Substitution mortars for application in historical buildings exposed to the sea environment. Analysis of the viability of several types of compositions

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Abstract

In Portugal, many historical buildings in coastal areas have renders based on lime. Despite the severity of the sea environment – high content in soluble salts, namely chlorides, and high relative humidity - these old mortars have proved to be sufficiently resistant and durable. They are frequently in good condition, showing especially good cohesion and adherence to the background, although they often present degradation on the surface, as a result of biological colonization, efflorescences and superficial cracks. Interventions based on substitution of old mortars for incompatible new ones can produce the premature degradation of masonries through cohesion and adherence loss or contamination with soluble salts that previously did not exist. In this context, the study of compatible mortars with old and durable renders exposed to sea environment becomes fundamental, not only for the building image but also for the maintenance of its integrity. The purpose of this paper is to present a collection of different lime based mortars main characteristics, studied in LNEC, for substitution of old mortars: air lime mortars, air lime and cement mortars, air lime and hydraulic lime mortars, air lime mortars with pozzolanic additions and with other additions and admixtures. The main physical characteristics - capillary absorption and water vapour permeability - and mechanical characteristics – flexural and compressive strength and dynamic elastic modulus - of these mortars are analyzed and compared. Ranges of values obtained for each type of composition are defined and the viability of those applications in sea environment is studied. Some procedures are taken into consideration concerning the formulation and application care in order to improve the mortars' performance and durability to be used in historical buildings in coastal areas.

Keywords: additions, conservation, durability, lime, mortar, pozzolans.

1. Introduction

Renders are vulnerable constituent of constructions. They are used as decorative and protective coats, acting as sacrificial layers. The renders of historical buildings in coastal areas have been subjected, all over the years, to an aggressive environment of salty mist, high humidity, hot sun, dry wind and sometimes, in fortresses and lighthouses (fig. 1), even to waves' strength, Nowadays, these old lime based renders appear in generally good conditions but they usually present some localised degradation – superficial cracks, detachments, erosion, loss of cohesion – and so there is a need of repair and partial substitution. The lack of knowledge about these renders, as a material, conservation techniques and maintenance principles, are factors that can also promote degradation.

In conservation action, the priority is to achieve compatibility and optimize the durability of the whole building (Veiga *et al*. 2007a). The compatibility should be in terms of chemical compatibility between the new renders and the old materials, physical compatibility – related with similar water transport and thermal properties – and mechanical compatibility – associated with deformability and tension state. A strong and rigid repair mortar restrains movement and transmits stresses that can originate the degradation of the masonry; an impermeable mortar keeps the water inside masonry or forces its transport through the more permeable old mortar and masonry.

Since the appearance of Portland cement, there is a disuse of lime-based mortars, consequently their traditional manufacture and application has almost been lost (Lanas and Alvarez 2003).

The increase of the use of lime-based mortars in conservations works, in order to achieve the required compatibility, justifies the research about these materials, as they present nowadays some problems in terms of durability and protection to water (Magalhães *et al*. 2006). The choice of adequate materials to be used as conservation mortars is fundamental to the success of the conservation action.

Lime based mortars need a long time for carbonation, thus a curing period of 28 days is not enough to get significant test results. The binder, namely the kind of lime and its preparation, as well as the additions used, influence greatly the mortar characteristics. The grain size distribution and the nature of the aggregate are also important factors. An adequate grain size distribution can allow for the development of high strength. With siliceous aggregate the reactive silica can react with lime, producing CSH compounds in the interface that improve mortar strength (Lanas and Alvarez 2003).

Natural and artificial pozzolans are important additions used since Roman times to improve the resistance to the action of water and the durability of lime based mortars. There are many intrinsic factors that influence the pozzolan's reactivity: active silica content, grain size distribution, specific surface. In terms of artificial pozzolans some other parameters play a significant role to their reactivity, such as the calcination temperature (Moropoulo *et al.* 2004).

