DURABILITY OF LIME BASED RENDERS: A REVIEW OF SOME DEGRADATION MECHANISMS AND ASSESSMENT TEST METHODS

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Abstract

Lime based mortars used for the repair and renovation of old lime renders have important functions in historic buildings, such as the protection of the masonry and aesthetics of the surfaces. Hence, they have a significant contribution to the durability of the walls, which often are structural elements.

Cracking and loss of adherence are two of the most severe defects for renders, as they drastically affect their functional capacity. Cracking is related to shrinkage, elastic characteristics, and kinetics of the gain of strength as well as to water transport properties of the render. Most of these aspects are governed by the porous structure of the mortar, which is a function of the composition of the mix and application issues. Loss of adherence is related to the compatibility of the render with the substrate, concerning mechanical, thermal and hygric aspects. Loss of cohesion, due to leakage of the binder, freeze-thaw, salts crystallization or other causes, results in significant damage, difficult to repair. The appearance of stains either by pollutants deposition or by biocolonization is also a concern related to durability of renders.

In the present paper the degradation mechanisms leading to cracking, loss of adhesion or cohesion and stains formation are analysed based on literature, and a review of assessment test methods are carried out. Finally, the need for test improvement in this area is highlighted.

Keywords: Lime render; Degradation mechanism; Cracking; Loss of adhesion; Test method

1. INTRODUCTION

Lime based mortars used for the repair and renovation of old lime renders have essential functions in historic buildings. In particular, they are meant to protect the masonry, hence they have a significant contribution to the durability of the walls, which are often structural elements. Repair lime renders are mainly intended to increase the durability of the masonry. However, their durability is also an important issue. They are directly exposed to weathering agents and to all external actions and their main anomalies are: cracking, loss of adherence, loss of cohesion, chemical reactions related to pollution and soluble salts and biological colonization.

Cracking is due to shrinkage and thermal, hygric and salt-related dimensional variations [1]. It depends on the elastic characteristics of the mortar and their evolution in time, as well as with the kinetics of the gain of strength [2]. The water transport properties of the render are also significant factors, as they condition shrinkage. Most of these aspects are governed by the porous structure of the mortar, which is a function of the composition of the mix and application issues. Loss of adherence is related to the compatibility of the render with the substrate, concerning mechanical, thermal and hygric aspects [3,4]. Differences in the modulus of elasticity and in thermal and hygric dilation coefficients of the materials generate stresses in their interface; variations in water transport produce water vapour pressure and accumulation of soluble salts between layers; these mechanisms are important causes of loss of adherence. The appearance of stains due to pollution emissions also affect the state of conservation of renders and their durability [5,6]. Atmospheric pollutants are also very aggressive for calcitic materials, which are the main constituents of lime renders. The aesthetic quality of renders can also be seriously affected by biological stains caused by the growth of microorganisms [7] which may even reduce the durability of the renders by biodeterioration [8].

2. SYNTHESIS OF MAIN ANOMALIES AND CAUSES

Anomalies of renders may be caused by inappropriate composition or application of the render or by particularly aggressive unforeseen external factors. For historical materials, natural weathering is also a cause of degradation. The main anomalies that affect the functionality and durability of renders are summarized in table 1 along with their respective causes.

Table 1 – Main anomalies of renders, consequences, and causes

Main anomalies	Functions affected xxx (maximum) to – (doesn't affect)				Causes
	Protection of masonry	Aesthetics of the façade	Durability of the masonry	Durability of the render	

Cracking	XXX	XXX	XXX	XXX	• High shrinkage + stiff mortar
					  ◦ Mixing ratio between lime and sand
					  ◦ Sand curve
					  ◦ Fat or lean lime, crystal structure of lime
					  ◦ Thickness of render in comparison to suction of substrate
					  ◦ Unfavourable curing conditions
					• Movements of the substrate (structural or due to thermal and hygric variations)

					• Formation of expansive compounds in the substrate • Weak adhesion to the substrate, promoting stress concentration • Freeze-thaw cycles • Salts crystallization
Loss of adherence	XXX	XXX	XX	XXX	• Incompatibility with the substrate: Physical; Chemical; Mechanical • Lack of adequate pressure in application • Surface film of lime of each layer of render • Freeze-thaw between layers • Salts crystallization between layers
Loss of cohesion	X	X	-	XXX	• Crystallization of soluble salts inside porous network • Dissolution and leaching of the lime binder, caused by frequent or severe water circulation
Stains	-	XXX	-	X	• Pollution • Biological colonization • Leakage of soluble salts and other products from bricks and stones

3. CRACKING – CAUSES AND ASSESSMENT METHODS

Cracking produces complete loss of the renders' protective function against water and aggressive solutions, hence reducing the durability of the masonry and damaging its aesthetic appearance. It is caused by stress, usually tensile stress, induced by: a) drying shrinkage of the mortar restrained by the adhesion to a stiffer substrate; b) movements of the substrate that are transmitted to the render; c) volume increase of products inside the porous structure, such as water (freeze-thaw), soluble salts (dissolution-crystallization and hygroscopic volume changes) and expansive compounds formed.

