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RILEM TC 243-SGM: CONSOLIDATION OF RENDERS AND PLASTERS

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1. Introduction

This document focuses on consolidation in the field of renders and plasters. In many cases, degraded renders and plasters will just be replaced with new materials. However in case historic mortars are concerned, a specific, heritage related, value of the ancient mortar may exist and should be assessed: for example, the mortar may be furnished with mural paintings that are to be preserved or else the material of the mortar itself can be important as a document of ancient technology. In those cases conservation of the ancient material is important and a consolidation treatment may be the way to ensure this.

Consolidation is in this context a treatment meant to re-establish the material's cohesion in a mortar (render or plaster). This action usually requires the introduction of a new binding agent into the degraded layer. The binding agents applied for this purpose, in a liquid state, on degraded materials, are called consolidating agents, consolidating products, consolidants or strengtheners. The products can be applied to the surface using different procedures (coating, spraying, pouring, sometimes using compresses, i.e. poulticing or injection) and tools (brush, sprayer, syringe, pipette etc.) and should penetrate the degraded layer for an appropriate depth, which is related to the degraded zone.

This paper addresses the consolidation of plasters and renders for a depth of several mm up to several cm. After absorption of the liquid product by the mortar, drying, setting and hardening processes will start and reactions, which are typical for the specific consolidant, will take place. The final distribution of the new binding agent in the mortar depends on the consolidant type in combination with the treatment conditions and mortar properties.

The efficiency of a consolidation treatment depends on the product, on the mortar characteristics, on the application procedure and on the ambient conditions during and after the product application. A consolidation treatment should therefore be chosen and applied, taking into account all relevant aspects such as:

- mortar characteristics and conditions (physical, chemical properties, water content, form and cause of degradation, geometry of the surface to be treated, depth of degradation);
- product characteristics (chemical composition, concentration and strengthening capacity, penetration capacity /(particle size and viscosity), setting time, type of solvent or medium;
- application procedure and regime (process of application, applied amount in one application, number of applications, time intervals between applications);
- ambient conditions during and after treatment (temperature, humidity, wind speed).

It is necessary to select the appropriate materials and procedures for a correct consolidation treatment. The main aim of this paper is offering a guideline for the selection and assessment of consolidation treatments for renders and plasters, taking into account possible risks or harmfulness of the consolidation products and offering information on how to assess their efficiency, compatibility and durability under given conditions.

2. Methodology of consolidation intervention

Typical steps of a consolidation intervention are:

- characterisation (composition, binder type, porosity etc.) of the mortar (i.e. plaster or render), which should be consolidated;
- damage assessment (decay forms and quantification);
- dealing with damage causes, such as elimination (or mitigation) of moisture and salt sources;
- removal of salts present in the render / plaster (using poultices etc.)
- taking care of damage types which are not treatable with consolidants, like loss of adhesion, flaking and or exfoliation (using for example non structural grouting, etc.)
- choosing a number of (compatible) consolidation agents, potentially adequate for the mortar and situation;
- tests of the consolidation agents in laboratory (possibly combined with a site exposition);
- choosing the most adequate application method (spraying, brushing, poulticing, …);
- verification of the consolidant (or consolidants) chosen, applying it on a small area on site;
- treatment by consolidation of typical damages (mainly related to loss of cohesion, i.e. granular disintegration, such as chalking, powdering, sanding, crumbling);
- depending on the type of consolidant some kind of curing could be favourable;
- monitoring of the consolidated surface.

In case of decorated surfaces, such as mural paintings, the risk of impairing colours should be carefully considered.

3. Identification of the type of damage

In this chapter the methodology on how to identify the type of damage and its causes is discussed.
Before deciding on any treatment, it is important to first identify the type of degradation and its origin, i.e. the conditions that can be the cause of damage to the render / plaster.
A restoration project should always start with an assessment of the current condition (state of conservation) of the building (see fig. 3.1) or construction to be restored/repaired and with gathering data about previous maintenance and treatment. This is a necessary step for defining the problem to be solved. This step includes decisions on the investigations to be performed, i.e. analyses (in situ and lab) to better understand the causes of the damage as well as the material parameters involved.

The assessment of the technical state of conservation (technical assessment), includes[1]:

- damage assessment *(decay forms and quantification);*
- exposure conditions, including moisture and salt content of the substrate;
- description and identification of materials (material characterization);
- problem diagnosis, including risk assessment and a description of the mechanism(s) of decay.

Fig. 3.1 Disintegrated and partly detached render on Renaissance castle masonry (l). Peeling tests performed before the consolidation treatment (r), Pernštejn castle (Czech Republic)

Decay forms of the to be treated plaster, render or mural painting may include:

- crumbling
- sanding
- powdering
- chalking
- exfoliation, scaling, flaking
- micro-cracking → crazing
- bursting
- bulging / blistering

A more complete, illustrated overview of damage types related to plasters is provided in a table to be found at http://resolver.tudelft.nl/uuid:1530635f-74e2-457f-b317-177e192670c3. In the table the damage types treatable with consolidants are shown first, whereas further in the table other damage types occurring on renders and plasters are shown.

In general damage types in the form of a granular disintegration can be considered treatable with consolidants; those in the form of a layering not.

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[1] Chapter 3 - FROM PROBLEM TO INTERVENTION: THE DECISION PROCESS (RILEM TC203-RHM Repair Mortars for Historic Masonry)

Sometimes, the type of damage is such that no doubt exists on the question whether or not it would be treatable with a consolidant; in these cases the damage concerns clearly a form of loss of cohesion, i.e. granular disintegration.
Very often a combination of decay forms may be found, where both loss of cohesion and a form of layering exist and which may need a combination of treatments, like consolidation together with (non structural) grouting. See also fig. 4.1.