Capillary absorption is used as an indicative of the vulnerability to degradation of building materials and it is a consequence of the porous nature of building materials and their exposition to environmental conditions (Arandigoyen *et al.* 2005).

Many renders' solutions are being recommended for old buildings. However, some of them present some problems due to their incompatibility with the background and with existent surrounding mortars or due to inadequacy to particular environment conditions. In this paper, ranges of values obtained in previous work carried out in LNEC are presented, with different binders and aggregates and with diverse curing conditions.

Fig. 1 – Fortresses in the coast of Lisbon

2. Requirements

In order to achieve the desired compatibility related with the mortars performance to water entering the substrate and concerning adequate mechanical characteristics, without transference of forces to the background masonry, general requirements were established, taking into account both the characteristics of old mortars and the properties of the most common historical masonry in Portugal (Veiga *et al.*, 2001; Veiga and Carvalho, 2002). The results obtained for the different lime based mortars of the present study will be compared with those requirements, presented in table 1.

Table. 1 General requirements concerning some characteristics for rendering and repointing substitution mortars for ancient buildings

Type of render	**Mechanical characteristics at 90 days (N/mm^2)**			**Water behaviour**	
	Rt	**Rc**	**E**	**Sd (m)**	**C ($kg/m^2.min^{1/2}$)**
Exterior render	0,2 – 0,7	0,4 – 2,5	2000 - 5000	< 0,08	< 1,5; > 1,0
Interior render	0,2 – 0,7	0,4 – 2,5	2000 - 5000	< 0,10	-
Repointing mortar	0,4 – 0,8	0,6 – 3,0	3000 - 6000	< 0,10	< 1,5; > 1,0

Buildings in coastal areas are subjected to severe actions, and renders, whose main function is the protection of walls, are particularly exposed. Samples collected from several constructions located in Lisbon and coastal surroundings show clearly that very resistant and durable materials were used (Santos Silva, 2002), usually based in air lime and additions or aggregates that promoted pozzolanic reactions. Thus, the mortars to use in repair and replacement interventions must have special properties to assure durability to the referred actions, as well as keeping compatibility characteristics. The mortars must have high mechanical strength to resist erosion of sea wind and salt crystallization pressure, moderate elasticity modulus to accommodate deformations due to sudden thermic variations, moderate capillary coefficient and high water vapour permeability to retard the entrance of water and allow for quick drying. Besides, they should not have high contents of salts, to avoid the increase of salt contamination into the walls. Some studies (Charola, 2000; Gonçalves, 2007) refer a synergetic effect of chlorides and sulphates that imply an aggravation of salt attack when both are present, so the contamination with sulphates (present in cement and some kinds of hydraulic limes) may be particularly harmful.

3. Experimental work

3.1 Mortar formulation and conditioning

The studied mortars were formulated with: cement, cement and air lime, hydraulic lime (natural or artificial of classes 5 and 3,5 respectively), hydraulic lime and air lime, air lime and air lime and pozzolanic additions (two natural pozzolans and six artificial pozzolans). Some pre-dosed mortars based in hydraulic lime and air lime were also studied. The mortars were formulated with different dosages in volume and different types of aggregates, within several research projects. Although they were tested mainly in the same laboratory (LNEC's wall coverings laboratory) by members of the same research group, the tests were carried out in different years and slight differences on procedures and materials can explain some heterogeneity of results for apparently similar compositions.

All mortars were prepared according to standard procedures – EN1015-2 -, and were cured under the conditions specified by EN 1015-11 with the exception of pure air lime that were cured only in dry conditions (23ºC and 50% HR). Mortars AL-PCV1, AL-PCV2 and AL-G, besides the conditions of EN 1015-11, were also exposed to different curing conditions.