The ability of the render to accommodate stress without cracking depends of: a) the magnitude of the stress; b) the ductility of the mortar and in general of its ability to deform without cracking during the stress application period; c) the tensile strength of the mortar in the period of stress development. Stress is often not instantaneously induced in mortars, on the contrary, it is slowly developed: shrinkage occurs for several days or months after application, with increasing values; thermal and hygric variations follow the rhythm of weather changes. This slow process allows for relaxation and creep phenomena to contribute to the cracking susceptibility [9,10,11,12]; creep is higher (more favourable) for lime mortars than for cement ones [13]. In most cases, tensile stress is transmitted through the substrate, hence the bond between the substrate and the render as well as its uniformity are important parameters. Poor adhesion causes stress concentration in some areas, which is a cause of cracking. Many factors are involved and their interrelation is complex. The definition, improvement and validation of a reliable test for the assessment of the cracking behaviour of rendering mortars, taking into account all the most significant factors, is then needed.

The methods found in literature to assess the cracking susceptibility of mortars may be grouped into several types:

– **Determination of ductility using flexural strength tests**

Cracking susceptibility has been related to ductility since long time ago [9]. Recent studies have used three-point bending test and analysis of the force-displacement curve [14] sometimes with a crack artificially produced at middle span [15]. These methodologies are easy to perform, do not require special equipment and give quantitative information, however, the values obtained are comparative and cannot be directly related to in-service stresses.

– **Ring tests**

Ring tests are among the oldest quantitative tests developed with the aim to determine stress due to restrained shrinkage [9,16,17,18]. Different variations of the test are still used by many researchers [19,20]. They are based on molding the mortar inside two concentric metallic rings, measurement of the rings deformations and calculation of stress induced in the mortar. They are both quantitative and qualitative methods, allowing to obtain stress, deformations, and patterns of cracks, due to restrained shrinkage. The drawbacks are: for low modulus mortars, like renderings, very large rings are needed in order to have restrained shrinkage stress high enough to produce cracks; very specific equipment is needed; the stress measured is difficult to relate with real stress installed in-service, due to the shape of the specimens.

– **Uniaxial linear restrained shrinkage tests**

These tests are based on moulding a uniaxial specimen inside a device that allows blocking the deformation, and measurement of the force induced by restrained shrinkage [11,21,22,10,2] (Figure 1 a). Free shrinkage can be measured simultaneously in similar specimens. Some advantages of this type of method are: curves force-displacement and force-time can be drawn; restrained shrinkage can be compared with free shrinkage; parameters such as energy of fracture and maximum elongation at rupture load may be determined; due to the simple geometry of the device, the values obtained can be simply related to stress and strain to be obtained in-service. A drawback is that a very specific equipment is needed.

Figure 1 – Restrained shrinkage tests: a) Uniaxial test; b) Slab test

– **Bidimensional restrained shrinkage tests (slab tests)**

These methods [23,24,25] are based on the application of a mortar on a stiff substrate, such as a concrete slab, which simulates the wall that restrains shrinkage (Figure 1 b); the cracks formed are observed and several parameters are measured: time of opening of the first crack; pattern and area of cracking; number of cracks; maximum crack width, etc. These are the tests that better simulate the in-service conditions and they are easy to perform and do not need complex equipment. They allow comparison between different materials, however, they are mainly qualitative, not permitting stress measurement.

Simplified analytical models for predicting the age at cracking, based on elastic modulus, tensile relaxation, shrinkage strain and tensile strength, have also been developed [12].

Nevertheless, studies on cracking have been mainly performed on cement-based mortars. Thus, some of the referred methods may be inadequate for low strength lime mortars.

