td>
</tr>
<tr>
<td>Bad</td>
<td>Good</td>
<td>Good</td>
<td></td>
<td>Repair the substrate with techniques of low intrusivity; Keep the render/plaster filling lacunae and reintegrating aesthetically</td>
</tr>
<tr>
<td>Bad</td>
<td>Bad</td>
<td>Good</td>
<td></td>
<td>Repair the substrate with techniques of low intrusivity; Partial substitution of render/plaster</td>
</tr>
<tr>
<td>Bad</td>
<td>Good</td>
<td>Bad</td>
<td></td>
<td>Repair the substrate with techniques of low intrusivity; Reinforce the render/plaster in a compatible way</td>
</tr>
<tr>
<td>Good</td>
<td>Bad</td>
<td>Bad</td>
<td></td>
<td>Analyse the viability of repair and consolidation of the render/plaster against partial substitution with compatible techniques and materials.</td>
</tr>
<tr>
<td>Bad</td>
<td>Bad</td>
<td>Bad</td>
<td></td>
<td>Repair of the substrate and substitution of the render/plaster with compatible materials</td>
</tr>
</tbody>
</table>

2 Choice of materials

2.1 Fulfilment of main functions

The main functions of renders and plasters are:

- Protection of masonry (against external actions such as impact, abrasion, weather, pollution).
• Regularisation (making look smooth or consistent) of the walls.
• Finishing and decoration.

The repair or renewal of renders and plasters is intended to fulfil these main functions. They have no structural functions, but they have a significant role in the protection of structural old masonry and hence on its durability and general good performance. The mortars to use don’t need high strength, but some resistance to friction and impact, some deformability to follow masonry displacements without cracking and some ability to delay rain water penetration and to allow the easy evaporation of water from inside old porous walls.

2.2 Compatibility

Renders and plasters are a part of the walls. Materials both for their repair and for their renewal should be compatible with the existing mortars and substrates [8-11].

This means essentially:
• there should be no production of new damage;
• they should be consistent with the overall appearance, now and after ageing.

How can repair and substitution materials be harmful to existing materials? Some properties of new mortars can produce damaging actions:
• The introduction of stress due to higher stiffness and different thermal dilation coefficients, producing differential deformations in relation to the old materials in contact. Shrinkage of the new mortar, thermal variations and deformations of the masonry will produce stresses at the interface between old and new materials, damaging the weakest material (Fig. 7). The stresses are higher when differences between characteristics are larger [12]. As the existent material should be preserved, it must not be the weakest.
• The reduction of the drying ability of the wall through the application of renders with lower capillarity and lower water vapour permeability than the existing ones may result in the retention of water inside the masonry and higher capillary rise on the wall. This could become a problem in historic buildings, especially when there is water coming from under the foundation level or when the masonry is water saturated due to roof deterioration. Any soluble salts present in the walls will be transported by capillary rise and spread into larger areas of the masonry. Eventually they will crystallise at the new drying surface, often the interface between masonry and render, producing damage of the masonry and detachment of the render (Fig. 8).
• Driving the water through older mortars or stones, due to lower capillarity compared to new materials. In fact, when more impermeable materials are used, the water transport through the capillary net is diverted to the most permeable old materials in contact, accelerating their degradation.
Introduction of new salts due to the presence of cement or other constituents containing soluble salts [13].

How can new products affect appearance?

- Different texture or colour due to different aggregates, different binder nature or different pigments.
- Differential ageing due to the different nature of constituents (resins, organic pigments, etc).

A set of compatibility requirements can be established considering these issues. In Table 2 a correspondence is established between compatibility requirements and material characteristics.