Additional problems to be faced may include situations like inclusions of iron elements with corrosion, presence of salts, deformations or cracks and previous incompatible treatments (ranging from incompatible binder systems to water-repellents).

4. Assessment of the renders / plasters to be treated

The assessment starts with a sound description of the decay type that can be observed (see Table 3.1), as well as the determination of the extent and depth of the decay.
Another important step is the characterization of the material (i.e. the decayed mortar), which may include:

- physical properties, such as porosity, pores sizes, water absorption rate, water drying rate and water vapour permeability;
- mechanical properties, such as flexural and compressive strength (porosity and chemical composition could give an indication, or special methodology of mechanical testing can be used [1,2,3,4] because the application of standard testing procedures is very difficult due to small and non-standard sized specimens), surface hardness and cohesion (for example shore hardness, Scotch tape/peeling test) and/or drilling resistance measurement (see the remarks made on this method in chapter 5.2.2 with respect to the number of drillings) are suggested;
- colorimetric characterisation;
- chemical and mineralogical composition;
- stratigraphy and micro-structural identification: a cross section of the affected plaster layer (see fig. 4.1) may provide important information to base the treatment on.

Fig. 4.1 shows an example of a practical situation that could be met.

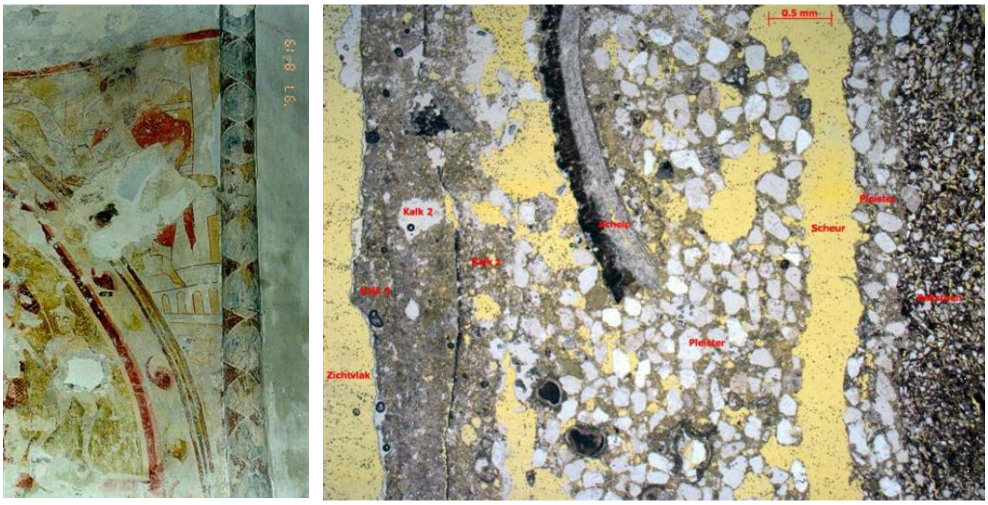

Fig. 4.1 Painted plaster on brick masonry (left) and thin cross section of the decayed plaster (right): it consists of differently composed layers on a brick substrate. The two top layers are composed of lime (thickness ca. 0.5 mm each), the base coat is a lime-sand mixture. The base coat shows a poor coherence as well as a crack parallel to the brick surface.

5. General requirements

In this chapter compatibility and performance requirements and criteria [21], will be dealt with.

5.1 Compatibility requirements

The consolidation treatment should be effective (improving the cohesion/strength of the degraded mortar) and compatible with the mortar. A consolidation treatment can be considered compatible if it does not lead to technical (material) or aesthetic damage to the existing materials; the treatment as such should further be as durable as possible.

Compatibility criteria and requirements can be defined on this basis. The compatibility requirements have been subdivided in physical, chemical, mechanical and aesthetic requirements. The aspects considered important are listed and explained hereafter.

5.1.1 Physical requirements

5.1.1.1 Porosity / pore size distribution

Porosity and pore size distribution should not differ too much from those of the sound material, in order to avoid a completely different behaviour of the treated zone under influence of moisture (moisture absorption and drying). Assessment of this parameter, before and after treatment, might be indirectly obtained using the water absorption and drying behaviour.

5.1.1.2. Drying behaviour

The drying behaviour of the render / plaster should be influenced as little as possible by the consolidation. A consolidation, which inhibits or delays the drying, may enhance decay processes as salt and frost action and biodegradation. Treated, decayed material should be compared with untreated, decayed material, and if possible with untreated sound material. In [5] examples are described of the possible unfavourable effect of surface treatments (water repellents and consolidants) on the drying behaviour of brick substrates.

Fig. 5.1 shows the effect of a consolidant, on the drying behaviour of a mortar-like material; the slower drying of the treated material is clearly visible.