4. LOSS OF ADHERENCE – CAUSES AND ASSESSMENT METHODS

The adhesion resistance between substrate and mortar is an important mechanical property affected by many parameters such as the roughness of the substrate, the penetration of water and binder into the pores of the substrate, depending on the suction conditions and the porosity of the base. Other parameters such as compaction, curing conditions and design of the mortar are also important. The influence of substrate texture and rheological characteristics of the mortar on the shear and tensile bond strength of mortars on concrete slabs were tested by researchers concluding that the rheology of the mortar is the main factor controlling their bonding capacity [3]. In the case of mortar-brick system, the parameter of the firing conditions of the brick and its role in the adhesion was tested leading to the conclusion that the firing temperature and its microstructure is an important variable influencing the adhesion [26]. Application techniques were also found to be a key factor for good adhesion [27]

A method for determining the adhesion strength between mortar and substrate is described in EN1015-12 and is defined as the maximum tensile strength applied by a direct load perpendicular to the surface of the mortar on a substrate. The adhesive strength obtained is the quotient between the failure load and the test area. It is commonly known as pull-off method and is performed with a pull-off dynamometer specified also in several standards and Guides [28,29,30]. Pull-off is a widespread method (Figure 2 a), easy to perform. However, it has some drawbacks concerning air lime mortars: their tensile strength is very low, and as the test is based on the application of a tensile load, the obtained adhesion values are in the range 0.01-0.10 MPa [31,32], corresponding to applied forces of 20-100 N, which significantly reduce the precision of the method. In fact, pull-off devices commonly available with the best accuracy have capacity until 5000-6000 N, and low sensitivity to small variations of load. Additionally, the load application control is limited. Hence, the accuracy of results for low strength mortars is insufficient. A method based on a tensile load applied on a composite specimen substrate-mortar by a mechanical machine of higher precision and allowing adequate control of load application has been tested and results obtained proved to be more sensitive [31,32] (Figure 2 b). However, this method is not applicable on site.

Figure 2 Adhesion with a) pull-off apparatus and b) tensile machine

5. LOSS OF COHESION – CAUSES AND ASSESSMENT METHODS

The cohesion of lime mortar is obtained by the bond between the binder matrix and the aggregates. Several factors may affect that bond, such as cracking, salts attack, and leaching of the binder. Loss of cohesion can be assessed by different methods such as Shore hardness [33] and peeling method [34, 35] which can be applied in laboratory and *in situ*.

6. STAINS – CAUSES AND ASSESSMENT METHODS

The main responsible for stains on renders surfaces are the deposition of airborne particulate matter, aerosol dry deposition and, sometimes, the irreversible formation of black crusts. Some of the pollutant gases that produce stains present an acidic character (sulfur and nitrogen oxides), so that their interaction with calcium carbonate of the lime-based renders and later formation of soluble salts (mainly sulfates and nitrates) leads to calcium leaching of the renders and a loss of cohesion.

The assessment of the black soiling on surfaces has been carried out by either monitoring the colour changes using a colorimeter [36], or by quantifying the elemental and organic carbon deposited. A method based on combustion/chromatographic determination of CO_2 combined with dissolution after different chemical attacks have been also proposed [37] and tested [38].

Regarding the biological colonization, algae and cyanobacteria are considered as pioneering inhabitants of outdoor exposed surfaces, being able to adapt to a large variety of substrates (stones, mortars, plasters…). For renders, chemical composition and pore structure affect water retention on external surfaces. This allows the growth of algae and cyanobacteria, and subsequently of lichens and moss, thus accumulating large amounts of biological matter.

To assess the biocolonization, Tiano [39] suggests, on one hand, the investigation of biological markers as indicators of the presence of viable micro-organisms. Bioluminescence methods to determine ATP have been proved on stone surfaces [40]. The non-invasive portable fluorescence remote Lidar sensing has been successfully applied to monitor the biodeteriogens on outdoor surfaces [41].

7. CONCLUSIONS

Besides their proved durability along time, lime renders suffer different kinds of anomalies, such as cracking, loss of adherence, loss of cohesion and different kinds of stains due to biocolonization and pollution. Cracks occur in mortars in the fresh state due to plastic shrinkage and in the hardened state due to restrained shrinkage, stress by displacement, freeze-thaw or salt crystallisation. There are methods to measure stress induced by restrained shrinkage and to analyse and identify cracks, both by quantitative and qualitative methods. Loss of adherence is related to the hygric properties of the mortar and is currently assessed by the pull-off test frequently using equipment with low sensibility for the strength of lime-based mortars. Therefore, the tensile load applied on a composite specimen substrate-mortar by a mechanical equipment with higher precision and allowing adequate control of load application seems to be a more suited method. Loss of cohesion of lime renders and plasters can be indirectly assessed by several methods such as the Shore hardness test or directly by the peeling test. Stains have very different causes and different degrees of damaging potential. The assessment can be based on the origin of the stains, with resource to diversified methods, or more simply by measurement of colour changes, when there is no need of evaluating the causes. This review identified needs of research to define and validate adequate methods for assessment of susceptibility to different kinds of degradation mechanisms of lime-based repair mortars for historical renders and plasters, in order to contribute to the selection of durable repair materials.

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