RILEM TC 277-LHS report

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RILEM TC REPORT

RILEM TC 277-LHS report: properties of lime-based renders and plasters—discussion of current test methods and proposals for improvement

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Abstract Renders and plasters have significant functions in buildings. Their functionality is closely related to their properties, which depend on the mortar itself, the application technology, the interaction with the environment and the substrate. There are many basic characteristics that influence the performance of renders and plasters; however, many of them are interrelated, thus the set of characteristics to be determined in each case is different, depending on the specific at each time use. These characteristics, their interrelations and the grouping of them are discussed and schematically described in the first and introductory section. Three groups are considered for renders and plasters: properties of fresh mortars; properties related to the hygric behaviour; and the mechanical behaviour. The properties of lime-based mortars measured in laboratory are highly affected by factors, such as: need of long time for development of representative values for prediction of their life-time behaviour, proper climatic conditions adequate for carbonation or/and hydration, sensitivity to the suction of water by the substrate. The last two factors—environment and substrate—have an important role for rendering and plastering with lime-based mortars, since both their exposed surfaces and the substrate areas they cover are large. Due to those specificities, the current test methods that have been mainly developed for cement-based mortars are not always fitted to characterize lime-based mortars, and in particular to assess lime-based renders and plasters. In section two the main characteristics and current standardized test methods are discussed based on experience in using them. Furthermore, needs of

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improvement are identified and changes are proposed, or, in some cases, new methods are outlined. Some of the most significant changes proposed are the possibility, as an option, to apply the mortar on a porous substrate, instead of moulding specimens in metallic moulds, together with modifications on curing conditions and times of mixing and testing. Additionally, test methods developed at laboratory to evaluate the cracking tendency due to restrained shrinkage and to determine the modulus of elasticity of under checking mortars are proposed, as well as alternative test methods for adhesion. In the case of testing other properties, smaller changes are proposed, in order for the standardized test methods to be adapted to the particularities of lime-based renders and plasters. As conclusions, in the third section, a synthesis of the proposed changes and complementary tests has been made in formulated tables, that could be considered as a first approach of adapted requirements for better performance of lime-based mortars for renders and plasters.

Keywords Render · Plaster · Lime · Test · Mechanical behaviour · Hygric behavior · Fresh state behavior

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1 Introduction

1.1 Framework and definitions

The terms renders and plasters are referred in this article as the constructive elements that cover the external walls (renders) and the internal walls and ceilings (plasters) but also as the mortars that are applied on the masonry to produce the constructive elements. These definitions are consistent with European standards related to these elements [1–3] that define renders and plasters as the materials and also as the functional elements.

Lime-based mortars are defined in the European Standard EN 1015-11 [4], as mortars with mass of lime of at least 50% of the total binder mass and this simple definition is adopted in this article.

Furthermore, lime-based mortars are nowadays mainly used for restoration and lime-based mortars for restoration are described in detail in a previous work, the RILEM TC 277-LHS report “Lime-based mortars for restoration—a review on longterm durability aspects and experience from practice” [5] which includes several categories of binders, such as: air lime as only binder; Natural hydraulic lime; lime and pozzolans; air lime plus a percentage of cement (lower than 30% of the binder, in order to retain the porosity

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and moisture transport properties of the old mortar) and also other mixes of these binders. These categories of lime-based mortars for renders and plasters are also covered by the proposals made in this article.

Renders and plasters have different functions in the building. Both elements have protective and aesthetic functions. However, renders are exterior wall coatings, as such they are exposed to outdoor climatic actions, thus resistance to water penetration and to thermal and hygric variations are of utmost importance, while plasters, being interior coatings for walls and ceilings should also contribute to the comfort and health of inhabitants.

1.2 Main properties of renders and plasters

There are many significant characteristics, with different degrees of importance, for mortars used as renders or plasters [1]. However, many characteristics are interrelated; therefore, even those that seem less relevant may indirectly be very influential. Three interrelation groups may be identified (see Figs. 1, 2 and 3). As such, whenever it is not possible to determine all the properties for a rendering/plastering mortar, some properties of each group should at least be determined, in order for have an indication of the overall behaviour of the material.

Workability is certainly one of the most important properties of fresh renders/plasters in which other properties, such as consistency and cohesiveness, are embodied. It largely depends on the water content, which in the end greatly affects the porosity and also the performance and durability of a mortar in the hardened state. It also depends on the binder; for example, lime putty is widely known for its good plasticity and cohesiveness. The use of some chemical additives[1] to improve workability may reduce the water needed; however, their influence on other characteristics should be checked. In addition to the mixing water, the workability of a fresh mortar also depends on its water retentivity, air content and internal friction of the particles used in the mortar composition. In general, using an optimized packing density of solid materials allows achieving an adequate workability and plasticity of the lime-based mortars, with a reduction of the amount of water required for a given flow consistency. This reduction may also be achieved through the use of fillers and air entraining agents acting as "lubricants", due to decreasing the friction between the largest particles, or by increasing the distance between them [6]. Improving particle packing may also contribute to enhancing the water retentivity of a mortar and increasing its bulk density. The properties of mortars in the fresh state are thus directly related with the amount of water needed for adequate workability, and they determine the microstructure and in particular the porosity of the mortar in the hardened state.

The performance of lime-based mortars in the hardened state is mostly influenced by their porosity and pore structure, which is in turn conditioned by the compactness of the mortar in the fresh state; high compactness leads to a decrease of the capillary rise kinetics and to the development of high compressive strength [7, 8].

The hygric properties in a lime-based mortar are essentially determined by their pore system, in

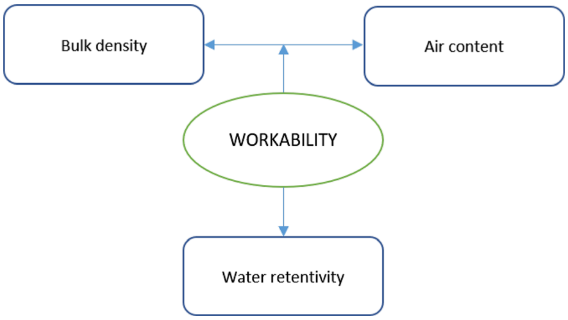


Fig. 1 Properties of fresh mortars for renders and plasters

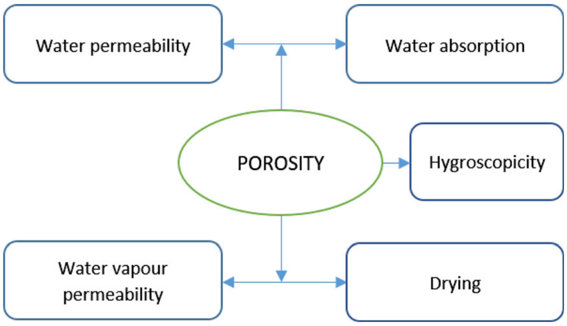


Fig. 2 Properties related to the hygric behaviour of hardened rendering and plastering mortars

[1] The word additive is used in this document according to the definition of EN 16572 Conservation of cultural heritage—Glossary of technical terms concerning mortars for masonry, renders and plasters used in cultural heritage.

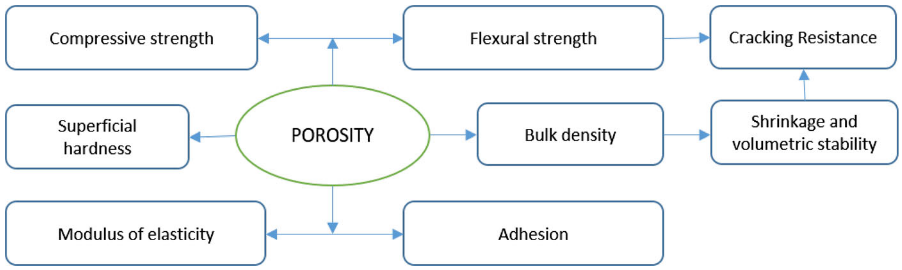


Fig. 3 Properties related to the mechanical behaviour of hardened mortars for renders and plasters

particular by the main pore size, the shape of pores and the interconnection between them (as well as by the total porosity), since these factors mostly determine the amount of water absorbed and the kinetics of absorption/desorption. In general, the higher the connected porosity, the higher the water absorption, while the rate of absorption is highly dependent on the capillary pore sizes. In fact, when the main pore diameter peak is shifted towards a larger capillary diameter range, the rate of absorption increases and, as a consequence, the capillary absorption coefficient is higher [8, 9]. At the same time, an increase in the pore diameter can make lime-based mortars less vulnerable to degradation by mechanisms such as salt crystallization and freeze–thaw [10]. Contrary to liquid transport, water vapour diffusion occurs through the whole range of interconnected pores, including both the small capillary pores and the coarse pores (above the capillary range); therefore, an increase in open porosity leads to higher water vapour diffusion.

Likewise, the mechanical strength of the lime-based mortars is strongly influenced by the volume and diameter of the pores. In general, an increase in volume and diameter in the coarse porosity (> 1 µm), leads to a reduction in mechanical strength [7] and modulus of elasticity, and for renders/plasters applied on a porous substrate, to a reduction in bond extent and bond strength. Conversely, the existence of a certain volume of coarse pores in the mortar tends to mobilize more active pores of the substrate, increasing the bond strength [8, 11]. Shrinkage, which could lead to microcracking, is strongly related to gel capillary porosity. Microcracking may act in opposition to the direct influence of the pore dimensions, reducing the mortars’ stiffness and the mechanical strength, especially the flexural strength.

These relations point out that the pore structure influences both the hygric and mechanical properties in different (sometimes opposing) ways.

There are standardized test methods for determining the aforementioned properties. However, in general these methods were designed for materials other than lime-based mortars and are therefore often not well adapted to their properties, functions and use. Thus, the results may not express the in-service behaviour of lime-based mortars with enough accuracy and they may not give the best information for the design of mortars for the conservation of historical construction.

Besides the properties of the mortar itself, the performance of renders and plasters is highly dependent on their compatibility and interaction with the substrate, as both materials have a large area of contact. So, the substrate should also be taken into account, especially in the case of lime-based renders and plasters designed for conservation purposes. To begin with, the application technique (i.e., preparation and suction behaviour of the substrate, pressure of application, elapsed time between the application of different layers, layer thickness, etc.) influences the need of water for good workability. Furthermore, the porosity and the pore structure of the mortar are modified by the suction of the substrate, thus influencing all the properties of the hardened mortar [12].

The existing standard test methods and the need of improvement for their application for lime- based renders and plasters are analysed for each group of properties in Sect. 2—*Test methods: Needs for improvement,* and they are summarized in Sect. 3—*Synthesis of test methods for lime-based renders and plasters and needs for improvement.*

2 Test methods—Needs for improvement

2.1 Fresh state

2.1.1 Mixing

Base standard to consider

EN 1015-2—*Methods of test for mortars for masonry—Part 2: Bulk sampling of mortars and preparation of test mortars* [13].

Needs for improvement

The time of mixing defined in the standard may be insufficient for lime-based mortars, thus the mixing method must be adjusted, keeping it at low velocity.

Proposal

Allow the possibility of mixing for a longer period. For example: 15 s + 150 s + 30 s.

2.1.2 Workability

Base standards to consider

EN 1015-3—*Methods of test for mortars for masonry—Part 3: Determination of consistence of fresh mortar (by flow table)* [14].