The cement based mortars formulations in volume are discriminated in Table. 2 (Veiga and Carvalho, 1994; Veiga and Carvalho, 2002; Veiga et al, 2007a). The hydraulic lime based mortars are discriminated in Table 3 (Magalhães and Veiga, 2005; Veiga et al., 2007b; Veiga and Carvalho, 2002, Veiga and Carvalho, 1994, Fragata et al., 2007a). The air lime based mortars are discriminated in Table 4 (Magalhães and Veiga, 2005; Veiga et al, 2007b, Magalhães et al, 2006; Veiga and Carvalho, 2002; Margalha, 1997; Margalha et al, 2006; Velosa and Veiga, 2005; Velosa, 2006; Velosa et al, 2007; Fragata et al, 2007b).

Table. 2 Composition of mortars with cement or cement and air lime

Mortar reference	Cement	Air Lime	Sand	Composition
C-1a	1	-	4	Cement; sand T
C-1b	1	-	4	Cement; sand C
C-1c	1	-	2+2	Cement ; sand C
C-AL1a	1	1	6	White cement; Air lime; sand T
C-AL1b	1	1	5,5 + 0,5	Cement; Air lime; sand M
C-AL 2a	1	2	9	White cement; Air Lime; Well graded siliceous sand
C-AL 2b	1	2	4,5 + 4,5	Cement; Air Lime; sand C
C-AL3	1	3	12	Cement; Air lime; sand T

T – siliceous sand from Tagus river; C – Corroios sand (siliceous pit sand with some clay); M – siliceous pit sand

Table. 3 Composition of mortars with hydraulic lime or hydraulic lime and air lime

Mortar reference	Hydraulic Lime	Air Lime	Sand	Composition
HL-1a	1	-	3	HL 3,5; well graded siliceous sand
HL-1b	1	-	1,5 + 1,5	HL 3,5; sand T + sand C
HL-2	1	-	3,5	NHL 5; sand T
HL-3a	1	-	4	NHL 5; sand T
HL-3b	1	-	4	NHL 5; sand C
HL-3c	1	-	2+2	NHL 5; sand T+sand C
HL-AL1	1	1	3 + 3	HL 3,5; sand T+sand C
HL-PD	-	-	-	Pre-dosed based in hydraulic lime
HLAL-PD	-	-	-	Pre-dosed based in hidraulic lime and air lime

T – siliceous sand from Tagus river; C – Corroios sand (siliceous pit sand with some clay); M – siliceous pit sand

Table. 4 Composition of mortars with air lime or air lime and pozzolans or other additions

Mortar refer.	Air Lime	Natural Pozzolan	Artificial Pozzolan	Sand	Composition
AL-1a	1	-	-	3	Air lime; sand T
AL-1b	1	-	-	3	Air lime; well graded siliceous sand
AL-1c	1	-	-	1,5+1,5	Air lime; sand T+ sand C
AL-1d	1	-	-	3	Air Lime; sand M
AL-1e	1	-	-	3	Air Lime; 2/3 sand M (coarse) and ½ sand M (fine)
H-AL	1	-	-	1,5+ 1,5	Water repellent lime; sand T + sand C
PD-AL	-	-	-	-	Pre-dosed based in air lime with acrylic addition
AL-PCV1	1	1	-	4	Air lime; Cabo Verde pozzolan; sand T
AL-PCV2	1	0,5	-	2,5	Air lime; Cabo Verde pozzolan; sand T
AL-PA	1	1	-	4	Air lime; Açores pozzolan; sand T
AL-M1	1	-	1	4	Air lime; metakaolin; sand T
AL-M2	1	-	0,5	2,5	Air lime; metakaolin; sand T
AL-PT	1	-	1	4	Air lime; brick powder; sand T
AL-CV	1	-	1	4	Air lime; fly ashes; sand T
AL-RAE	1	-	1	4	Air lime; expanded clay filler; sand T
AL-SF	1	-	0,25	2,5	Air lime; silica fume ; sand T
AL-G	1	-	1	4	Air lime; glass powder; siliceous sand from Tagus river