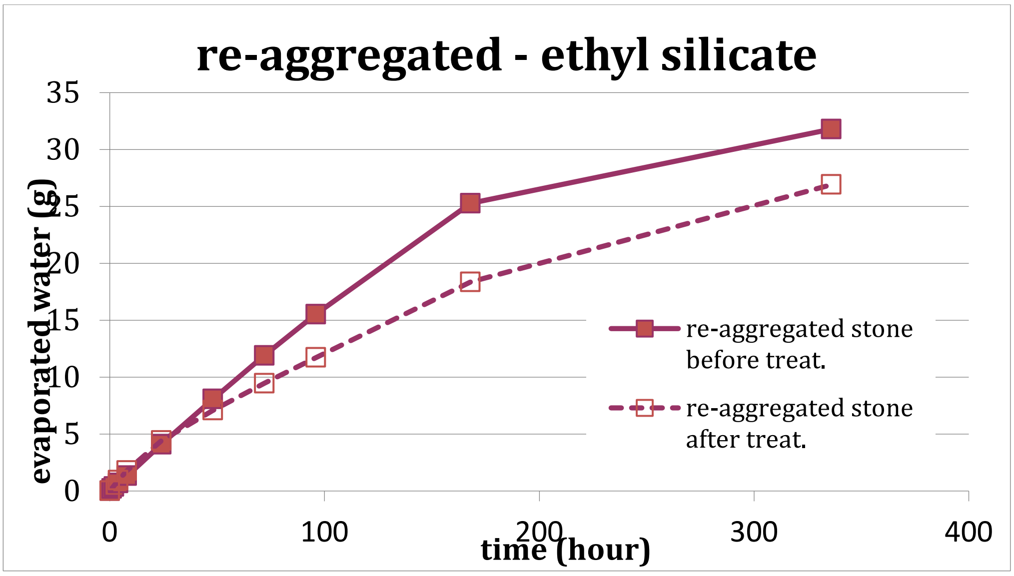

Fig. 5.1a Effect of consolidation treatment on drying behavior. Artificially degraded Maastricht limestone, obtained by re-aggregating limestone particles with lime resulting in a mortar-like material[2]*. Solid lines untreated, dotted lines treated with consolidant*

Fig. 5.1b Specimen of Maastricht limestone, with on top the re-aggregated, mortar-like layer, before treatment

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[2] Lubelli, B., Hees, R.P.J. van, Nijland, T.G. & Bolhuis, J., 2015. A new method for making artificially weathered stone specimens for testing of conservation treatments. Journal of Cultural Heritage 16 (2015), pp. 698-704 DOI information: 10.1016/j.culher.2015.01.002 [31]

5.1.1.3. Thermal & hygric dilation

Dilation of mortars should not be significantly influenced by the consolidation treatment, in order to prevent damages such as spalling of the treated zone.

5.1.2 Chemical requirements

5.1.2.1. Undesired chemical reactions

Harmful chemical reactions between treated render / plaster and environmental factors (air pollution, salts, etc.) should be avoided as much as possible and the selection of treatments should have this factor into consideration.

5.1.2.2. Solubility

Solubility under the influence of environmental factors (like acid rain) of treated and untreated render / plaster should be comparable in order to avoid selective weathering. The alternative is the treatment of the full exposed surface.

5.1.3 Mechanical requirements

5.1.3.1. 'Hardness' and cohesion

The effect of the consolidation treatment should be such that an improvement of the 'hardness' and coherence of the decayed surface is obtained. However the 'hardness' of the decayed, treated material should not surpass that of the sound material (possible methods: DRMS, USV, Shore, *Vickers, Rockwell,* Bending, Compression).

5.1.3.2. Deformability

The consolidation treatment should not reduce significantly the deformation ability of the render / plaster, which can be evaluated by the *dynamic* modulus of elasticity (to be measured by *frequency of resonance or by ultra sound)*[3]. The modulus of elasticity of the consolidated material should not surpass that of the sound material.

5.1.4 Aesthetic requirements

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[3] *N.b. acc. to [32] TAMIN, P. F. - Étude du comportement mécanique des revêtements de façade. Enduits. Thèse de doctorat. Paris, Ècole Nationale des Ponts et Chaussées (ENPC), décembre 1986, the static Elastic Modulus/Dynamic elastic modulus by frequency of resonance lies between 0.76-0.79 for elastic modules in the range of 2-8 Gpa.*

No visible discoloration or increase of surface gloss should occur due to the consolidation.

5.2 Performance and long-term behaviour criteria

Next to compatibility criteria also performance (related to effectiveness) and long-term (related to durability) behaviour can be defined in the following fields:

5.2.1 Cohesive effect (in comparison with untreated degraded substrate)

This aspect is closely related to hardness. The cohesive effect can be assessed by several methods, such as: Shore hardness measurements (surface hardness) [11]; a scotch tape (peeling) test; an abrasion test; or other test validated for this effect, like drilling resistance or ultra sonic velocity test, see 5.2.2). A relatively new method is Acoustic Microscopy. [4]

5.2.2 Penetration depth of the product

Penetration depth of a product gives important information on its potential performance. For the assessment of penetration depth, methods with indicator liquids can be used (fig.5.2 a and b) or microscopic examination of the cross section (fig. 5.3 a and b).

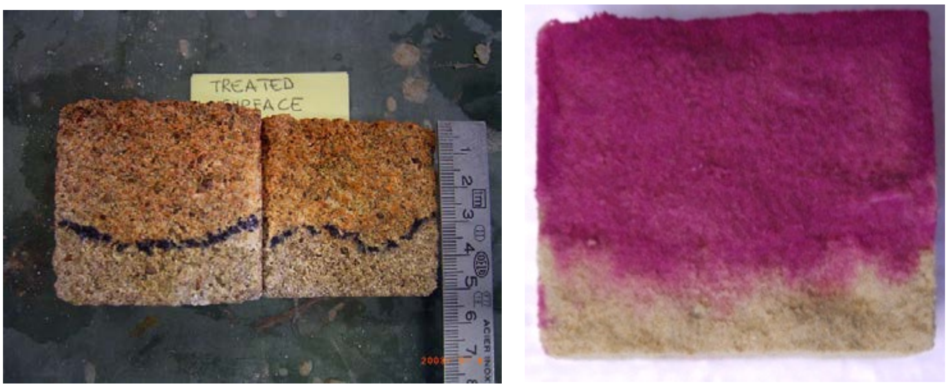

Fig.5.2 a/b Use of indicator liquids to assess the presence of a product in a substrate. Left – dithizon, used for ethyl silicate; right – phenolphthalein used for the assessment of the penetration of a nanolime consolidant [33]