EN 1015-4—*Methods of test for mortars for masonry—Part 4: Determination of consistence of fresh mortar (by plunger penetration)* [15].

Analysis of workability tests for renders and plasters

Workability affects the behaviour of a mortar during its application, working, finishing as well as its long-term behavior. It is greatly influenced by the flow properties of the mortar—its cohesiveness and retention of moisture against the suction of the substrate and evaporation to the environment. The existing standards are usually applied in the laboratory, although the plunger penetrometer can easily be applied in situ and give an estimation on the fluidity of the achieved mixture. The two methods are complementary and may contribute to assess the workability and to decide upon additives, grain size distribution of the aggregates and any materials used for the mix design.

They are of great importance when comparisons are to be made to decide upon different additives. Nevertheless, experience shows that there is a different demand of the consistence based on the use of the mortar in the structure and on the binder. For instance, lime putty mortars can be highly workable even with low fluidity [16], while some natural hydraulic lime (NHL) mortars may need higher fluidity to be workable.

Measuring the workability is a safe way of controlling that the right mix proportions are incorporated. This is of paramount importance, especially when additives/admixtures or new materials are tested in the mortar mixes. Workable mortar clings to vertical surfaces and resists flow during the placement of masonry units and the application of renders and plasters. Achieving the best long-term performance of mortars is strongly affected by this first state of preparation.

Needs for improvement

In EN 1015-3 [14], no limits are given for different mortars produced while 15 strokes proposed by the standard are many for high fluidity mixtures. In the case of EN 1015-4 [15], again, no limits are given for the different mortars produced, whilst mortar mixtures rich in aggregates with maximum size > 4 mm present difficulty in testing workability by plunger penetration [17].

Proposal

To adjust the method of flow table and solve the different demands for consistence values, the proposal is to keep the flow test as described in EN 1015-3 [14], with the following adjustments:

- Add qualitative information to the quantitative flow value, such as: *No significant exudation, segregation or bleeding should be visible after the test*;
- Include qualitative description, such as: *Stiff, fat, lean, sticky, light, smooth.*
- If possible, do a trial application on the real substrate or on a model, to confirm if the consistence is adequate in practice.

Besides the determination of the flow after mixing, another determination should be made 15 min after the first measurement to assure the workable life of the mixture.

Other approaches, such as the plunger test following EN 1015-4 [15], may be more appropriate for in situ testing. However, the same adjustments, concerning qualitative information, description and importance of a trial application should be considered.

2.2 Hardened state—Properties related to mechanical behaviour

2.2.1 Moulding

Base standard to consider

EN 1015-11—*Methods of test for mortars for masonry—Part 11: Determination of flexural and compressive strength of hardened mortar* [4].

Needs for improvement

Most standards on mortars prescribe the use of steel moulds for the production of mortar specimens to assess their physico-mechanical properties. Very often prisms with a size of 40 mm × 40 mm × 160 mm are used; this is certainly common for cement-based mortars, and usually for lime-based mortars similar prisms are used.

A first disadvantage consists in the size, which often does not reflect the size (thickness) in the real application of the mortars: layers of plasters or renders are usually much thinner (and the same applies to most cases of bedding and pointing mortars).

Another important drawback of the use of steel moulds is the fact that suction of water contained in the fresh mortar by the surrounding porous materials does not occur. That may result in completely different microstructure and, therefore, hygric properties of the mortar specimens produced in this way. Porosity and pore size distribution differ, resulting, for example, in a clearly different water absorption coefficient. Also, suction by a porous substrate induces stress on the pores of the fresh mortar, reducing their diameter and producing a more compact mortar; thus, the mechanical properties, such as the compressive strength and stiffness of the hardened mortar may be considerably increased.

Mould with absorbing substrate—Laboratory research (examples)

Three independent researches have been carried out at TNO, LNEC and UCY concerning the comparison of the hygric and mechanic characteristics of lime-based mortars prepared in standardized metallic moulds and on porous substrates. Those experiences are described in detail by Wijffels et al. [18], Veiga and Vilhena [19] and Ioannou et al. [20].

The tests are illustrated in Figs. 4, 5, 6, 7 and 8 and the results are summarized in Table 1.

The results presented in Table 1 point out to an increase of about 60% in the dynamic modulus of elasticity (DME) (only measured in the case of LNEC's experiments) and a reduction in capillary absorption coefficient at the order of 50%, as well as a very significant reduction in porosity. Concerning the compressive and flexural strength, even higher variations were found, namely increases that achieved 300%.

Conclusions on moulding

Three different experiments, carried out in different laboratories by different groups, using several substrates and methodologies, all indicate that mortars applied on a porous substrate show higher mechanical characteristics, lower porosities and lower water absorption coefficients than the same mortars tested as prismatic specimens moulded in metallic moulds.

(a) (b)

Fig. 4 Moulds with absorbing and non-absorbing substrate; the substrate is covered with a filter paper (**a**); filling of the mould (**b**) [18]

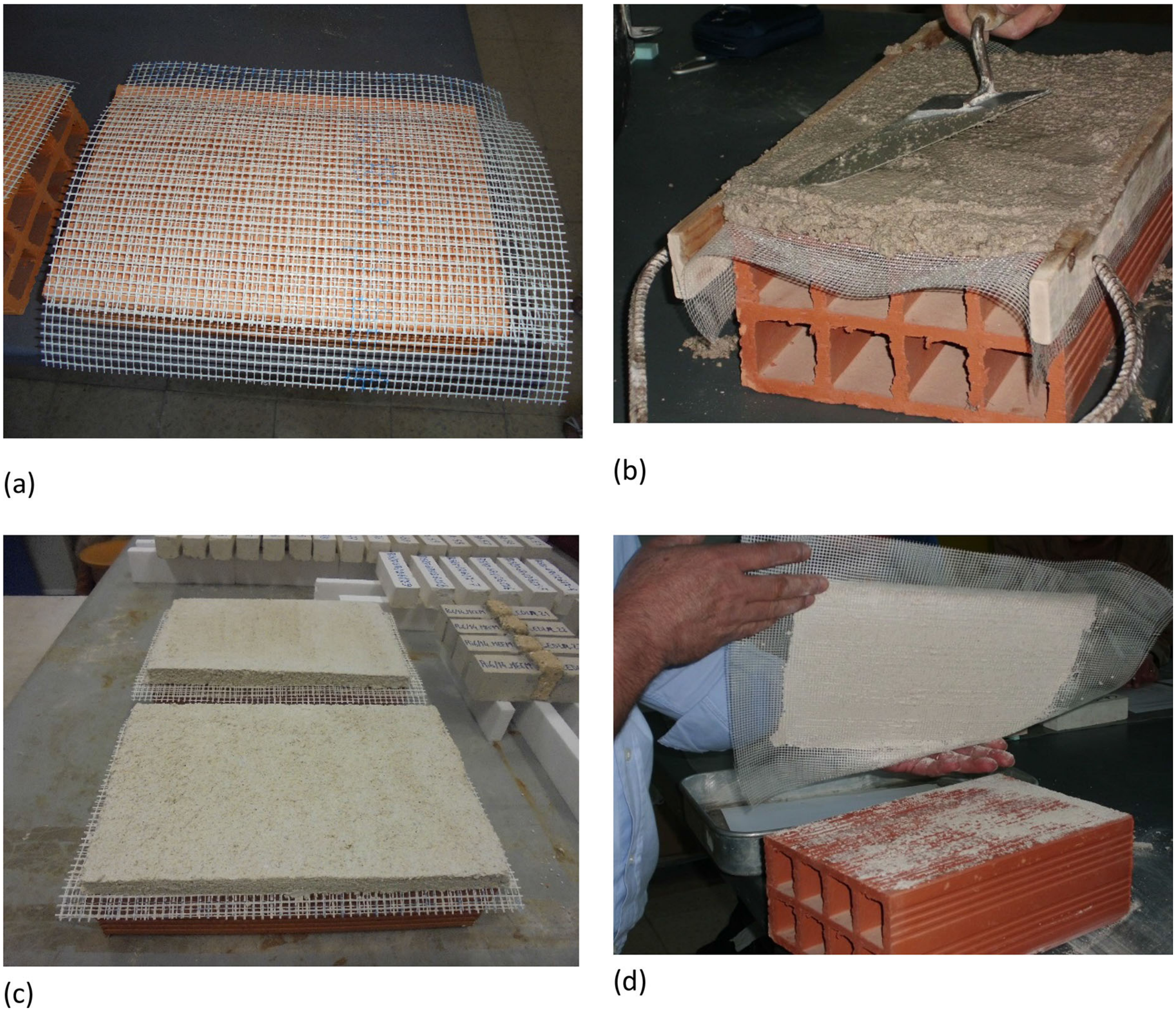


Fig. 5 Application of a rendering/plastering mortar on an absorbent substrate [19]: (**a**) application of a glass-fibre mesh to reduce adherence (to facilitate future detaching) without hindering water suction; (**b**) applying the mortar on the brick porous substrate simulating a render/plaster; (**c**) coating layer (20 mm) of mortar after application on the brick; (**d**) detaching the rendering/plastering mortar specimen layer after hardening

The differences are very relevant, in the order of 50% in the case of water absorption coefficients and 100% for mechanical characteristics. These results are also in accordance with the literature [12].

Proposal

Considering the results obtained, a method, which is alternative to EN 1015-11 [4] is proposed for moulding lime-based mortar specimens for testing their mechanical and hygric characteristics:

- Choose a porous substrate similar to the one that will be used in practice (brick, stone, or other).
- To get shape definition and thickness accuracy, sideway elements could be used. However, those elements should not allow sideward absorption; they can, for example, be made of extruded polystyrene (XPS), maritime plywood or of plastic.
- Characterise the water absorption of the substrate (by capillary water absorption test, by sponge method, or other); in the future, categorisation of water absorption of the substrates may also be established. This measurement and/or categorization are registered to establish the scope of the test.