### 2.3 Environmental considerations

The choice of materials is also limited by some environmental conditions: weather, the proximity of the sea and pollution. Rainy weather, salty fog and spray of salty water and high pollution are factors that may militate against the use of pure air lime mortars. In Portugal air lime mortars were used in the past in misty, salty environments [14, 15], but today it is difficult to guarantee appropriate conditions of application and curing, so some hydraulicity is advisable. In moderately dry climates (like the South of Portugal), away from the sea, air lime mortars can be a good solution, except when high levels of pollution exist and create the danger of damage by acid attack.
### Table 2 Compatibility requirements and new mortars characteristics

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Rc and Rf</th>
<th>E</th>
<th>C</th>
<th>W vp</th>
<th>S</th>
<th>α</th>
<th>Materials (direct influence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection against impact and abrasion</td>
<td>M</td>
<td>M</td>
<td>-</td>
<td>-</td>
<td>L-M</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Protection against rain penetration</td>
<td>-</td>
<td>-</td>
<td>M</td>
<td>-</td>
<td>L</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Protection against pollution attack</td>
<td>-</td>
<td>-</td>
<td>M</td>
<td>-</td>
<td>L</td>
<td>-</td>
<td>Air lime (Ca CO₃) is vulnerable to acid rain and pollutant gases in general (SO₂, CO₂ and NO₂)</td>
</tr>
<tr>
<td>No introduction of stress</td>
<td>L</td>
<td>L</td>
<td>-</td>
<td>-</td>
<td>L</td>
<td>Similar to old mortars and substrate</td>
<td>No high proportion of cement</td>
</tr>
<tr>
<td>No retention of water inside walls</td>
<td>-</td>
<td>-</td>
<td>M</td>
<td>H</td>
<td>-</td>
<td>-</td>
<td>No water repellents, no resins</td>
</tr>
<tr>
<td>No driving water through old materials</td>
<td>-</td>
<td>-</td>
<td>Similar or higher than old mortars</td>
<td>H</td>
<td>-</td>
<td>-</td>
<td>No water repellents, no resins</td>
</tr>
<tr>
<td>No introduction of new salts</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No cement</td>
</tr>
<tr>
<td>No affecting the appearance</td>
<td>-</td>
<td>Low</td>
<td>Similar or higher than old mortars</td>
<td>H</td>
<td>L</td>
<td>-</td>
<td>No cement, no resins, Similar aggregates, similar binder, similar pigments</td>
</tr>
<tr>
<td>Global analysis</td>
<td>L-M</td>
<td>L-M</td>
<td>Medium</td>
<td>H</td>
<td>L</td>
<td>Similar to old mortars and/or substrates</td>
<td>No cement, no water repellent, similar aggregates, similar binder, similar pigments</td>
</tr>
</tbody>
</table>

Rc – compressive strength; Rf – flexural strength; E – modulus of elasticity; Wvp – water vapour permeability; S – shrinkage; α – coefficient of thermal dilation; L – Low; M – Medium; H – High.
2.4 Site testing

Compatibility is defined in relation to the background and the existing mortars. Thus, it is important to determine the main characteristics of the masonry and the old renders, in order to design new mortars with similar characteristics. *In-situ* testing, especially using non-destructive methods, is a first approach to evaluate significant characteristics (Figs. 1, 2, 9 to 12). Generally they have to be used in a comparative basis, as there are currently no sufficient correlations with laboratory tests.

In Table 3 some simple tests, non-destructive or slightly destructive, are considered, and related (qualitatively) with performance.

<table>
<thead>
<tr>
<th>Table 3 Relation of in situ tests with performance characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture measurement</td>
</tr>
<tr>
<td>Mechanical Strength</td>
</tr>
<tr>
<td>Dynamic modulus of elasticity</td>
</tr>
<tr>
<td>Water permeability</td>
</tr>
<tr>
<td>Presence of salts on the surface</td>
</tr>
</tbody>
</table>

**Fig. 7** Mechanical damage due to incompatible new render  
**Fig. 8** Damage due to reduction of water permeability of the walls
It is also now possible to perform *in-situ* some mineralogical tests with portable equipment. One of the most used is X Ray Fluorescence, with portable equipment, permitting for example, the discrimination of the type of binder, or other compounds present, such as salts. The “Hercules Centre”, of Évora University, in Portugal, makes this equipment available to the scientific community. X-ray diffraction with a portable apparatus is also possible.