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[4] Acoustic Microscopy is a non-destructive technique, using very high frequency ultrasound. The ultrasonic waves are emitted from the transducer into the measured sample through the used coupling medium. Since ultrasound propagates from the transducer to subject, echoes are generated by the interfaces of different micro-structures within the material. An echo is the reflective component of the initially generated wave. The density of the reflection depends on the difference of the acoustic impedances of the engaged materials. By measuring the depth a wave travels into the material, conclusions may be drawn on the penetration depth of a consolidant [28]

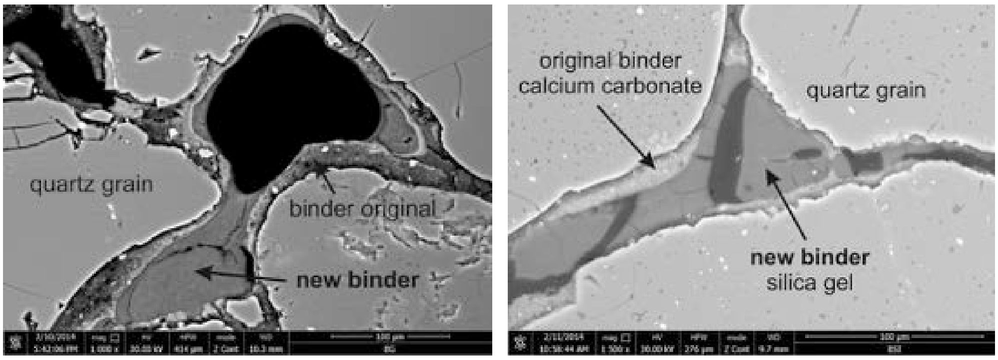
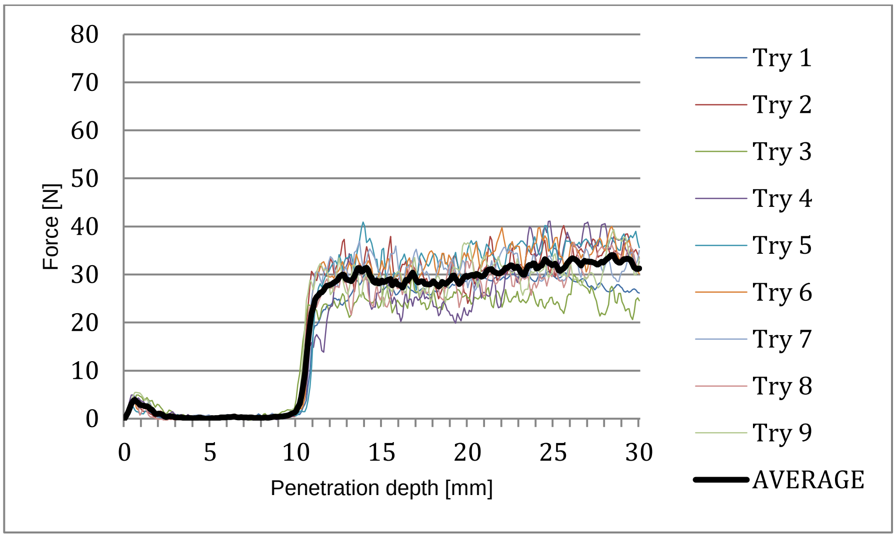


Fig.5.3 a/b Use of SEM- BSE microscopy to detect the presence of a product in a substrate. Left – nanolime treatment result: new calcium carbonate layers detected in pores near the treated mortar surface; right – silica sol treatment result: silica gel detected at the depth of 2 mm under the treated mortar surface

Alternatively, drilling resistance (DRMS, see [38]) may, under circumstances (fine grained sand, ..), be used to assess the penetration depth (fig. 5.4). Because of the inhomogeneity of a mortar (sand grains versus binder) a sufficient number of drillings is necessary; assessing the average of 10 drillings is suggested.



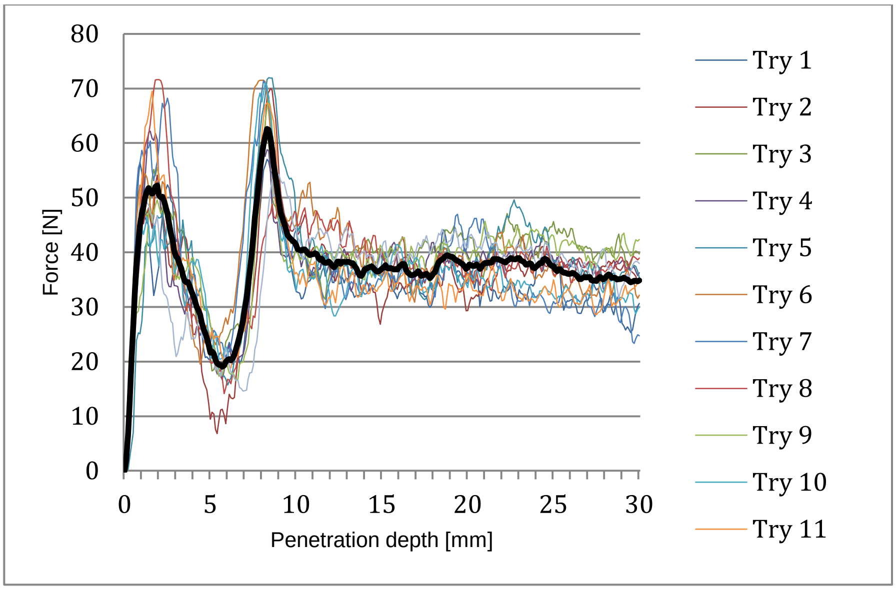


Fig. 5.4 Example of drilling resistance measurement on Maastricht limestone with artificially degraded render (10 mm), before and after treatment with ethyl silicate. The average of the drillings is given in the black curve

5.2.3 Salts, frost, biodegradation (in comparison with untreated degraded mortar)

The behaviour of a treated mortar under influence of salt crystallization cycles and frost cycles should be in between that of a not treated sound mortar and that of a degraded mortar, or as similar as possible to the sound mortar, without becoming more resistant.