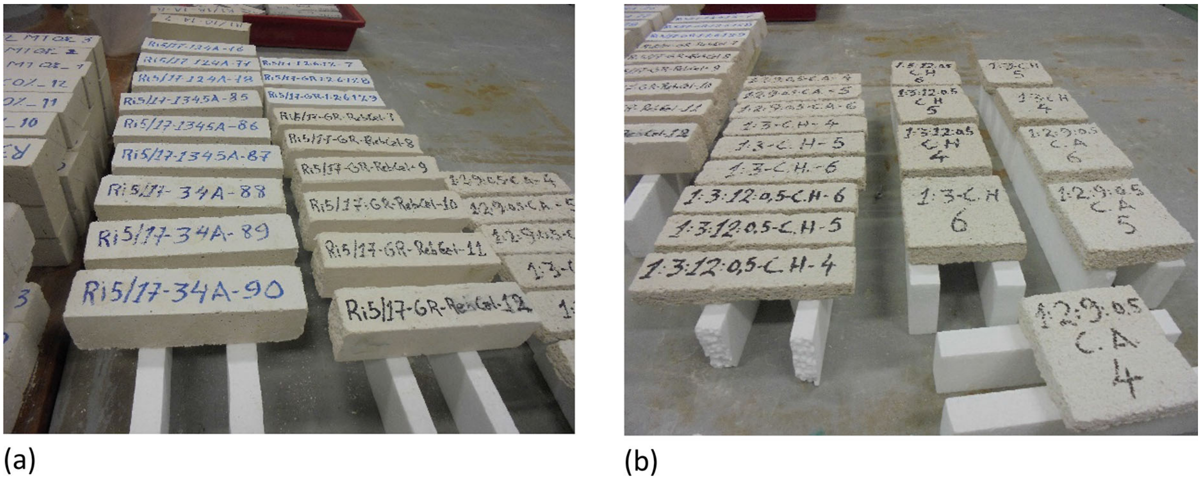


Fig. 6 Rendering/plastering mortar specimens [19]: (**a**) moulded in metallic moulds; (**b**) applied on a porous substrate, after being cut in samples for different tests

Fig. 7 Prismatic limestone moulds with crushed brick-air lime mortar cast in them [20]

Fig. 8 Pilot application of crushed brick-air lime rendering mortar on wallettes constructed of stone (front row) and fired clay brick (back row) masonries

- Apply a mesh or a filter paper on the substrate; the aim is to allow the contact with the substrate and the suction of the fresh mortar, while also allowing to detach the render layer after hardening.
- Humidify the substrate, following the recommendations for the render/plaster to be tested (i.e., sprinkling of water profusely but without saturation).
- Apply the mortar in a 20 mm layer with a trowel, applying some pressure (Fig. 5).
- Curing according to standard or to practice (for example spray with water twice a day).
- Detach the hardened layer after 28 days curing and cut the specimens to carry out the tests on the previously defined ages (Fig. 6).
- For the specimens, use dimensions similar to the standardized tests, except for the thickness, which is the 20 mm previously defined for the coat thickness.

This method should be used in parallel with the standardized moulding method (EN 1015-11 [14]) during a transition period in order to get comparative results. Additional research is needed for better definition of the method. In particular, some issues should be carefully analysed such as the shape and size

Table 1 Average values for rendering/plastering lime-based mortar specimens applied on different substrates

Laboratory	Mortar	Specimens dimensions (mm) / number of specimens	Substrate	Open porosity (% V/V) Average values	WAC ($kg/m^2s^{1/2}$)	Dynamic modulus of elasticity (MPa)	Compressive strength (MPa)	Flexural strength (MPa)
TNO (Wijffels et al.) [18]	1:3 to 1:5 (binder: aggregate) After 28 days	200 × 100 × 20 24 specimens	Non absorbing substrate: extruded polystyrene	33.5	0.062	–	–	–
		200 × 100 × 20 24 specimens	Absorbing substrate: calcium silicate brick	31.8	0.032	–	–	–
LNEC (Veiga and Vilhena) [19]	1:3 (binder: aggregate) at 90 d	160 × 40 × 40 6 specimens compressive str; 3 spec. other tests	Non absorbing substrate: metallic	24.5	0.322	2921	1.0	0.5
		160 × 40 × 20 6 specimens compressive str.; 3 spec. other tests	Absorbing substrate: ceramic bricks	23.5	0.129	4712	4.6	1.8
UCY (Ioannou et al.) [20]	1:3 (binder: aggregate) at 28 d	160 × 40 × 40 6 specimens compressive str.; 3 spec. other tests	Non absorbing substrate: metallic	Higher porosity than in absorbing moulds-	Higher WAC than in absorbing moulds-	–	2.1	0.9
		160 × 40 × 40 6 specimens compressive str.; 3 spec. other tests;application on a Wallette	Absorbing substrate: limestone and bricks	Lower porosity than in the previous	Lower WAC than in the previous	–	4.0	1.1

WAC—Water absorption coefficients by capillarity effect [21] and the effect of the anisotropy of the specimen created by the fact that one face is exposed to the air and the other one adherent to a substrate. However, renders and plasters are applied in thin coats on the masonry, hence specimens thinner than the standardized 40 mm × 40 mm section prisms and with one face previously submitted to the absorption of a porous substrate are realistic conditions for mortars with these functions.

2.2.2 *Curing*

Base standards to consider

EN 1015-11—*Methods of test for mortars for masonry—Part 11: Determination of flexural and compressive strength of hardened mortar* [14].

Needs for improvement

The existing curing conditions: 20 °C/95% RH for 7 days and 20 °C/65% RH after 7 days, are not appropriate for all lime-based mortars. For example, pure air lime mortars will not begin carbonation with 95% RH, while lime-pozzolan and NHL mortars may need a longer period of humid curing.

In fact, the carbonation reaction requires the contact of the mortar with CO_2 and also needs a certain degree of humidity in order to enable the dissolution and transport of the gas; on the other hand the mortar pores should not be saturated to guarantee conditions for the diffusion of the CO_2 water solution into the mortar pore network. So, according to several studies [22–27] the adequate moisture conditions are intermediate, approximately in the range 40% RH–80% RH, with moderate temperature. It is also known that the moisture variations, namely wet-dry cycles, contribute to accelerate carbonation.

Proposal

In the case of mortars with air lime as the only binder, the period of conditioning at 20 °C/95% RH may be reduced, as very limited carbonation will occur with such high relative humidity. As an alternative, the use of more appropriate curing conditions may be used, as long as they are reproducible on site, such as moderate moisture (e.g. 75% RH, or cycles of humid/dry or simply use 20 °C/65% RH during the entire curing period).

The time for demoulding should be adapted to the binder type: between 3 and 7 days for lime-based mortars.

2.2.3 *Free shrinkage*

It is an indicative characteristic that may assist in the evaluation of cracking behaviour and it may be useful for comparison between different mortars, to choose aggregates or additions.

Base standards to consider

prEN 1015-13:1993—*Methods of test for mortars for masonry. Determination of dimensional stability of hardened mortars* [28].

EN 12617-4:2002—*Products and systems for the protection and repair of concrete structures—Test methods—Part 4: Determination of shrinkage and expansion* [29].

The method described in prEN 1015-13 [28] is based on the measurement, using an apparatus provided with length gauges, of the length variation of prisms with 160 mm × 40 mm × 40 mm dimensions, during drying, since their demoulding, for at least 91 days (or when the length variation due to shrinkage is considered negligible).

EN 12617-4 [29] prescribes two methods, one is to measure the unrestrained shrinkage (or also to measure expansion after immersion in water), from 24 h until 56 days, and the second one to measure the restrained shrinkage based on loss of adhesion and tendency to crack, when applied on a reference substrate and subjected to shrinkage or expansion.

For the unrestrained shrinkage test, the specimen dimensions and the basic procedure of EN 12617-4 [19] are similar to those proposed by prEN 1015-13 [28], although there are differences concerning curing, times and some other aspects.

On the other hand, the restrained shrinkage test is, in fact, a test of susceptibility to cracking and as such it will be discussed in the next section (2.2.4).

Needs for improvement

The standardized methods to measure free shrinkage evidence an important drawback for lime-based mortars: the initial measurement is after demoulding. As lime mortars have slow hardening, demoulding takes place a few days after moulding. In addition, lime mortars need a significant amount of mixing water to become workable and most of that water evaporates, producing shrinkage, during the first days. Thus, the initial length measurement, which is considered the zero point, is in fact made after a large part of the shrinkage has occurred and the values obtained in the following measurements may not be representative of the total drying shrinkage.

Proposal

To overcome the aforementioned main drawback, it is possible to adopt one of the following procedures:

Method 1:

- Measure the specimen just after demoulding with callipers and register the difference between the length value obtained and the prismatic mould dimension (as referred by 20-DIN 18947 [30]): ΔL0.
- Measure the following length variations ΔLi as described in prEN 1015-13 [18] or in EN 12617-4 [29] (unrestrained shrinkage method) and add the registered initial value obtained: ΔL0 + ΔLi.
- Determine shrinkage as the ratio of the total length variation to the mould length dimension: (ΔL0 + ΣΔLi)/L

Method 2:

- Prepare a specimen in a mould without bottom, on a low-friction substrate, in order to allow free shrinkage.
- Place fixed points in the specimen and measure the distance variation between them, since moulding until shrinkage is considered stabilized.

A variation of this Method 2 is presented by De Vekey et al. [31], in which water absorption by the substrate is allowed and the measurements are made with a microscope, by photographic documentation, or with callipers.

Another variation is presented by Veiga et al. [32], where a non-absorbing substrate is used to maximize shrinkage and the measurements are made with LVDT at the edges of the specimens (Fig. 9).

2.2.4 *Susceptibility to cracking due to restrained shrinkage*

Base standards to consider

EN 12617-4:2002—*Products and systems for the protection and repair of concrete structures—Test methods—Part 4: Determination of shrinkage and expansion* [29].

There is no specific standard to evaluate the cracking behaviour of rendering and plastering mortars. However, this is a very important issue because cracking may significantly affect the performance of renders in use, allowing easy water infiltration, reducing durability and ruining the aesthetics. Thus, an adequate methodology should be considered.

The restrained shrinkage test described in EN 12617-4 [29] is, in fact, a test of susceptibility to cracking. It is based on the application of the mortar on concrete slabs, followed by the storage of the specimens in environmental drying shrinkage conditions—20 °C/60% RH—or, in the case of expansion evaluation, in water immersion. After 56 days of storage, the specimens are inspected to verify the existence of cracks or delamination and pull-off tests are performed, to evaluate the possible loss of adhesion.

Causes of cracking

Cracking may affect the functionality of the render causing it to ultimately become unable to protect the substrate from water and aggressive solutions,

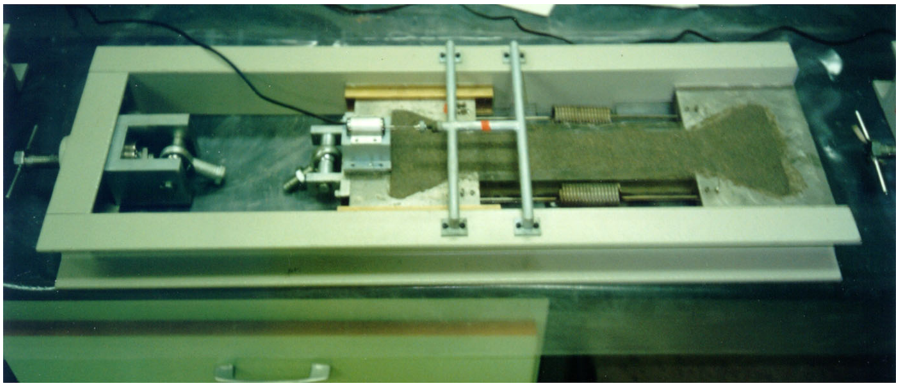


Fig. 9 Apparatus prepared for a free shrinkage test based on measurements of dimensional variations of the edges of the specimen with an LVDT. The equipment allows free displacement of the unfixed head of the apparatus (designed with negligible friction) [33]

essentially reducing the durability of the masonry. It may also result in loss of aesthetic function.

Cracking is caused when the stresses (usually tensile), reach or exceed the strength of the mortar. The stresses are often induced by the drying shrinkage of the mortar, restrained by the adhesion to a stiff substrate. Thermal and hygric volume variations restrained by the substrate are usually added to restrained shrinkage. Other causes may be added, in some cases depending more on the substrate characteristics or on other exterior causes than on the mortar itself: movements of the substrate that are transferred to the render; heterogeneous substrates, composed by different materials, with differential deformations that are transmitted to the render; volume increase of products inside the porous structure, such as water (freeze–thaw), salt solutions (dissolution-crystallization) or the formation of expansive compounds.