For current situations *in-situ* tests may give enough information for decision making concerning materials.

### 2.5 Laboratory testing

More specific tests are carried out in the laboratory, whenever needed (Figs. 3, 4). Laboratory tests require the collection of samples, so in this sense they are always destructive. For this reason and also for economic and time constraints, they must be complementary to site testing and usually be limited to those that are unavoidable. Due to limitations of dimensions, shape and cohesiveness of plaster samples collected from buildings, not every laboratory technique can be used and
the number of possible tests is smaller than for laboratory produced specimens. In Table 4 the most useful groups of complementary laboratory tests are presented and related to characteristics and performance.

**Table 4** Relation of laboratory tests with performance characteristics

<table>
<thead>
<tr>
<th>Main laboratory tests on samples removed from site</th>
<th>Chemical mineralogical and microstructural characterisation [10, 16]</th>
<th>Compressive strength [17]</th>
<th>Capillary water absorption [18]</th>
<th>Porous structure by MIP [19]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>Composition; microstructure; products of alteration</td>
<td>Protection from mechanical loads</td>
<td>Protection from water penetration and promotion of drying</td>
<td>Hygric behaviour, behaviour to salts and to ice</td>
</tr>
</tbody>
</table>

**2.6 Requirements**

The characteristics of the mortars to use can be established based on the sets of results obtained, in order to fulfil both functionality and compatibility, as summarised in Table 2. However, sometimes it is not possible to get enough data concerning the old materials, especially about masonry, which is rather more difficult to test than mortars. For that situation, some general requirements have been established, based on previous work carried out on Portuguese historic masonry buildings, which can be used without risk of damaging existing materials [10]. These requirements, summarised in Table 5, consider medium to low strength masonry of irregular stone, agglomerated with lime mortars, which are very common in old buildings in the south of Portugal.

**Table 5** General requirements concerning some characteristics for rendering and plastering repair mortars for historic buildings

<table>
<thead>
<tr>
<th>Type of render</th>
<th>Mechanical characteristics at 90 days (N/mm²)</th>
<th>Hygric behaviour at 90 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rf</td>
<td>Re</td>
</tr>
<tr>
<td>Exterior render</td>
<td>0.2 – 0.7</td>
<td>0.4 – 2.5</td>
</tr>
<tr>
<td>Interior render</td>
<td>0.2 – 0.7</td>
<td>0.4 – 2.5</td>
</tr>
</tbody>
</table>
Rf – flexural strength; Re – compressive strength; E – modulus of elasticity; A – adhesive strength; Wvp – water vapour permeability; Sd – thickness of air with equivalent diffusion; S – shrinkage; α – coefficient of thermal dilation

2.7 Global analysis and decision making for repair and substitution solutions

A global analysis of all the data – observations, tests and available conditions – is then needed to choose a mortar for repair or substitution.

Table 6 Average range of characteristics of some types of mortars

<table>
<thead>
<tr>
<th>Mix and volumetric proportion binder:aggregate</th>
<th>Range of values (indicative)</th>
<th>Basic application field (indicative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>Dynamic modulus of elasticity (by frequency of resonance)</td>
<td>Water capillary absorption coefficient</td>
</tr>
<tr>
<td>Lime:sand (1:3)</td>
<td>0.2 – 0.8</td>
<td>2300 – 4100</td>
</tr>
<tr>
<td>Lime + pozzolan:sand (1:2 to 1:3)</td>
<td>0.5 – 2.3</td>
<td>2500-4500</td>
</tr>
<tr>
<td>Lime + some hydraulic lime:sand (1:2 to 1:3)</td>
<td>0.4-1.0</td>
<td>1600-5600</td>
</tr>
<tr>
<td>Hydraulic lime*:sand (1:2 to 1:3)</td>
<td>0.6-3.1</td>
<td>1100-7500</td>
</tr>
<tr>
<td>Lime + some cement:sand (1:3)</td>
<td>0.9-5.1</td>
<td>3000-6500</td>
</tr>
</tbody>
</table>

* use hydraulic lime free of salts and of low hydraulicity (NHL 3.5 or HL 3.5)

What are the choices for possible compositions of binder to use? The most compatible binders are: air lime, hydraulic lime free of salts and air lime plus pozzolans (either natural or artificial). Although cement should be avoided as a
single binder for the repair of historic lime mortars, lime-cement mixes can also be acceptable binders for that purpose, in some circumstances [20, 21].