Biological growth on a treated mortar should not increase in comparison with that on a not-treated mortar.

An additional general performance requirement for all damage mechanisms would be that damage development in a degraded mortar after treatment should be clearly slower than in an untreated, degraded mortar.

6. Selection and assessment of product

6.1. Consolidation products

Historically, the available conservation materials for building materials were mainly lime, gypsum and natural organic compounds based on vegetal oils, waxes, polysaccharides (vegetal gums and starch), proteins and natural resins. (In several regions of the world, traditional plaster materials exist, in which natural additives were added, based on for example gluten from wheat flour glutinous (sticky) rice or jaggery (from cane sugar after boiling) and several authors state [35, 36, 37] that these kinds of adhesives have been used also as consolidants for this type of mortars). Later, with the development of chemistry, barium water, ethyl silicate, synthetic polymers came into building materials conservation practice [34].

Many of these natural and synthetic substances failed to satisfy compatibility and performance requirements for the consolidation treatment.

Recently, more attention has been paid to the use of inorganic consolidating materials. An important advantage is that hydrophilic inorganic products are free of the problems caused by hydrophobic properties of organic-polymeric products [24] and are less susceptible to microbiological attack than organic compounds.

Limewater was recommended in some literature of the 20th century [6] for consolidation of mural paintings, particularly for fixation of released surface paint layers. Useful contributions dealing with limewater applications on mortar have been given during the last 15 years [7,8,9,10,11,12,13]. Silica based consolidants, mainly utilized for (sand)stone consolidation, can be used also for consolidation of specific types of mortar, particularly earthen mortars. Calcium hydroxide sols (nanolimes) were developed in recent years in order to get improved efficiency of lime-based consolidants [11,12,13,14,15,16]. The natural conversion of calcium carbonate to calcium oxalate led to experiments in Italy, using a treatment based on ammonium oxalate to protect stone and lime plaster against acid rain [22, 23]. Later, ammonium phosphates were proposed for consolidation of calcareous substrates and tested on limestone [24,25,26] and mortars. The most important physical-chemical characteristics of common consolidation products are given in Table 6.1.1. Some positive and negative aspects, which should be considered in relation to consolidation treatment, are mentioned in Table 6.1.2.

Table 6.1.1 Characteristics of consolidation products for renders, plasters and wall paintings

Common name	Active phase chemical composition	System	Active phase size and concentration		Solvent or Dispersion medium
			Size	Concentration	
Lime water	$Ca(OH)_2$	Solution, homogeneous mixture, dissolved phase (Ca^{2+} cations, OH^- anions) in water	0.11 nm (Ca^{2+}) 0.14 nm (OH^-)	maximum (saturated sol.) 0.16 % w. (1.6 g/l)	Water
Barium water	$Ba(OH)_2 . 8H_2O$	Solution, homogeneous mixture, dissolved phase (Ba^{2+} cations, OH^- anions) in water	0.15 nm (Ba^{2+}) 0.14 nm (OH^-)	maximum (saturated sol.) 5.6 % w. (56 g/l)	Water
Nanolime	$Ca(OH)_2$	Colloid, Sol, dispersed phase (calcium hydroxide particles) in alcohol	50-300 nm	max. in products about 8 % w. (80 g/l) usually used 5-25 g/l	Ethanol, Isopropyl alcohol, etc.)
Nanosilica	SiO_2	Colloid, Sol, dispersed phase (silica particles) in water	7-125 nm	max. in products 50 % w. (500 g/l) usually used 30-100 g/l	Water
Silicic acid ester, TEOS, Ethylsilicate	Tetraethoxy silane or tetraethoxy orthosilicate	Homogenous phase, Monomer	1.5-3 nm	about 28 % w. SiO_2	None
	Ethoxy oligomeric siloxane or ethyl polysilicate	Homogenous phase, oligomer, partly pre-condensed	<15 nm	about 40 % w. SiO_2	None
	Tetraethoxy silane or ethoxy oligomeric siloxane	Solution, homogeneous mixture, dissolved phase-ethyl(poly)silicate molecules- in solvent	<15 nm	about 10 % w. SiO_2	Organic solvent e.g. ketone, ethanol
Acrylic resins	Acrylate/ methacrylate (co-)polymer	Solution (homogeneous mixture), dissolved phase - acrylate (co)polymer molecules- in solvent	<10 nm	35-100 % w. usually used 1-5 % w.	Acetone, Toluene, Xylen, Ethanol, Isopropyl-alcohol etc.
Acrylic dispersions	Acrylate/ methacrylate (co-)polymer	Colloid, Sol, dispersed phase -acrylate (co-)polymer particles- in water	170-200nm	40-50 % w. usually used 5 % w.	Water
Ammonium oxalate	$(NH_4)_2C_2O_4$	Solution, homogeneous mixture dissolved phase (NH_4^+ cations, oxalate anions) in water	0,14 nm (NH_4^+) <1 nm (oxalate)	usually used 2,5- 5 % w.	Water
Ammonium phosphates	Di-ammonium hydrogen phosphate (DAHP) $(NH_4)_2HPO_4$ or Ammonium di-hydrogen phosphate (ADHP) $(NH_4)H_2PO_4$	Solution, homogeneous mixture, dissolved phase (NH_4^+ cations, phosphate anions) in water	0,14 nm (NH_4^+) <0,5 nm (PO_4^{3-})	usually used 5 % w.	Water