This section deals with cracking due to restrained shrinkage which is a significant problem for renders and plasters, due to their large exposed area, which enhances drying shrinkage, and the consequences of cracking concerning their functionality (Fig. 10).

The ability of the render to accommodate stress without cracking depends on: (a) the magnitude of the stress; (b) the ductility of the mortar and in general 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 due to restrained deformations is often not instantaneously induced in mortars; on the contrary, it is slowly induced and shrinkage occurs over several days or months after the initial application, with increasing values; thermal and hygric variations follow the rhythm of the weather changes. This slow stress induction allows for relaxation and creep phenomena to have a positive role in reducing the crack susceptibility [32–36].

Most tensile stress is transmitted through the substrate: shrinkage produces stress because the substrate restrains deformation; thermal and hygric differential variations between the render and the substrate are causes of stress. Hence, adhesion to the substrate is an important parameter. In fact, poor adhesion hinders stress transmission and causes stress concentration in some areas, which is a cause of cracking.

Considering all those aspects, to minimize cracking, an ideal mortar should have simultaneously the following characteristics: (1) low modulus of elasticity; (2) high ductility; (3) high relaxation and creep ability; (4) high tensile strength; (5) low shrinkage; (6) high adhesion to the substrate; (7) thermal and hygric dilation coefficients similar to the substrate. In fact, many factors are involved, their interrelation is complex and some of them are even contradictory—for example factor 4 is contradictory to 1, 2 and 3; 6 is generally contradictory to 1.

The definition and validation of a reliable test for the assessment of the cracking behavior of rendering mortars, considering the most significant factors, is then needed.

Assessment methods from the literature

A short review of the methods found in the literature to assess the cracking susceptibility of mortars is presented in [37]. They may be grouped, as following:

- Determination of ductility—energy of rupture, deformation in rupture using flexural strength test with:
  - Determination of the curve force–elongation and calculation of the energy of rupture;
  - Indentation to localize and favour cracking.

Cracking susceptibility has been related to ductility since a long time [23]. Based on this idea, recent studies have used the three-point bending test, subsequently analysing the force–displacement curve [38], sometimes with a crack artificially produced at middle span [39, 40]. The advantages of these methodologies are that they are easy to perform, do not need special equipment and give quantitative information. A disadvantage is the fact that the obtained values are merely comparative and cannot be directly related with in-service stresses. However, it is possible to establish a classification with some additional work.

An application of this method, also adding other parameters related to ductility, is presented in [40].

- Ring tests
  Ring tests [34, 41] are among the oldest quantitative tests developed with the aim to determine stress due to restrained shrinkage [34, 41–44]. Different variants of these tests are still being used by many researchers [45–47]. They are based on moulding the mortar inside two concentric metallic rings, measurement of the ring's deformations and calculation of the stresses induced in the mortar.

(a) (b) (c)

Fig. 10 Different examples of cracking problems due to restrained shrinkage in lime-based renders. (**a**) cracking of a thin finishing coat producing fine cracks on the thin coat very visible due to the finishing colour; (**b**) cracking of the render favouring the rainwater penetration and as a consequence the development of biological colonization; (**c**) cracking of a thick coat of render together with loss of adhesion due to the high stresses of restrained shrinkage

Qualitative results are also obtained, such as patterns of cracking, age of crack, number and width of cracks. There are many versions of these methods, concerning the parameters used, the shape (usually circular rings are used, but there are studies with elliptic rings) and the dimensions. The most used diameters are between 0.20 and 0.50 m.

The ring tests are both quantitative and qualitative, allowing to obtain stress, deformations, and patterns of cracks due to restrained shrinkage. The drawbacks are: (i) for low E-modulus mortars, like renders, very large rings are needed in order to have a restrained shrinkage stress high enough to produce cracks; thus, very specific, rather complex equipment is needed; (ii) the stress measured is also difficult to relate with real stress in-service, because the shape of the specimens is very different from the real one.

- Uniaxial restrained shrinkage tests

These tests are based on the moulding of a uniaxial specimen inside a device that allows blocking the deformation, and measuring the force induced by restrained shrinkage [32, 33, 48–51] (Fig. 11). Free shrinkage can be measured simultaneously in similar specimens. The specimens used have different dimensions, depending on the use of the mortar, but 0.40 m is the adopted length in several studies. Some advantages of these methods are: curves showing force–displacement and force–time can be drawn (Figs. 12, 13); 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 with the stress and strain to be obtained in-service. As a drawback, the equipment needed is very specific and has some complexity.

- Bi-dimensional restrained shrinkage tests (slab tests)

These bi-dimensional restrained shrinkage methods [34, 48–52] are based on the application of a mortar on a stiff substrate, such as a concrete slab, which simulates the wall that restrains shrinkage (Fig. 14a). The cracks formed are observed and several parameters are measured: time of opening of the first crack; pattern of cracking; area of cracking; number of cracks; maximum crack width, etc. The dimensions of applications on slabs are very diversified. Some indicative dimensions used are: 1.00 m × 1.00 m × 0.02 m; 0.32 m × 0.25 m × 0.04 m.

These tests simulate the in-service conditions, they are easy to perform and do not need complex equipment. They allow comparison between different materials; however, they are mainly qualitative and do not allow stress measurement. The main drawback is the need of large areas to be representative. The mortars may also be applied on site, on a test panel, which may solve the drawback of large area needed (Fig. 14b).

The method described in EN 12617-4 [29] for the restrained shrinkage test can be included in this type of test, using concrete slabs of 300 mm × 300 mm × 100 mm as substrate, and including some additional improvements, namely the quantification of the loss of adhesion.

Fig. 11 Uniaxial restrained shrinkage test

Proposal

The method to choose should be relatively simple to perform but allow some quantification. It should also permit comparison between mortars with different (lime-based) binders. Thus, the following methods are recommended:

Method 1—Unidimensional restrained shrinkage test

This method is described in [51]. It consists of restraining the shrinkage deformation in unidimensional mortar specimens, since the moment of moulding until relative stabilisation takes place, and measuring the tensile stresses developed (Fig. 15).

Dogbone specimens are used because they optimise conditions for tensile tests. The thickness adopted for the specimens is 20 mm, due to being a representative thickness for common render coats applied on external walls.

The moulding may also be done in contact with a porous substrate, but with a mesh that reduces adhesion and allows stress transmission to the sensors.

Force/time curves—F(t)–are plotted from the restrained shrinkage tests, with a maximum value identified as Fm (Fig. 12a).

At the ages of 28 days (for lime-based mortars), a tensile test is performed on the specimens submitted to restrained shrinkage. Force/displacement curves are plotted from the tensile tests, with a maximum value Rt corresponding to the tensile resistance.

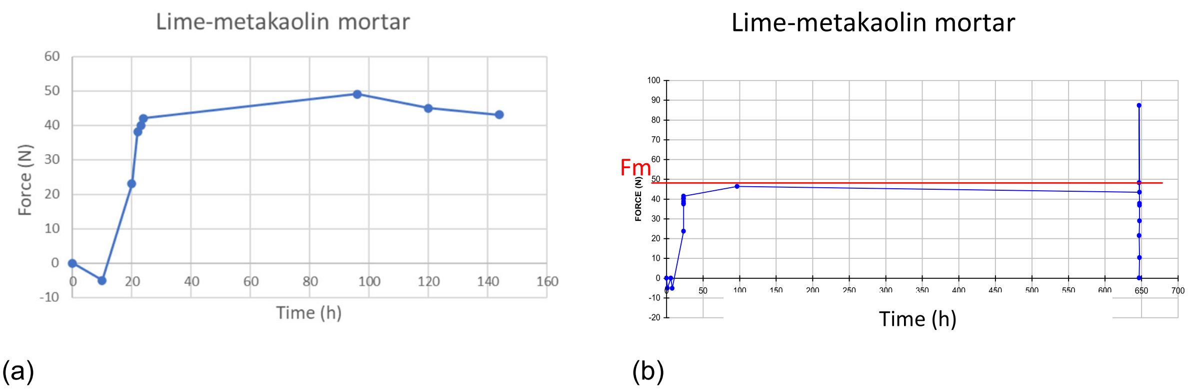


Fig. 12 Force–time curve for a lime-metakaolin mortar (lime-MK:sand volumetric proportions 1:0, 10:3): (**a**) restrained shrinkage test for 28 days, with Fm (maximum restrained shrinkage induced force) indicated; (**b**) tensile test after restrained shrinkage for 28 days with Fm and Rt (rupture force) indicated [51]

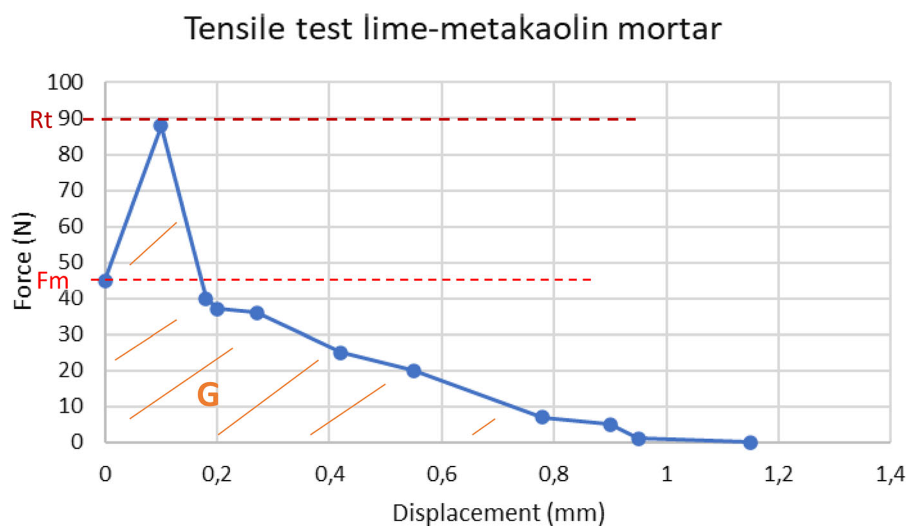


Fig. 13 Force–displacement curve of a tensile test after a restrained shrinkage test for a lime-metakaolin mortar (lime-MK:sand volumetric proportions 1:0, 10:3) with indication of G (rupture energy) [51]

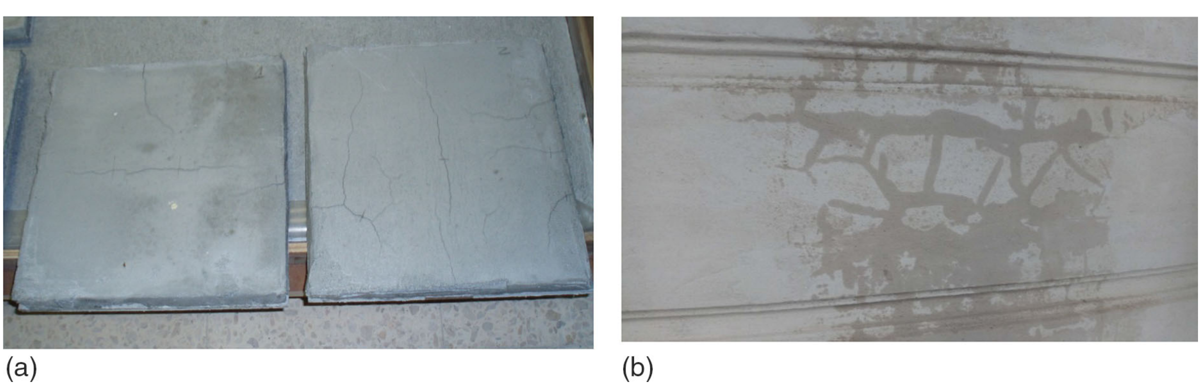


Fig. 14 Restrained shrinkage test: (**a**) Slab test and (**b**) cracking tendency of a lime mortar applied on a brick wall

Fig. 15 Set of restrained shrinkage apparatus during a test

The quantified data obtained with this test allow two types of classification: (a) Classification of cracking susceptibility and (b) Classification concerning mechanical compatibility with the substrate, based on the stresses transmitted to the substrate.