T – siliceous sand from Tagus river; C – Corroios sand (siliceous pit sand with some clay; M – siliceous pit sand

3.2 Methods

The determination of mechanical strength – compressive strength (Rc) and flexural strength (Rt) was based on EN 1015-11 methods; the elastic modulus (E) was determined by the method of the resonance frequency following French standard NF B10-511 (1975); the water absorption coefficient due to capillary action (C) and the water vapour permeability (Sd) were based on EN 1015-18 and EN 1015-19, respectively. Some of these methods are illustrated in figures 1 to 4.

Fig.1 Determination of specimens capillarity absorption

Fig.2 Determination of specimens permeability to water vapour

Fig. 3 Equipment used to the determination of specimens flexural and compressive strenght

Fig. 4 Determination of specimens elasticity modulus

The test results presented, on tables 5, 6 and 7, are a synthesis of values obtained for different mixes with the referred compositions. For each mix at least three specimens were tested and the average was calculated. The values presented are the extreme values of the mean values obtained.

3.3 Results and discussion

3.3.1 Cement or cement and air lime mortars

The range of results obtained for the mortars containing cement is presented in table 5.

Concerning mechanical characteristics, it can be stated that cement mortars are too strong and rigid to be used as old buildings' renders replacement materials. They are less deformable, transferring the stress to the weak background and promoting the degradations of pre-existent structures. Mortars composed with the same dosage in volume of cement and lime are still too strong for most backgrounds, although the other characteristics are acceptable. Mortars with lower dosage of cement have acceptable mechanical characteristics.

Concerning the water behaviour, any of these mortars fulfil the general requirements for water vapour permeability, but for the coefficient of capillarity some values are out of the limit range for all the formulations.

As it can be seen in Table 5, the formulations 1:2:9 and 1:3:12 fulfil the requirements, with the exception of water absorption coefficient for the formulation 1:3:12. Although generally too strong for most backgrounds, there is an advantage in using the formulation 1:1:6 (cement and air lime mortar) when compared with 1:4 (cement) because all the characteristics approach the requirements without a significant loss of resistance from the mechanical and water points of view. The big range of values obtained in terms of mechanical characteristics and water behaviour seem to be due mainly to the type and nature of the aggregate.

Table 5. Ranges of values of mortars formulated with cement or cement with air lime

Mortar reference	Volumetric dosage	Mechanical characteristics (MPa)			Water behaviour	
		Rt	Rc	E	Sd (m)	C (kg/m2.min1/2)
C-1	1:4	0,9 -1,7	3,1-6,9	5530-9810	0,07-0,14	0,7-1,9
C-AL1	1:1:6	0,7-1,6	2,1-5,1	4770	0,10	1,0-1,8
C-AL 2	1:2:9	0,7	1,6-1,9	4810(1)	0,11(1)	1,4-1,6
C-AL3	1:3:12	0,5	0,9	3010	0,10	2,0

Rt – Flexural strength; Rc – Compressive strength; E – Modulus of elasticity; Sd – Thickness of air layer with equivalent diffusion of water vapour; C – Capillarity coefficient

1) Results obtained with mortar formulated with silicious sand and Corroios sand (C-AL2b)

3.3.2 Hydraulic lime and hydraulic lime and air lime mortars

The range of results obtained for the mortars containing hydraulic lime is presented in table 6.

Mortars based in hydraulic lime with volumetric dosage 1:3 appear to be too strong and rigid. The other formulations present good characteristics in terms of mechanical properties and water behaviour, with the exception of the capillarity coefficient of dosage 1:4, which is too high.

A large difference is observed between the formulation with 1:3 dosage and all the other formulations with hydraulic lime. As a matter of fact, the products covered by the designation hydraulic lime are much more diversified than those covered by the designations cement or air lime, because there is a whole range of products originated from calcination of different proportions of limestone and clay, with different calcination temperatures and different treatments. This means there is a need of identifying clearly each specific kind of hydraulic lime and studying each type separately, in order to understand the influence of the different factors involved.