Table 6.1.2 Positive and negative aspects of consolidation products in relation to consolidation treatment

Common name	Advantages	Disadvantages	Risks
Lime water	- good chemical match with lime mortar - little change of all mortar characteristics (porosity, water absorption, …) after consolidation	- low content of the active phase and resulting low strengthening effect after one application - repeated water saturation of mortar due to treatment -high pH of lime water	- salts crystallization and damage - white haze after many cycles - instability of some pigments due to high pH of the water - reduced strength of wet mortar - freezing in cold climatic periods
Barium water	- sufficient content of the active phase - chemical stability of the $BaCO_3$ -stabilization of sulphates in mortar	- created $BaCO_3$ differs from $CaCO_3$ - high pH of barite water	- raising of colour intensity after more cycles (yellowing, whitening) - instability of some pigments due to high pH of the water - reduced strength of wet mortar - freezing in cold climatic periods
Nanolime	- sufficient content of the active phase - good chemical match with lime mortar - non-aqueous system (may be suitable for salt laden mortars)	- particle size of nanolime may be a limiting factor for some fine porous mortars - fast evaporation of alcohol from nanolime may cause agglomeration of $CaCO_3$ near the surface	- white haze due to fast evaporation of alcohol resulting from high temperature or high air ventilation during the treatment, high product concentration or too many applications or too fine pores in treated mortar
Nanosilica	- good strengthening effect - economic product	- created SiO_2 differs from $CaCO_3$ - particle size of silica sols may be limited for some fine porous layers of mortar - high content of the active phase (often need to be diluted for mortar consolidation)	- white haze, glossy surface - surface over-strengthening due to wrong choice of the product concentration, and limited penetration etc.
Silicic acid esters	- good strengthening effect - good penetration depth; - good chemical compatibility with the earthen mortar binder	- created SiO_2 differs from $CaCO_3$ - reduction of mortar water absorption after treatment (persisting hydrophobic features)	- white haze, glossy surface - surface over-strengthening due to wrong choice of the product concentration or due to application on wet or salt laden mortar - detachment
Acrylic polymers	- good strengthening effect - good adhesion effect	- acrylate resin differs from $CaCO_3$ (no chemical match) - drying and water vapour permeability retardation after treatment - low penetration depth	- increase of degradation of surrounding not treated zones due to significant changes of moisture behaviour - detachment of the surface layer due to low permeability of water vapour - differential weathering by comparison with untreated material
Ammonium oxalates	- an increase in cohesion was observed after treatment - the wetting properties are retained and the passage of water is not prevented - the treated surface is	- created calcium oxalate phases differ from $CaCO_3$ - the nature of the reaction determines its spontaneous termination only a few microns below surface [23] - not enough data are available to evaluate the	- ammonium affects copper based pigments such as malachite, verdigris, and azurite.

	more resistant to acid attack	consolidating effect on mortars/plasters	
Ammonium phosphates	- sufficient content of the active phase - absence of toxicity - very low solubility of the reaction products (calcium phosphate compounds) - low viscosity = good penetration into the stone - good strengthening effect	- created calcium phosphate phases differs from $CaCO_3$ - not enough data are available to evaluate the consolidating effect on mortars/plasters	- ammonium affects copper based pigments such as malachite, verdigris, and azurite.

What effect may be expected and how many subsequent treatments are necessary

Often, a higher number of subsequent treatments is needed to achieve an adequate consolidation effect. Some examples of consolidation treatments for specific plasters/renders are given in Table 6.1.3. The term "cycle" in this table ~~was~~ is used for the impregnation of the decayed mortar layer with a consolidant and ~~following~~ the subsequent drying ~~out~~ of the treated layer. The required amount of a consolidant for 1 impregnation cycle can be derived from the mortar porosity accessible for water.

Table 6.1.3 Examples of possible procedures and indication of the number of treatments for the consolidation treatment for different mortar type and condition

Render/ plaster type	lime water (saturated solution)	nanolime in alcohol 15-25g $Ca(OH)_2$/l	ammonium oxalate 25g/l, or ammonium phosphate (ADHP) 50g/l, or barium hydroxide 40g/l	ethylsilicate 100 g SiO_2/l	nanosilica in water 30- 100 g SiO_2/l
lime mortar, very weak cohesion, salt-free	100 cycles	5-7 cycles	3-4 cycles	2 cycles	2 cycles
lime mortar, quite good cohesion, pores > 10 µm, salt-free	50 cycles	3-5 cycles	2 cycles	1 cycle	1 cycle
lime mortar, fine pores (1 µm), salt -free	30-50 cycles	-	2 cycles	1 cycle	-
lime mortar, contaminated with salts	-	3-7 cycles	-	1 cycle	-
earthen mortar	-	3-7 cycles	-	1-2 cycles,	1-2 cycles

The preliminary selection of consolidants to be used for testing in a specific case should be done considering several aspects. Generally, chemical similarity between the consolidant and the mortar binder is favourable. Consolidants, which transform~~s~~ into calcium carbonate in a mortar, are preferred for the consolidation of non-hydraulic (aerial) lime plaster/render; a treatment based on a combination of lime based products (lime water and nanolime) with silica based products (ethylsilicate and nanosilica) can be suitable for hydraulic lime consolidation; ethylsilicate or nano silica appear most appropriate for earthen mortars.