For the classification of cracking susceptibility, two parameters are defined:

The first one is the safety coefficient to the opening of the first crack, the S parameter, defined as S = Rt/Fm, with: Rt—Tensile resistance; Fm—Maximum measured force during restrained shrinkage.

The first crack opens if $S < 1$.

The second criterion is energy related and is quantified by the resistance coefficient to cracking evolution, defined as $R = G$/Fm, with G—Rupture tensile energy; Fm—Maximum measured force during restrained shrinkage.

A classification based on the referred criteria is presented in Table 2 [33, 51, 56].

For the assessment of lime-based mortars for renders of ancient buildings, besides S and R and the susceptibility to cracking classification, other values are also relevant: the maximum force (Fm) induced by restrained shrinkage is very relevant for compatibility assessment, because it gives a scale of the forces that can be transmitted to the substrate contributing to its deterioration; the rupture energy (G) (Fig. 13) is also of major importance, because it measures some deformability before rupture, and ancient walls, having structural functions as well as fulfilment and protection functions, are submitted to deformation and require adaptable renders.

Table 2 Classification of cracking susceptibility based on S and R coefficients for general buildings

Cracking susceptibility class	S	R (mm)
1 (Low cracking susceptibility)[a]	≥ 1	≥ 1
2 (Medium cracking susceptibility)[a]	≥ 1	≥ 0.6 and < 1
3 (High cracking susceptibility)[b]	< 1	< 0.6

[a]It must satisfy both conditions

[b]It must satisfy one of the conditions

Considering these specific requirements of renders for historic buildings, another performance classification, adequate for compatible lime mortars, was established, as presented in Table 3.

The compatibility criteria are defined to avoid that the new material produces damage in the historic materials, in this case, to avoid that the new repair render/plaster deteriorates the old substrate. For this it

Table 3 Classification of mechanical compatibility

Mechanical compatibility class	Fm (N)	G (N mm)	S	R (mm)	Interpretative notes
Compatible	< 70	> 40	> 1.5	≥ 0.7	All criteria fulfilled
Limited compatibility	< 100	–	> 1.0	≥ 0.6	–
Non-compatible	≥ 100	–	< 1.0	< 0.6	At least one criterion fulfilled

is important that the forces transmitted by the mortar (Fm) are lower than the resistance of the masonry to traction and to friction. It is also needed that the render/plaster may follow the deformations of the substrate, which are usually higher than modern masonry, due to more deformable materials and also to higher stresses as a consequence of being structural elements. The rupture energy to traction (G) is an interesting parameter to assess the latter property, as it measures the deformation ability before rupture. The limit values of the referred characteristics depend on the substrate itself; however, the aim of the test is to classify the mortars independently for an average old masonry substrate. The limits proposed are not rigid and should be considered as a whole.

This method has been developed and previously published in [51].

The main drawback of this test is that it requires specific equipment, with some complexity.

Method 2—Bi-dimensional restrained shrinkage test

A test based on EN 12617-4 [29]—restrained shrinkage method—could be adopted, albeit with adjustments.

The main adjustment should be the type of substrate: instead of the concrete slab proposed by the standard, a more porous substrate should be used. A composite substrate composed of two (or three) porous ceramic bricks with large lime mortar joints (Fig. 16) is proposed.

The lime mortar to be tested is applied on the composite substrate and exposed to dry curing conditions, for example 20 °C/50% or 65% RH.

2.2.5 *Modulus of elasticity*

Dynamic Modulus of elasticity

Base standards to consider

Test methods for dynamic modulus of elasticity based both on resonance frequency [57–59] are adequate for lime-based mortars.

EN 14146—*Natural stone test methods. Determination of dynamic modulus of elasticity (by measuring the fundamental resonance frequency)* [57].

EN 12504-4—*Testing concrete in structures. Determination of ultrasonic pulse velocity* [58].

EN 14579—*Natural stone test methods. Determination of sound speed propagation* [59].

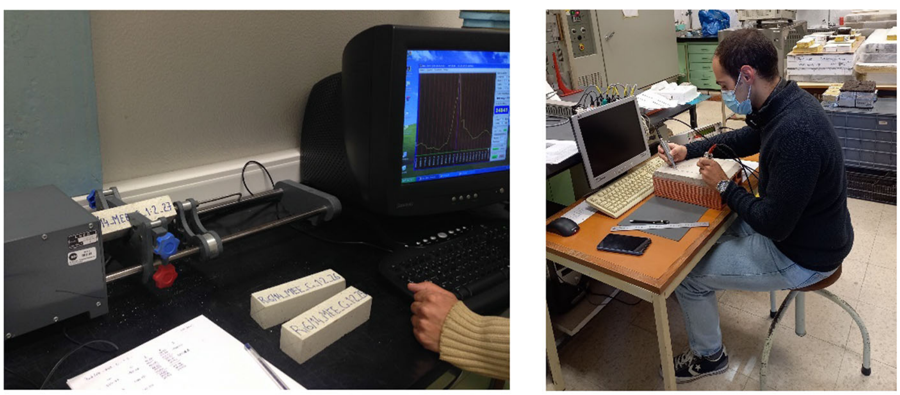
Proposal

The method of frequency of resonance may be used, as described in EN 14146 [57]. Standard prismatic mortar samples are needed (Fig. 17a), and their weight and dimensions have to be determined. With those values, the apparent bulk density of the rendering/plastering mortars can be determined.

For the ultrasound method, it is proposed to use the indirect method and draw a trend line of several measurements, the slope of which should be the velocity of ultrasound pulse (Fig. 17b). The dynamic modulus of elasticity is then calculated accordingly. Usually, Poisson's Coefficient for rendering mortars ranges between 0.20 and 0.25, therefore it can be assumed so for the following calculation of the dynamic modulus of elasticity. Conversely to the direct method, this method also gives information about the existence of cracks or other discontinuities and has better sensitivity to the heterogeneities of mortars; Moreover, it can be used on a mortar applied on a substrate and even in situ, which makes it a very useful method for renders and plasters. Samples with surface dimensions of at least 100 mm × 50 mm are needed. The frequency of the transducers used should be in a range between 20 and 150 kHz.

Consider moulding and curing conditions, as referred in 2.2.1.

Fig. 16 Porous composite substrates of ceramic brick and lime mortar and application of lime mortar on them



(a) (b)

Fig. 17 Measurement of dynamic modulus of elastic (**a**) by Frequency of resonance on a prismatic specimen (**b**) by ultrasound impulse velocity on a specimen of an applied render (indirect method)

It is important to take into account that for the determination of dynamic modulus of elasticity using any of the above-mentioned test methods, the specimens must be dry. This means enough curing time (28 days or more is adequate) should be allowed and the specimens should reach a constant mass in a relatively dry environment, such as 23 °C/65% RH.

Static modulus of elasticity

The static modulus of elasticity can also be measured, using improved methods for the measurement of deformations [60]. It may not be needed for characterization but may be important for modelling purposes.

The comparison included in Marques et al. [60] of the static E-values with the dynamic modulus of elasticity, both by the frequency of resonance method [57] and by the ultrasonic pulse velocity method [58, 59], by direct and indirect methods, indicates that the three methods give good quality and reliable values.

As expected, the values of the dynamic modulus of elasticity measured by different methods—frequency of resonance method [57] or ultrasonic pulse velocity, determined both by direct and indirect methods [58, 59]—are very similar. On the other hand, the static modulus is lower than the values obtained by the dynamic methods, with a ratio between $E_{dynamic}$ and E_{static} varying between 1.1 and 1.5, depending on the ranges of values (1.1 for lower values and a higher ratio for higher values of modulus of elasticity).“

Proposal

Use the method described in [60]. The experimental methodology proposed aims to improve the reliability of the collected data and solve issues related to internal defects and overall geometry of the specimen. It is based on a standard cyclic compression test for concrete specimens, according to the standard ISO 6784 [61], complemented with the application of some measures designed to solve the reported problems of low accuracy:

- Use of a measuring device equipped with two displacement transducers (Fig. 18a), which integrate a larger specimen length than more common solutions like strain gages, to obtain more reliable strain data.
- Use of pressure screws, applied on the specimen against reinforced areas, to allow moving the device without damaging the specimen.
- Establishment of adequate criteria to gauge specimen quality regarding geometric and volumetric defects.
- Application of a revised experimental testing methodology, based on the previous concepts, consisting on the application of an initial small load, followed by one cyclic compression test on the specimen up to 0.33 of its σ_c, to make sure that any internal voids and gaps are closed; finally, without fully unloading the specimen, another cyclic compression test comprising three loading cycles is performed, again up to 0.33 of the specimen's σ_c. This series of three loading cycles provides the data to define stress–strain curves and calculate the specimen's E value (Fig. 18b).

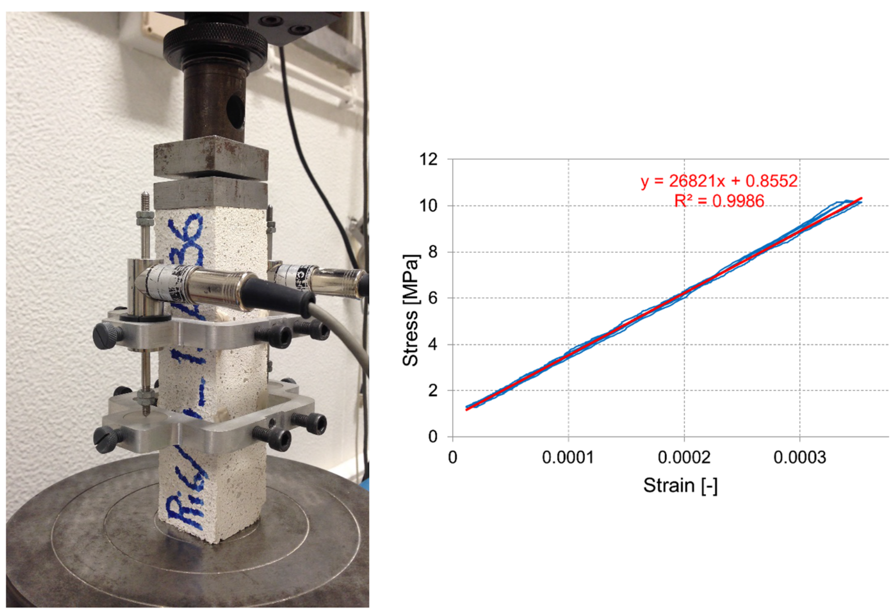
2.2.6 *Adhesion to the substrate*

Base standard to consider

EN 1015-12—*Methods of test for mortars for masonry—Part 12: Determination of adhesive strength of hardened rendering and plastering mortars to the substrate* [62].