The volumetric ratio 1:3 (binder:aggregate), or near this proportion, is currently adopted. This is the proportion that theoretically assures the highest compaction of the mortar, when the aggregate has a complete grain size distribution. It has also been verified in practice that contemporary renders with a higher proportion of binder have a strong tendency to crack, although there is much evidence of their successful use in the past.

The groups of mixes considered as possibly compatible, and their basic average range of characteristics, are compiled in Table 6. The range of results presented is based in previous work [20-24].

The characteristics of all these types of mixes may be adjusted and improved by manipulating the aggregate type and grain size distribution, the type of lime, relative proportions when two binders are mixed, improving the method of application and the curing conditions and, possibly, using some additives or admixtures.

3 Application

After decisions about materials are made, it is important to guarantee the appropriate conditions of application, concerning technique, workmanship and curing.

For lime mortars, the application technique is particularly important: the exact quantity of mixing water (enough for good workability but not too much, for good compaction); long mixing; several thin coats; careful curing, avoiding quick drying and closing cracks when they occur during the early stage of application etc. [25, 26]. The application of air lime renders, or air lime and pozzolan renders, requires careful and rigorous workmanship. Current construction workers, not used to the application of this kind of mortars on large surfaces, will probably not achieve good results (appropriate physical and aesthetic characteristics), except if constant supervision is provided.

Appropriate curing is one of the main secrets of ensuring the success of lime renders. The carbonation of calcium hydroxide requires some humidity for the dissolution of the carbon dioxide but not too much, to allow its reaction with calcium hydroxide. This reaction is slow, so it is necessary to provide special conditions for several days, maybe some weeks. On the other hand, most of the mixing water of lime mortars is not used up in hydration reactions as happens in hydraulic binders, so it leaves the mortar, through evaporation or absorption by the substrate, causing high shrinkage. This can produce cracks, which must be closed while the mortar is still in a plastic state [22].
4 Examples

Some case studies of historic buildings’ renders and plasters repaired with compatible mortars are represented in Figs. 13-16 [1, 6, 7, 14].

![Fig. 13 Main LNEC building: repair with air lime mortar](image1)

![Fig. 14 Inglesinhos Convent: substitution air lime render](image2)

![Fig. 15 Sacramento church: repair and partial substitution of plasters using air lime plus hydraulic lime mortars and gypsum and air lime mixes](image3)

![Fig. 16 S. Bruno Fortress: substitution air lime plus cement render](image4)

5 Conclusions

Decisions about conservation strategy and about the materials to use for the conservation of historic renders and plasters are based on several factors, both of a subjective and an objective nature. Tests play an important role, for an evaluation of the severity of anomalies and for an assessment of compatibility by a comparison of the characteristics of existing materials and proposed solutions. However, they are only a part of the methodology. They should come after a careful expert observation and they must be adequately interpreted. The type of
tests and their localisation are to be chosen in order to obtain the maximum information with the minimum intrusion and disruption to the original fabric, and without taking more time than is necessary to fulfil the objectives. Hence, in-situ tests must be used first followed by complementary laboratory tests. Previous results in similar buildings and materials must be taken into account. Functionality, compatibility and adaptation to the prevailing environment and foreseen actions must be considered. Considering all of these factors carefully, creates a new perspective that aims to ensure the improvement of the durability of the whole building, respecting its characteristics.

To plan adequate interventions on historic buildings is a complex task, requiring many skills; therefore a multidisciplinary team must be chosen to do it and given a reasonable amount of time.

6 References