Regarding the chemical reactivity of the consolidant with the mortar, it is advantageous if the consolidant can form chemical bonds with the mortar particles (for example ethyl silicate reacting with the OH- groups of silicate minerals present in mortar). The consolidation treatment can be more durable and effective in these cases.

The consolidated plaster/render should be re-treatable, i.e. allow the application of other required conservation materials, e. g. repair mortars, paints or protective treatments. Therefore, hydrophobic consolidating materials may be problematic if ~~it~~ the application of water based materials in following conservation steps is foreseen. For example, hydrophobic features of surfaces treated with ethylsilicate persist often longer than 1 month~~,~~ and this fact should be considered before application of this product.

The penetration ability of the consolidating liquid depends on its viscosity and surface tension. Low viscosity and high surface tension (low contact angle) are favourable characteristics for a good penetration and fast absorption of the consolidant by the mortar. The particles size of the consolidating material is another important parameter, particularly in the case of consolidants, that are based on the dispersion of nanoparticles in water or alcohol, e. g. nanolime, nanosilica, dispersions of synthetic resins in water. The particles of the consolidating agent need to be significantly smaller (ten to hundreds of times) than the pores of the mortar to be able to penetrate into the mortar effectively and therefore the last mentioned products have bad chance to penetrate deeply into fine porous plasters or renders.

6.2 Application methods and procedures

The application procedure of the consolidant depends on the consolidant penetration properties, on the mortar suction ability, on the type and location of the element to be treated and on the exposition (for example interior or exterior). It is not possible to give one standard application method and procedure, which could cover all mortar substrates, degradation types and environmental conditions. A general indication on the most appropriate application method is given in table 6.2.

Table 6.2 Application methods for different circumstances. General indications

	Practice large surface, interior	Practice large surface, exterior	Practice small surface or ornaments	Laboratory large surface	Laboratory small surface
Spraying	x	x		x	
Brushing	x	x	x	x	x
Poulticing			x		
Capillary absorption					x

In most cases the consolidant must be applied on site, without removing the element. In those circumstances the application is done by: i) spraying (or squeezing from a bottle) the mortar surface: several repetitions with small intervals, until the mortar is saturated to the required depth (thickness)
ii) brushing: several brushing operations with small intervals, until the substrate is saturated to the required depth; or even by iii) poultice application.
In laboratory, for comparison of the effect of different treatment products or concentrations, vertical capillary absorption of the liquid, may under circumstances be the most adequate application method.

6.3 Performance assessment

Methodology, parameters and measuring methods will be discussed hereafter.

6.3.1 Assessment methodology

The selection of the product to be used and the verification of its fitness should be done through laboratory testing and/or in situ assessment.
The following sequence of actions should preferably be carried out:

- Preliminary selection of consolidants based on the characteristics and requirements for selection of table 6.1.3.
- Testing of different application procedures and regimes (method of application, applied amount of consolidant per mortar surface unit during one application, number of applications, time intervals between applications).
- Testing the consolidation agents previously selected on trial specimens and subsequent comparison of the test results (as referred to in 6.3.2):
  - Preferably on site (but not on the object)
  - Alternatively on mortar specimens in lab: simulation of composition and porosity of mortar (render / plaster) to be treated; simulation of ambient conditions (T, RH) – can be important for the final distribution of the consolidant in the substrate and for the resulting

strength profile. Although it is difficult to produce artificially degraded mortar specimens in laboratory, that perfectly represent the degraded mortar in practice, it is considered possible to obtain a reasonable similarity, following a procedure that is described in [31] for artificially degraded stone surfaces; in [31] the use of a mortar consisting of stone particles, an adequate binder and a porosity comparable with that of the degraded surface in practice is described (see also fig. 5.1b in this article). Porosity of the artificially degraded mortar can be fine-tuned by adapting binder content and grain size distribution of the aggregate. For practical reasons the use of this procedure may be limited to very important plaster and wall painting surfaces.

- Assess properties on treated and not-treated mortar and compare results: cohesion, water absorption and drying, porosity, pores size, colour change and appearance in general, strength profile (ultrasonic velocity, drilling resistance, microscopy), thermal and hygric dilation, deformability (modulus of elasticity), microscopic and chemical analyses (new binder morphology, interaction of original mortar components with a new binder).
- Apply accelerated ageing (climatic cycles and salt crystallization cycles) on part of the specimens and evaluate the behaviour under these actions, in comparison with not decayed mortar.

6.3.2 Parameters to measure and measuring methods

The performance of the treatment should be assessed *in situ* or on model substrates (consisting of mortar or plaster layer, applied on brick or stone, see figures 6.1 and 6.1.2) following table 6.3 or with other tests proved to be adequate and evaluation of the results according to the requirements, based on comparison with the untreated material. Standardized measuring methods for testing mortars or modified methods for testing historical mortar [1,2,3,4,11,13,19] should be applied to determine mortar parameters. When such a method is missing, adoption of a method for testing stone [20, 27] can be considered.
Only after such an assessment the consolidant should be applied to the object.