Analysis of adhesion tests for renders and plasters

The pull-off method for determining the adherence of renders and plasters is described in EN 1015-12 [62]



(a) (b)

Fig. 18 Static modulus of elasticity [60] (**a**) Instrumented test specimen for a static E test; (**b**) average stress–strain curve and is similar to methods used for other elements of construction. It consists of applying the mortar on a common substrate, cutting a circular area (before or after hardening), gluing a circular metallic plate with the same dimensions, and applying a tensile strength until the cut circular area is separated from the substrate. However, for lime-based mortars, this method may, sometimes, be difficult to use, because the vibration of the drilling machine may be enough to detach weak mortars, or to significantly interfere with their adhesion. Another limitation of the pull-off method is that, for low strength lime-based mortars, the adhesion values are very low (or even displaying zero values for most determinations); thus, the pull-off values have very low accuracy, which makes it unable to distinguish between different cases.

So, whenever the standardized method is not adequate, other methods are recommended.

Method 1—Four-point flexural strength method

The four-point bending test method, described in [63] and illustrated in Fig. 19a and b, uses mortar specimens applied on a stone substrate, with dimensions 40 × 40 × 170 mm. The stone faces are firstly incised by special mechanical tools to provide a rough surface; the mortar is then applied to the sectioned stone surface and the stone pieces are placed levelly with the aid of special joint clamps. The loading forces are applied only on the stone pieces and not on the mortar. The tests are conducted using displacement control, with a displacement rate of 0.02 mm/s. The loading pins are supported by a spring mechanism, so no pre-loading is applied to the specimen. A variation of this test is performed as a direct tensile test, as illustrated in Fig. 19c, also using displacement control with a displacement rate of 0.02 mm/s.

Method 2—Direct tensile strength method

The method described in [11] consists of applying the lime-based mortar to be studied, with a thickness of 20 ± 2 mm (based on the average thickness usually applied in practice), on a porous ceramic brick piece of surface dimensions 6 × 6 cm, with a resource to a mould in order to get a flat surface. After 90 days of the mortars' application, in order to ensure a good carbonation and an improvement of the properties of the lime-based mortar, two metallic plates (60 × 60 mm) are glued, with an epoxy glue (or a thermoplastic hot glue), on each side of the sample (Fig. 20) and connected to an electromechanical

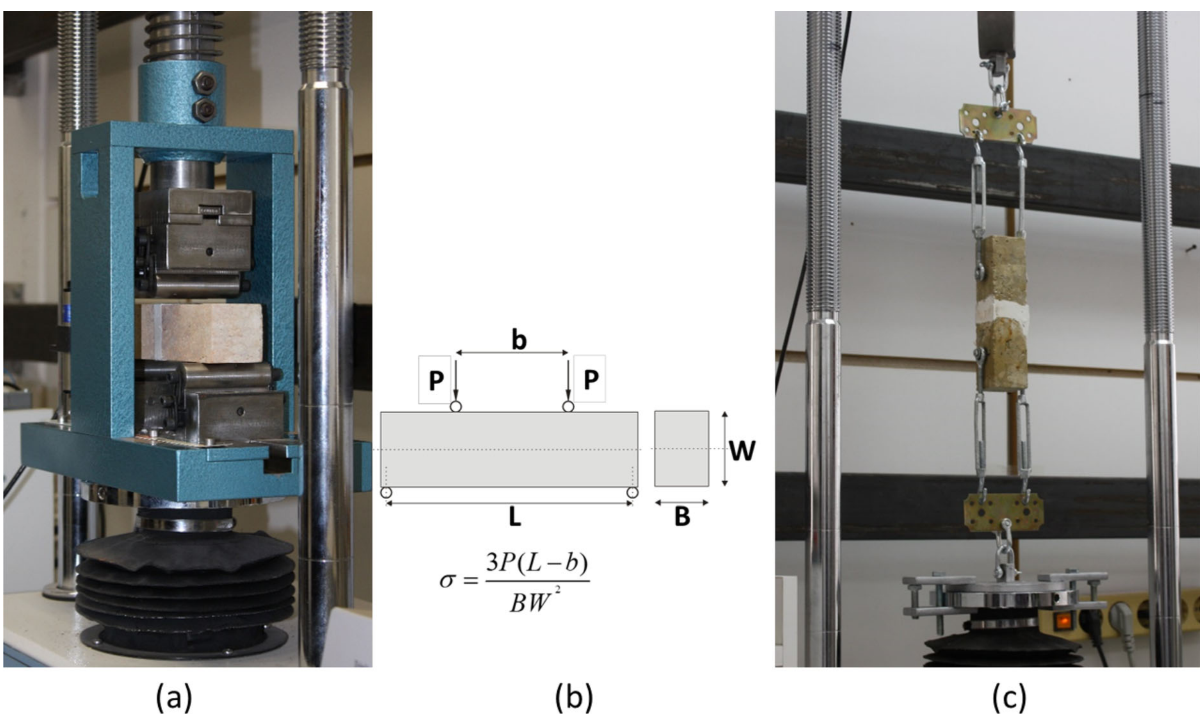


Fig. 19 (**a**) Four-point bending apparatus with variable support spans; (**b**) geometry and calculations for four-point bending test; (**c**) direct tensile test apparatus for stone mortar specimens

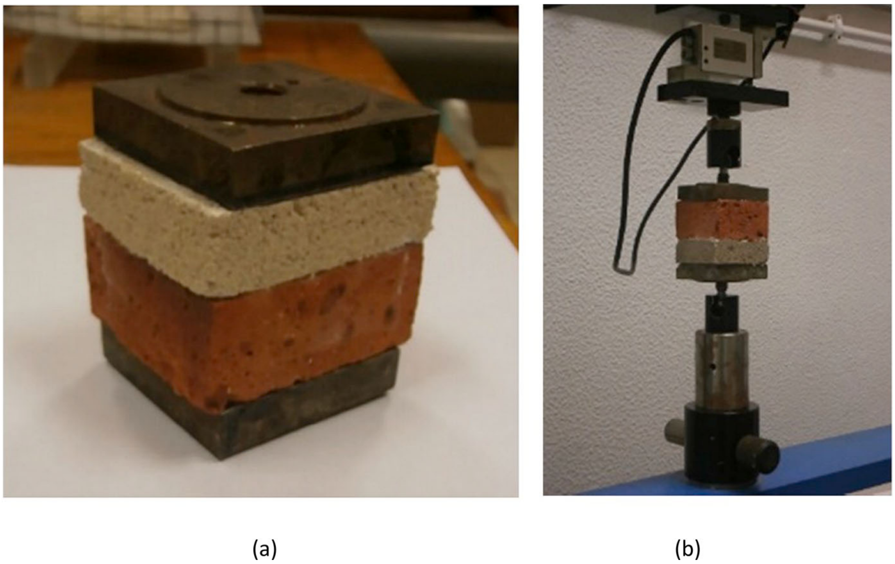


Fig. 20 Tensile bond strength test for lime-based mortars: (**a**) composite specimen prepared for testing with about 20 mm thickness and 60 mm × 60 mm surface dimensions; (**b**) test set-up

tensile testing device. A constant tension of 5 N/s is applied on the plates until failure of the system.

The experimentally measured adhesion strength (σ, in N/mm^2) of the specimens is determined using the equation $\sigma = F/a$, where $\boldsymbol{F}$ is the failure load, in N, and $\boldsymbol{a}$ is the test area of the specimen (mm^2). A minimum of three samples per mortar should be tested and the failure is classified as adhesive (A) when it is located on the substrate/mortar interface, and cohesive when located in the core of the mortar (CM) or substrate (Cs). The standard deviation must not exceed 0.03 MPa.

In [11] the results of the method are compared with the results of bond strength by the method of EN 1015-12 [62]. It is found that the average values obtained are rather similar; however, with the direct tensile method the variation coefficient is much lower (29% versus 73%) and null values are eliminated.

Method 3—Modified pull-off test

A modified pull-off method to evaluate the bond strength of air lime-based composites is described in [64]. The proposed non-standard test procedure is a modification of standard test method EN 1015-12 [62]. The first modification is eliminating drilling, which damages the bond between render/plaster and substrate, that is also admissible by the standard when the cut is made in the fresh render/plaster sample. The second modification is an increased diameter of the circular pull-head plate equal to 100 mm.

The procedure consists of casting the lime-based mortar to be studied, with a thickness of 20 ± 2 mm, on 100 mm diameter cylinders drilled from masonry units under consideration, such as brick or stone. The lime-based mortar to be studied is applied to the substrate using a mould without bottom previously placed on the cylinder (see Fig. 21a). Casting of the mortar is carried out using a small (conservation) spatula for applying adhesives, in two layers. Each layer is consolidated by using a tamper described in EN 1015-3 [14]. Testing is performed to the composite sample (Fig. 21b) at the age of 90 days or higher.

On the day of testing, a circular pull-head aluminum plate disk (diameter 100 mm and height 50 mm) is glued to the upper surface of the lime-based mortar using thermoplastic hot glue (air lime mortar) or epoxy glue. The test sample is inserted into a specially prepared metal frame that enables adequate clamping of the sample substrate (Fig. 22a) and the pull-off test is performed (Fig. 22b).

Test results obtained show much higher bond strength of the lime-based mortars to the substrate than results of the pull-off tests according to EN 1015-12 [62] for the same mortar composition.