Comparing the formulation 1:1:6 with hydraulic lime and air lime with the formulation 1:1:6 with cement and air lime (table 5), a lower resistance is obtained for the first one, but no significant difference on the coefficient of capillarity is observed.

The capillarity coefficient has almost the same range of values in all mortars with the exception of pre-dosed mortars, which showed reduced coefficients, probably due to admixtures. The water vapour permeability is similar in all mortars.

These mortars based on hydraulic lime should be submitted to an extended testing campaign in order to understand better their behaviour, as the results obtained until now are not conclusive.

Table 6. Ranges of values of mortars formulated hydraulic lime or hydraulic lime and air lime

Mortar reference	Volumetric dosage	Mechanical characteristics (MPa)			Water behaviour	
		Rt	Rc	E	Sd (m)	C (kg/m2.min1/2)
HL-1	1:3	1,0-1,2	2,6-3,1	7400-7510	0,08	1,3-1,9
HL-2	1:3,5	0,2	0,9	1650	-	-
HL-3	1:4	0,2-0,5	0,6-1,1	1130-3030	0,09	1,2-2,4
HL-AL1	1:1:6	0,3	0,6	1850	0,08	1,8
HL-PD	Pre-dosed	0,8	2,5	2930	0,07	1,0
HLAL-PD	Pre-dosed	0,4	1,0	1640	0,07	0,7

Rt – Flexural strength; Rc – Compressive strength; E – Modulus of elasticity; Sd – Thickness of air layer with equivalent diffusion of water vapour; C – Capillarity coefficient

3.3.3 Air lime and air lime and pozzolans or other additions

The range of results obtained for air lime based mortars is presented in table 7.

The range of values obtained was due to the different aggregates used – different size distributions and inclusion or not of a small content of clay - and also to some differences in the curing conditions for the mortars containing pozzolanic additions. In fact, the mortars with air lime and natural pozzolan of Cabo Verde and air lime and glass powder were submitted to several curing conditions besides the one established in NP EN 1015-11, to try to establish the best conditions to use in real work. In the case of air lime and glass powder, the best results were obtained with the conditioning characterized by 23ºC±2ºC and 50%HR±5%HR, which corresponds to rather dry conditions, frequent in Portuguese weather.

The higher resistance was obtained with air lime mortars additivated with natural pozzolan of Cabo Verde (with the volumetric proportion 1:0,5:2,5) and with expanded clay filler (with the volumetric proportion 1:1:4), which has, nevertheless, a coefficient of capillarity rather high.

Concerning the mortars formulated with air lime and metakaolin, the best results in terms of mechanical resistance and water behaviour were obtained with the proportion of 1:0,5:2,5. The other formulations used for this kind of mortars don't fulfil the general requirements. Nevertheless, further studies show that the proportions to use with metakaolin, and probably other pozzolans, vary with the product bulk density, because they are related with the consumption of silica by the reaction with calcium, thus the proportions must be assessed in weight rather than in volume for each product (Velosa et al, 2007).

A big range of results can be observed in the mortars formulated with glass powder (1:1:4) due to different conditioning, concerning water behaviour and mechanical characteristics. These mortars must be submitted to further studies in order to better understand their behaviour.