Fig. 6.1 Preparation of plaster/brick specimens and the application of a consolidant for tests to be performed on the system plaster and substrate

Fig. 6.2 Preparation of plaster on brick specimens for tests to be performed on the plaster: use of a glass fibre mesh (Japanese paper is also an option) between plaster and substrate and removal of the plaster after sufficient drying

Table 6.3a Parameters and laboratory test methods

	Parameter	Requirement	Test method	Criterion
Laboratory tests on a render/plaster (simulated mortar) before and after consolidation	***Application***			
	Product application	Comparison of different application techniques	--	
	Physical			
	Porosity	Not significantly different from sound material	Water absorption under vacuum (EN 1936: 2006), (RILEM 25-PEM 1.1; RILEM CPC 11.3), MIP, (Optical) microscopy (image analysis)	Small/moderate decrease of porosity acceptable, *generally max up to the porosity of the sound material*
	Pore size distribution	No significant change of pore size distribution	MIP	
	Water absorption	Moderate decrease of water absorption	EN 1015-18:2002 or EN1925: 1999	between 20 and 50% lower than before consolidation
	Drying behaviour / rate	Limited decrease in drying velocity (or drying rate)	RILEM 25-PEM II.5 EN 16322:2013	After 24h moisture content treated mortar =<80% of saturation
	Water vapour permeability	Limited decrease	EN 1015-19:1998 ISO 12572:2001	
	Thermal and hygric dilation	Limited change	EN 14581: 2004 (thermal) RILEM 25-PEM II.7 (hygric)	maximum 30% change[5]
	Chemical			
	Chemical, mineralogical composition and chemical reactivity	Harmful chemical reactions between treated render / plaster and environmental factors (air pollution, salts, ..) should be avoided	Methods of determination of chemical or/and mineralogical composition (SEM-EDX, FTIR, XRD, IC,etc.). Assessment of reactivity of determined substances	Reactivity, acidity of new compounds should be assessed with respect to untreated render/plaster composition

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[5] Normal shrinkage stresses of lime mortars that cause no significant problems are of about the same order of magnitude than those produced by a 30% difference of thermal dilation coefficient, for 20° C of temperature variation (approx. 0.06 MPa, due to restrained shrinkage) [30].

				and environmental factors
	Solubility	Water solubility of treated and untreated render/plaster should be comparable	Assessment of water solubility of render/plaster by weight	Similar or lower solubility of render/plaster compared to that of the untreated mortar
	Mechanical			
	Hardness	Improvement, but not surpassing the sound material Homogeneous effect over depth of treated zone	DRMS Shore hardness Ultrasonic velocity Bending test (Nb thickness plaster layer) Compression strength	
	Cohesion	Improvement, but not surpassing the sound material Homogeneous effect over depth of treated zone	DRMS Shore hardness Ultrasonic velocity Bending test (Nb thickness plaster layer) Compression strength Peeling test (strip test)	
	Deformability	No significant reduction	(Dynamic) modulus of elasticity EN 14146: 2006 (Frequency of resonance)	
	Aesthetic			
	Colour change and general appearance change	No visible / significant change of colour and/or appearance (except if render/ plaster is to be painted or to have chromatic reintegration after consolidation)	Naked eye, Spectrophotometry (also to be used for long term monitoring): acc. to EN 15886: 2010 Colour measurements of surfaces	
	Performance & durability			
	Cohesive effect	See above (cohesion)	DRMS Shore hardness Ultrasonic velocity Bending test (Nb thickness plaster layer) Compression strength Peeling test (strip test)	
	Penetration depth	Full decayed zone should be reached Homogeneous distribution	DRMS Indicator liquid Microscopic examination	
	Resistance to weathering	Improvement of the treated render/plaster	Frost-thaw cycles Salt crystallization	

		compared to the untreated one	cycles Wet-dry cycles Ageing in climatic chambers with SO_x, NO_x Resistance to sunlight / UV	

Table 6.3b Parameters and in situ test methods

	Parameter	Requirement	Test method
In situ tests on a render/plaster before and after consolidation	***Application***		
	Product application	Method of application should be practicable, considering the given conditions (area and depth of to be treated mortar, environment), sufficient penetration depth	Comparison of different application techniques and procedures, penetration depth assessment
	Physical		
	Porosity	Not to be measured on site	
	Pore size distribution	Not to be measured on site	
	Water absorption	Moderate decrease of water absorption	Karsten tube Drip method (droplet test)
	Drying behaviour / rate	Not to be measured on site	
	Water vapour permeability	Not to be measured on site	
	Thermal and hygric dilatation	Not to be measured on site	
	Chemical		
	Chemical, mineralogical composition and chemical reactivity	Harmful chemical reactions between treated render / plaster and environmental factors (air pollution, salts, ..) should be avoided	Methods of determination of chemical or/and mineralogical composition (Portable XRF, portable FTIR, Raman spectroscopy, etc.)
	Solubility	Not to be measured on site	
	Mechanical		
	Hardness	See under cohesion	
	Cohesion	Improvement, but not surpassing the sound material Homogeneous effect over depth of treated zone	DRMS Shore hardness Ultrasonic velocity Peeling test (strip test)
	Deformability	No significant reduction	(Dynamic) modulus of elasticity by ultra sound method
	Aesthetic		
	Colour change and general	No visible / significant change of colour	Naked eye, Spectrophotometry

	appearance change	and/or appearance (except if render/ plaster is to be painted or to have chromatic reintegration after consolidation)	(also to be used for long term monitoring): acc. to EN 15886: 2010 Colour measurements of surfaces
	Performance & durability		
	Cohesive effect	See above (hardness and cohesion)	DRMS Shore hardness Ultrasonic velocity Peeling test (strip test)
	Penetration depth	Full decayed zone should be reached Homogeneous distribution	DRMS After sampling: with use of indicator liquid and/or microscopic examination
	Resistance to weathering	After consolidation improvement when compared to before consolidation	Assessment effect of natural weathering on medium to long term (monitoring physical, chemical and mechanical properties)

Conclusion of the testing can be an (scientific) assessment of effectiveness, risks and durability of tested treatments under natural and artificial conditions and a list of aspects, which should be taken into account before decision making.

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