Proposal

For low strength mortars, such as pure air lime mortars, a more sensitive method is recommended, such as one of the following:

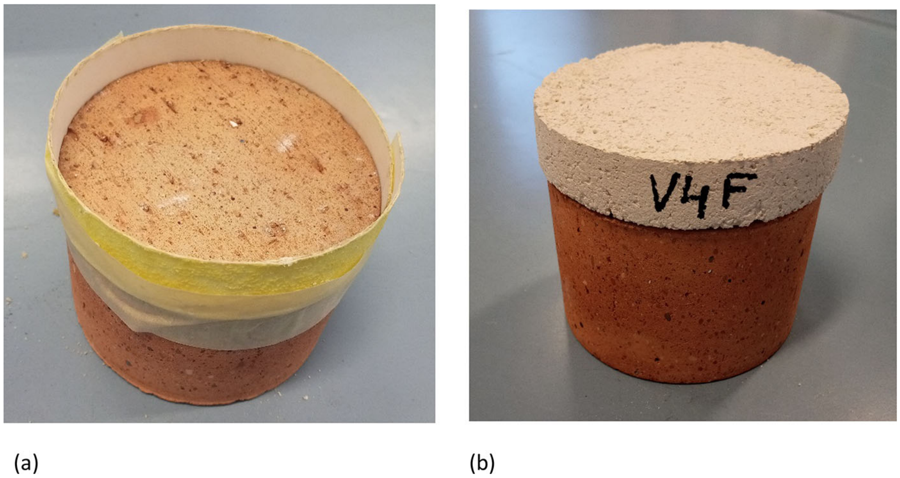


Fig. 21 Preparation of a specimen for pull-off modified test (**a**) Installation of the mould before the application of lime-based mortar and (**b**) mortar applied to the substrate

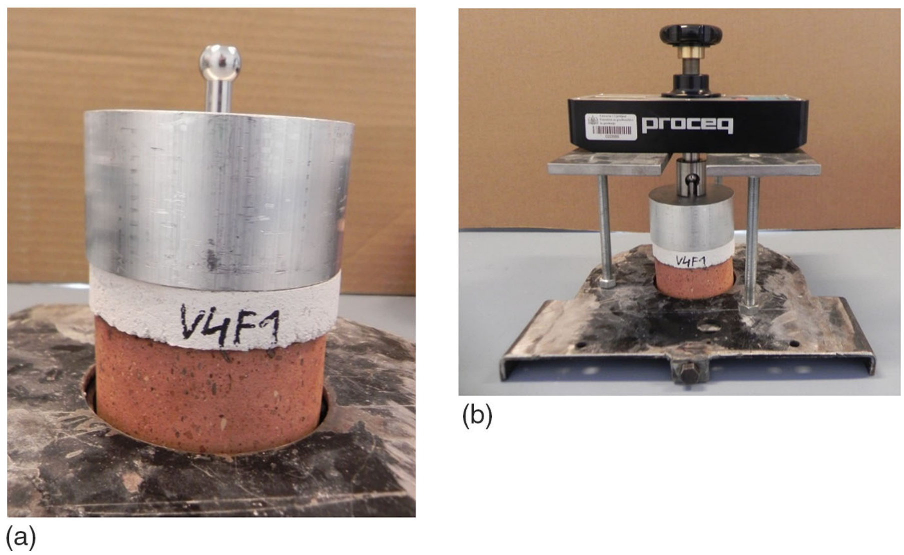


Fig. 22 Preparation of modified pull-off test for lime-based mortars (**a**) test sample with glued circular pull-head plate disk clamped to the lower part of the metal frame and (**b**) modified pull-off test

- Use tensile strength equipment with adequate accuracy and adapted specimens [11].
- Use a larger testing area (larger cut, larger metallic slab), thus needing a larger pull-off force [64].
- Use a method based on the four-point flexural strength of a composite stone-mortar specimen [61], although this method is more adequate for bedding mortars.

Adequate requirements should be defined, with higher and lower limit values: not higher than the substrate tensile strength; not lower than 0.05 MPa, unless cohesive fracture pattern by the mortar. A cohesive fracture pattern in the mortar is anyway preferential for low strength mortars.

2.2.7 Superficial cohesion and hardness

Base standard to consider

RILEM recommendation MR 18—Tape test [65].

The RILEM MR 18 method [65] is adequate to assess the superficial loss of material by lack of cohesion for lime-based renders/plasters.

The base of the method described in RILEM MR 18 [65] is adequate to assess the superficial loss of material by lack of cohesion for lime-based renders/plasters, as a comparison method for different materials (e.g. new versus old mortar; non-consolidated versus consolidated render). However, to be used in a broader basis, it must be defined in more detail, also considering research work already carried out [66].

Proposal

A defined reference tape should be used for comparison. A homogenous and comparable pressure should be applied on the tape. A spongy tissue, such as neoprene, should also be applied on the tape and a rigid piece should be applied on the tissue, without contact with the surface.

In the laboratory, the rigid piece has a defined weight [67]; for in situ tests, the person performing the test can be placed with an inclination of 30° to the wall, with his/her arm perpendicular to it and the hand pressing the rigid piece, that can be of wood.

The results can be obtained by visual observation of the tape and quantified by the difference of the weight of the tape. In the laboratory, it is easy to weigh the tape before and after the test; for in situ testing, the same size of tape should be used to avoid previous weighting, and the same type of plastic bag to condition the tested tapes.

However, additional research is needed if it is intended to consider absolute values and not only comparative values.

Additionally, Shore hardness tests (A and B) can be easily used with good results for superficial hardness, also showing good correlation with superficial cohesion [68]. In this case, a simple device is pressed to the render/plaster surface. As the mortar is a composite material, composed by the binder matrix and the aggregate, the result has to be the average of a minimum of 6 measurements.

2.2.8 Impact strength

Base standards to consider

EAD 040083-00-0404 *(2019)—External Thermal Insulation Composite Systems (ETICS) with renderings* [69].

EN ISO 7892—*Vertical building elements—Impact resistance tests—Impact bodies and general test procedures* [70].

In the standards referred the impact strength of a horizontal surface is evaluated based on the effect of a hard body impact with defined shape, dimensions and energy, carried out with a pendulum.

In the case of EAD 040083-00-0404 [69] (which refers to EN ISO 7892 [70]), there are two energies to consider: The hard body impact test of 10 Joules is carried out with a steel ball weighing 1.0 kg and from a height of 1.02 m, corresponding to a pendulum arm of 1.02 m. The hard body impact test of 3 Joules is carried out with a steel ball weighing 0.5 kg and from a height of 0.61 m, corresponding to a pendulum arm of the same length of 0.61 m.

The characterization of the impact strength is made by the following aspects:

- Cracking of the surface;
- Penetration of the render;
- Diameter of the resulting indentation, if any.

According to the experience collected with lime-based renders [71] the described methodology of EAD 040083-00-0404 [69] could be adequate for lime-based renders/plasters, using the energy of 10 J.

Proposal

The method proposed in [69] for the impact strength test is adequate to assess the impact strength of lime-based renders.

2.2.9 Resistance to surface abrasion

Base standard to consider

DIN 18947 (2018)—*Earth plasters—Terms and definitions, requirements, test methods* [30].

Proposal

The DIN 18947 [30] method is adequate for lime-based renders, with brush hardness and pressure adapted to this material. A circular brush (with defined hardness) is placed in contact (with a defined pressure) with a plaster/render specimen with an adequate area and rotates 20 times. The specimen surface is cleaned before and after the test. Qualitatively, the test results are obtained by observation of the abrasion sulk occurring; quantitatively, the specimen can be weighed before and after the test to determine the material loss by abrasion.

2.3 Hardened state—Properties related to hygric behaviour

2.3.1 Porosity—Pore structure

Base standards to consider

The methods used for recording the pore structure, including volume of pores and pore dimensions, can be divided into:

Direct: Microscopic techniques

The standards referring to them are:

ASTM C1324-20a. *Standard Test Method for Examination and Analysis of Hardened Masonry Mortar* [72].

ASTM C856/C856M-20. *Standard Practice for Petrographic Examination of Hardened Concrete* [73].

RILEM TC-COM:2004. *Scanning electron microscopy and optical microscopy, direct estimation of texture and pore size distribution* [74].

Indirect: Nitrogen adsorption/desorption, mercury intrusion porosimetry, water absorption

Relative standards:

EN 1015-18. *Determination of water absorption coefficient due to capillary action of hardened mortar* [75].

EN 1015-19. *Determination of water vapour permeability of hardened rendering and plastering mortars* [76].

ASTM D 4404-84. *Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry* [77].

RILEM recommendation CPC11.3 *Absorption of water by immersion under vacuum* [78].

ASTM D5604-96. *Standard Test Methods for Precipitated Silica—Surface Area by Single Point B.E.T. Nitrogen Adsorption* [79].

ISO 15901-1. *Determination of porosity distribution by mercury Intrusion Porosimetry and gas adsorption* [80].

Types of porosity of lime-based mortars

Porosity is one of the most important and commonly determined physical properties of building materials, mainly because of its influence on other important properties, such as the hygric behaviour, strength and durability. The types of pores of lime-based mortars and their classification and consequences are synthesized by Stefanidou [81]. Since porosity is related to strength, permeability, durability and building pathology, a combination of techniques should be adopted for its determination in order to cover, in a comprehensive way, the different pore scales existing in mortars' structure (Fig. 23).

The methods used for recording porosity have restrictions and advantages as well as many instrumental methods have assumptions that should be considered when evaluating the results. Some of them require specialized personnel, they are laboratory performed methods and give more than one property (e.g. total porosity, pore size distribution, mean pore diameter). Additionally, they need time and have a cost while others are quick, easy to perform and give a specific information (e.g. open porosity). The information on the porosity in old mortars is the result of many different parameters such as the pathology the materials suffer in combination with their structure. In the case of new mortars, the values are of particular interest when they have been designed to replace existing mortars or when new components are tested.

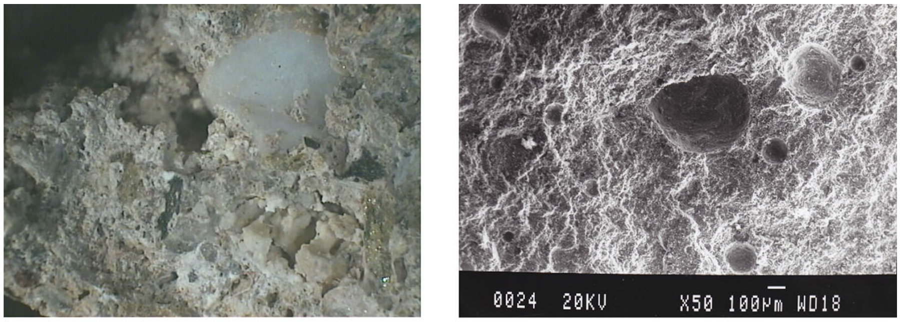
Proposal

The method to be selected for recording the porosity could be related to the required property. For example, when the permeability of mortars is of interest, the water absorption method can give satisfactory results. When pathology is investigated, microscopic methods should be employed as they give both qualitative and quantitative information of the sample. More detailed information on the porosity may be obtained through the determination of the pore size distribution by MIP and BET, which may also be complemented by image analysis techniques. It should be considered that, for techniques that require a small size sample, samples representative of the bulk material must be used, usually more than one sample.

2.3.2 Absorption under low pressure

Base standards to consider

EN 16302 [82], based on a RILEM procedure using Karsten tubes.



(a) (b)

Fig. 23 (**a**) Macro-scale porosity in lime-based mortar and (**b**) micro-scale under SEM

The method described by this standard is adequate for lime-based mortars.

2.3.3 Water absorption by capillarity

Base standards to consider

EN 1015-18. *Methods of test for mortars for masonry—Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar.* [75].

The method described in EN 1015-18 [75] is not adequate, because it proposes the calculation of the capillary coefficient in the part of the curve between 10 and 90 min. In some cases, namely for air lime mortars, the section of the curve between 10 and 90 min is not straight, because there is saturation before 90 min. When calculation is based on a non-straight curve, the capillary absorption value obtained is meaningless.

EN 15801. *Conservation of cultural property. Test methods. Determination of water absorption by capillarity* [83].

The method described in EN 15801 [83] is adequate for the calculation of the capillary coefficient. It proposes the drawing of the curve of water absorption by unit surface versus the square root of time, and the calculation of the capillary coefficient from the slope of the curve.

If specimens are moulded in metallic moulds, a cut sample surface should be used to avoid influence of demoulding agents previously applied in the moulds.

The asymptotic value can be compared when using samples with the same dimensions.