Table 7. Ranges of values of mortars formulated air lime or air lime and pozzolans or other additions

Mortar reference	Volumetric dosage	Mechanical characteristics (MPa)			Water behaviour	
		Rt	Rc	E	Sd (m)	C (kg/m2.min1/2)
AL-1	1:3	0,2-0,8	0,6-1,6	2330-4100	0,05-0,08	1,1-1,6
H-AL	1:3	0,2	0,6	2260	0,08	0,3
AL-PD	Pre-dosed	0,6	1,5	2740	-	1,9
AL-PCV1	1:1:4	0,3	1,1-1,4	2770	0,07(1)	1,3
AL-PCV2	1:0,5:2,5	0,1-0,6	0,9-1,9	3920	-	1,4-2,7
AL-PA	1:1:4	0,1	0,5	2490	0,07	2,0
AL-M1	1:1:4	0,2	0,7	2130	-	1,6
AL-M2	1:0,5:2,5	0,4	1,3	2960	-	1,6
AL-PT	1:1:4	0,2-0,5	0,7-1,0	4350(2)	0,06(3)	2,3-4,4
AL-CV						
AL-RAE	1:1:4	0,5	2,3	4020	0,07	2,3
AL-SF	1:0,25:2,5	0,6	1,5	2550	-	1,4
AL-G	1:1:4	0,1-0,5	0,3-1,2	1160-5130	0,05-0,06	1,1-3,0

Rt – Flexural strength; Rc – Compressive strength; E – Modulus of elasticity; Sd – Thickness of air layer with equivalent diffusion of water vapour; C – Capillarity coefficient

1) Conditioning following NP EN-1015-11; 2) Value relative to AL-CV; 3 value relative to AL-PT

3.3.4 Assessment of mortars for maritime environment

Having in mind both the general requirements and the special properties needed for maritime environment described in 2, the following considerations can be stated:

- Mortars based in cement and lime, with volumetric dosage 1:2:9 (C-AL2) can be a possibility. The greatest disadvantage seems to be the relatively high content of salts, namely sulphates, due to the presence of cement. This effect is nevertheless minimised by a low proportion of cement compared to lime. The use of sands free of salts is also needed to reduce risks.
- Generally, mortars based in hydraulic lime tested in this program do not show good results for this use, with the possible exception of the pre-dosed mortar HL-PD). However, a larger experimental program is needed to draw conclusions about the use of hydraulic lime mortars prepared *in situ*.
- Concerning air lime based mortars, it is clear that some formulations including pozzolanic additions offer good possibilities. Mortars with air lime and Cabo Verde natural pozzolan in proportions 1.1:4, air lime and expanded clay filler with similar proportions and air lime and silica-fume seem to have the best behaviour. No special disadvantages are known, besides some possible difficulties in application due to insufficient knowledge about this kind of materials. Air lime and glass residues with an appropriate cure can also be a possibility.

4. Conclusions

Mortars to use in old buildings must be compatible with the background and the pre-existing mortars. Ancient buildings placed in coastal areas are subjected to particularly severe actions that require specific characteristics of rendering mortars.

Mortars based in cement, hydraulic lime, air lime, air lime with an hydraulic binder – cement or hydraulic lime – and air lime with pozzolans have been tested in previous studies. Ranges of results concerning mechanical properties and water behaviour were obtained for different formulations with different binders, aggregates and additions and are synthesized and treated here.

Mortar conditioning and changes in composition (type of binder, volumetric dosage and type of aggregates, incorporation of admixtures and additions) play an important role in terms of mechanical characteristics and water behaviour.

The analysis of the ranges of results and the comparison of those values with requirements of compatibility for old buildings and exigencies established for maritime environment, points out that some types of mortars can be adequate to be used as replacement materials for old buildings: mortars composed by air lime and lower content in cement can be adequate, although there are some risks of introducing salts into masonry. Mortars formulated with air lime and pozzolans can be adequate depending on the type and proportion of pozzolan and curing conditions of the mortar.

Hydraulic lime mortars with different types of hydraulic lime should be submitted to a larger study in order to understand better their characteristics. Mortars composed by air lime and glass powder, as well as those composed by air lime and some other pozzolans must also be subjected to more tests, to achieve the best proportions and the most adequate cure conditions.

In order to fulfil the requirements for rendering purposes in old buildings of coastal areas, the mortars must be carefully studied case by case.

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