Proposal

- Use the EN 15801 [83] method.
- Do periodic measurements of water absorption, draw the curve of mass variation by square root of time, and then use the linear part of the curve (if possible, with at least 5 measurements) to determine the capillary coefficient.
- Additionally, determine the asymptotic value of water absorption (only useful for comparing specimens with similar dimensions)
- Establish a subclassification for W0 (W0 refers to Cc > 0.4 kg/(m^{2}min$^{1/2}$), and it is too broad for lime mortars): adopt the class W01 for Cc between 1.2 and 0.4 kg/(m^{2}min$^{1/2}$) and W02 for Cc > 1.2 kg/(m^{2}min$^{1/2}$).

Preferred option: Use the specimens that are moulded on a porous substrate, which are more representative of renders/plasters; as these have low thickness and saturate rapidly, use short weighting intervals at the beginning of the test.

2.3.4 Determination of water absorption by the sponge method

Base standards to consider

UNI 11432—*Cultural heritage. Natural and artificial stone. Determination of the water absorption by contact sponge* [84].

prEN 17655—*Conservation of cultural heritage—Determination of water absorption by contact sponge method* [85].

The contact sponge method is a water absorption test that is easy to apply, not only in laboratory, but also in situ, unlike other water absorption methods. Water absorption measurements using the sponge method are useful for the evaluation of the conservation state of a surface and of the performance of conservation surface treatments, in particular protective ones.

Analysis of the method

A sponge having pre-set characteristics and dimensions is charged with an adequate amount of water, taking care that when it is in contact with the surface it should not leak. For the application on the examined surface, a circular plastic plate is used.

The amount of water absorbed by the surface is calculated by difference, weighing the sponge before and after the application. The precision of the measurements directly depends on the precision of the used balance and the pressure applied by the user.

This method is considered adequate for lime-based mortars.

2.3.5 Drying

Base standard to consider

EN 16322. *Conservation of cultural property. Test methods. Determination of drying properties* [86].

The method is adequate for the determination of the drying parameters: drying rate of the first phase; drying rate of the second phase; drying index. It also allows for the possibility to be performed after saturation is achieved by the capillary absorption test.

For the calculations, not only the cross section, but all the samples areas where drying can occur (that is not blocked/waterproof) should be considered.

This method is considered adequate for lime-based mortars.

2.3.6 Water vapour permeability

Base standards to consider

EN 1015-19. *Methods of test for mortars for masonry—Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars* [76].

EN 15803. *Conservation of cultural property—Test methods—Determination of water vapour permeability* [87].

Needs for improvement

The test is considered adequate for lime-based mortars, as long as moulding, demoulding and curing are adapted as defined in 2.2.1; namely, preparation of specimens by application on a substrate and detachment after hardening.

The dimensions of the specimens defined in EN 1015-19 [76] should possibly be reduced and the periodicity of weighing should be increased. Specimens with a diameter of about 100 mm would be adequate. Weighing intervals of 6 h during the day and 12 h at night could be adopted.

3 Synthesis of test methods for lime-based renders and plasters and changes proposed

As conclusion, in Tables 4, 5 and 6, available test methods and changes proposed are summarized, based on the detailed analysis, fundamentals and proposals described in Sect. 2. The purposes of the tests and the justifications for the improvements proposed are

Table 4 Test methods for Lime-based Renders and Plasters: possible changes/improvements. Fresh mortars

Characteristic	Standards/current methods	Proposed improvements	Proposed requirement
Mixing	Standard: EN 1015-2 [13] Principle: Mixing 15 s + 60 s at low speed	Allow the possibility of mixing for a longer period. For example: 15 s + 150 s + 30 s (see 2.1.1)	–
Workability	Standard: EN 1015-3 [14] Principle: Measure flow value in two orthogonal directions, immediately after mixing; the average is the flow value, in mm	Indicate flow value immediately after mixing and after 15 min Indicate qualitative properties: exudation, segregation, or bleeding (see Sect. 2.1.2)	Flow value: 145–175 mm; application trial to verify workability (Note: 145 mm is a low value but it is adequate for some mortars, such as lime putty mortars and other air lime mortars) After 15 min loss of no more than 10% No exudation, bleeding, or segregation

Table 5 Test methods for Lime-based Renders and Plasters: possible changes/improvements

Characteristic/ Method	Standards/current methods	Proposed improvements/alternative methods	Proposed requirement
Moulding	Standard: EN 1015-11 [4] Principle: Metallic prismatic moulds (160 × 40 × 40) mm	Allow the possibility of application of a layer on a porous substrate using a net and after hardening detach the layer and cut the specimens (Proposed as an alternative/parallel method and additional research before eventual adoption) (see Sect. 2.2.1)	-
Curing	Standard: EN 1015-11 [4] Principle: 20 °C/95% RH for 7 days; 20 °C/65% RH after 7 days until test	Mortars with air lime as only binder: Reduction of the conditioning period at 20 °C/95% RH; Or More moderate 1st period of curing (e.g. 75% RH or cycles humid/dry); Or Use 20°C/65%RH during the full curing period (if the conditions on site are similar); Time for demoulding: adapted to the binder type: between 3 and 7 days for lime-based mortars (see Sect. 2.2.2)	-
Shrinkage	Standards: prEN 1015-13 [28] ASTM C1148-21 [88] 19-EN 12-617-4 [29] (unrestrained shrinkage test) Principle: in prismatic specimens—first measurement of the length, after demoulding; then periodical length variation measurements with gauges until stabilization or until 90 days	Measurement between moulding and demoulding with callipers—based on DIN 18947 and add the measured value to length variations after moulding Or Mould in a bottomless mould on a low friction substrate, place fixed points in the specimen and measure the distance variation between them from moulding until stabilization or until 90 days (see 2.2.3)	Low/Moderate. Reference value: 0.5×10^{-3}–1.0×10^{-3}
Cracking susceptibility due to restrained shrinkage*	No known standards	Restrained shrinkage test from the moment of moulding until relative stabilisation; measurement of the tensile stresses developed; determination of parameters needed for the criteria of susceptibility to cracking Or Application on a composite substrate (e.g. porous brick and lime mortar masonry) and registration of cracking patterns and crack dimensions (see Sect. 2.2.4)	Low or Moderate susceptibility to cracking

Table 5 continued

Characteristic/ Method	Standards/current methods	Proposed improvements/alternative methods	Proposed requirement
Dynamic Modulus of elasticity (DME)*	Standards: EN 14146 [57] (EN 12504-4 [58]) EN 14579 [59] (Ultrasound pulse velocity method)	Use the method of the frequency of resonance (EN 14146) or Use the ultrasound pulse velocity by the indirect method; drawing a trend line of several measurements; calculation of the velocity of ultrasound pulse through the slope; calculation of the DME accordingly. This method also gives information about the existence of cracks or other discontinuities, and can be used in mortars applied on a substrate including in situ Note that for determination of DME, the specimens must be dry enough (see Sect. 2.2.5)	Low modulus: reference values 2–7 GPa
Static Modulus of Elasticity	No standards generally adopted for mortars	Marques et al. [60]: Determination of the modulus in a compression test (Ec); device specially conceived to reduce errors; application of preparatory loads to eliminate voids; series of three loading cycles until 0.33 of compressive strength; definition of stress–strain curves; calculation of *Ec* value (see Sect. 2.2.5)	Low modulus. Reference values 1.5–6 GPa
Adhesion*	Standard: EN 1015-12 [62] Principle: Cut off 50 mm diameter circles; pull-off test with a pull-off dynamometer equipment	For low strength mortars (e.g. pure air lime mortars), use a more sensitive method: Use tensile strength equipment with adequate accuracy and adapted specimens Or Use a larger testing area (larger cut, larger metallic slab), so needing a larger force Or Use a flexural strength method in a composite specimen substrate-render/plaster (see Sect. 2.2.6)	Fracture Pattern: cohesive in the render or adhesive between render and substrate; avoid cohesive fracture in the substrate. Values: range 0.05–0.3 MPa; adhesion lower than the substrate tensile strength
Superficial hardness/cohesion*	No standards generally adopted for mortars	Measurements with Shore A and B MR 18—Tape test with improvements (see 2.2.7)	–
Impact strength*	No standards generally adopted for mortars	Impact test with a hard body applied with a pendulum following EAD 040083-00-0404 with energy 10 J [69] (one of the techniques specified in EN ISO 7892 [70] (see 2.2.8)	No penetration; Indentation diameter $\leq$ 20 mm
Resistance to surface abrasion	No standards generally adopted for mortars	Visual assessment and loss of weight of a plaster/render specimen after 20 circles	–

Table 5 continued

Characteristic/ Method	Standards/current methods	Proposed improvements/alternative methods	Proposed requirement
		with a defined brush at a low pressure DIN 18947 [30] (see 2.2.9)	

*Characteristics to determine after curing for: 28 and 90 days (90 days are needed for mainly air lime mortars)

Hardened mortars—properties related to mechanical behaviour

Table 6 Test methods for Lime-based Renders and Plasters: possible changes/improvements

Characteristic	Standards/current methods	Proposed improvements/alternative methods	Proposed requirement
Porosity–Pore structure*	Standards: ASTM C1324-20[a] [72] ASTM C856/C856M [73] RILEM TC-COM:2004 [74] Indirect: EN 1015-18 [75] EN 1015-19 [76] ASTM D 4404-84 [77] RILEM CPC 11.3 [78] ASTM D5604-96 [79] ISO 15901 [80] Direct: Microscopic tecniques	Select the method according to the required property. Add complementary methods to get detailed information, including direct and indirect methods (see 2.3.1)	–
Absorption under low pressure*	Standards: EN 16302 [82] (based on a RILEM procedure)	The method is considered adequate for lime-based renders/plasters (see 2.3.2)	–
Capillary water absorption*	Standards: EN 1015-18 [75] Principle: Measurements of water absorption; calculate the capillary coefficient based on the values at 10 min and 90 min EN 15801 [83]	Prefer EN 15801 [83] method: Periodic measurements of water absorption; draw the curve mass variation by square root of time; use the linear part of the curve (if possible, including at least 5 measurements) for determination of the capillary coefficient Additionally: Determination of the asymptotic value of water absorption (only for comparison of specimens with similar dimensions) Option: Use the specimens that are moulded on a porous substrate (see Sect. 2.3.3)	Establish a sub-classification for W0, as it is too broad for lime mortars: W01 for Cc between 1.2 and 0.4 kg/($m^2min^{1/2}$) and W02 for Cc $>$ 1.2 kg/($m^2min^{1/2}$) –

Table 6 continued

Characteristic	Standards/current methods	Proposed improvements/alternative methods	Proposed requirement
Determination of the water absorption by contact sponge	No standards generally adopted for mortars	Weighing of a sponge before and after application on the applied render/plaster; calculate the water absorbed by the surface (UNI 11432 [84]; prEN 17655 [85]) The method can be performed also in situ. (see 2.3.4)	
Drying*	Standard: EN 16322 [86]	The method is considered adequate for lime-based renders/plasters. (see 2.3.5)	–
Water vapour permeability*	Standards: EN 1015-19 [76] EN 15803 [87]	Reduction of the specimens dimensions to 10 mm diameter (instead of 20 mm of EN 1015-19); increase the periodicity of weightings to 12 h (instead of 24 h). (see 2.3.6)	–

*Characteristics to determine after curing for: 28 and 90 days (90 days are needed for mainly aerial lime mortars)

Hardened mortars—properties related to hygric characteristics

referred in the corresponding items of Sect. 2 and are not repeated in this section.

Declarations

Conflict of interest The authors declare no conflict of interest.

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