Repair mortars for a maritime fortress of the XVII th century

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Abstract

External renders covering façades of buildings placed in maritime zones suffer severe direct aggressions of the surrounding micro-environment, as they are subjected to the action of salty mist, strong winds, even to sea water (sprinkles and freatic water).

The mortars of these buildings often present pathology associated to these particularly aggressive conditions and the repair mortars to use in interventions have to be selected taking into account this situation.

In the present paper a study developed in Laboratório Nacional de Engenharia Civil (LNEC) about the rendering mortars of a XVII th century Fortress nearby Lisbon, placed at the Atlantic Coast close to the Tagus river estuary is presented. A brief description of the building and its History is made, the main defects observed in renders are referred and experimental *in situ* applications of several different renders and paintings are described. The tests carried out to verify their efficacy and their compatibility with old masonry and environmental conditions are also presented.

Intervention options are pointed out based on the observations carried out, the test results obtained and the existing conditions of work on site.

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Keywords: external renders, *in situ* tests, repair mortars.

1. Introduction

Santa Marta Fortress is an important building from the historical and architectonic points of view. Obeying to a military typology, it was probably constructed in the XVII th century within the program of construction of the defence line of the coast nearby Lisbon (fig. 1).

The fortress doesn't seem to have suffered any alteration until middle XVIII th century; when the first known interventions took place. According to researches the tracing and the volume of the fortress didn't change since 1786 (J. Boiça, 2001).The interesting lighthouse was constructed at the end of the XIX th century.

Structurally the fortress presented a good state of conservation. The battlements, composed by stone and brick irregular masonry, are very thick and presented a red-tile colour, due to the ancient lime mortars that incorporate local earth of a reddish colour. However, the surfaces of façades and battlements were uncharacteristic, as a part of the ancient mortars were substituted by new cement based mortars, evidencing several defects (figs. 2 and 3) (table 1).

Fig. 1 – General appearance of St. Marta Fortress before the intervention; detail of the lighthouse

Table 1- Synthesis of defects and their main causes

Local	**Defects**	**Probable cause**
External wall surfaces	Renderings	▪ High relative humidity of the region; ▪ Direct agression of the sea and salty sprinkle, bringing high salt content from the foundations and walls materials and from the air itself; ▪ Absence of drainage; ▪ Absence of solutions for protection and for transport of rain water; ▪ Absence of regular maintenance.
	Loss of cohesion, erosion, loss of adhesion, parasite plants, moist, biologic colonization, detachment, cracking, and generalized dirt.	
	Paintings	
	Detachment, loss of cohesion, cracking, and generalised dirt.	

Fig. 2 Appearance of the fortress wall covering

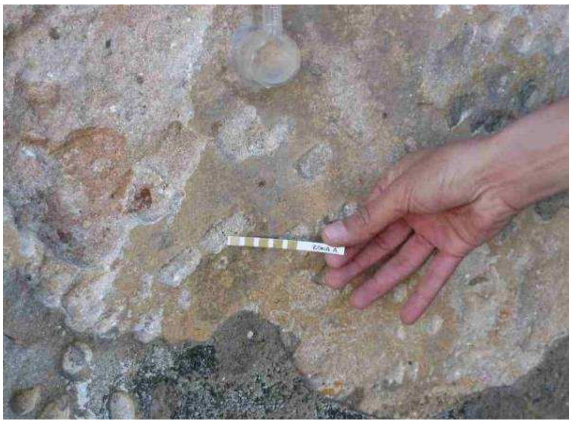

Fig. 3 In situ test for salt identification

2. Wall renderings for maritime zones

The buildings façades of maritime zones are exposed to severe environments, characterised by high relative humidity, salty atmosphere and salty soils and strong wind. In the Lisbon area, hot sun for several hours a day during a considerable part of the year is another severe climate factor. The moist environment requires the use of hydraulic mortars – with a hydraulic binder or additives that promote hydraulic reactions – able of hardening in a wet milieu and resistant to the aggression of the existing micro-environment. Mortars to use need also to be resistant to cracking by temperature variations and to salts.

The use of hydraulic mortars in moist environments is known and used since the Roman times by Vitruvius, the so called *Opus caementicium,* that subsisted until nowadays, on the surfaces of thousands of buildings spattered all over the Roman Empire (Vitruvius, 2006). After the Romans the study of hydraulic binders was born again on the XVIII th century, in 1756, when the English engineer Smeaton, responsible by the reconstruction of the Eddyston lighthouse (Plymouth) carried out researches on the most adequate lime to be used in a sea environment, which became known, at the time, as *water lime* (Sanchez, 2002).

The use of pozzolans and additions that promote hydraulicity to mortars is current in Portugal; recent studies prove their use since Roman times, passing by XVI th century in São Julião Fortress, in Oeiras (a coastal town nearby Lisbon), until the XIX th century in several waterside and coastal constructions of Portuguese harbours (Velosa, 2006).

The scientific interest by this theme in Portugal is latent since the decade of fifty of XX th century, with the pioneer study of Sousa Coutinho about pozzolans (Coutinho, 1958); however the Portuguese scientific community goes on with research on these binders and work is being developed on the incorporation of pozzolanic additions to lime mortars in order to make them able of being applied as substitution renders of old buildings in wet environment (Velosa, 2006; Fragata et als, 2007). Based in previous studies some mortars were selected to be experimentally applied and tested in the Fortress (Veiga, 2004 and Velosa, 2006).

3. Strategy of conservation and repair of renderings

The program established was developed in two phases:

First phase: i) evaluation of the state of conservation of the monument; ii) visual characterization and stratigrafic identification of the several coats of the renders; iii) selection of places for tests and deeper analysis.

Second phase: iv) *in situ* tests for old renderings characterization and evaluation of the zones to treat or to substitute; v) definition of possible substitution mortars and paintings for *in situ* testing; vi) experimental application of the selected mortars and paintings; vii) analysis of the test results, choice of the substitution mortar and painting.

This paper focuses on the second phase and mainly on the substitution materials testing, however a synthetic overview is carried out on the whole study.

4. Materials and methods

4.1 Selected renderings and paintings to test

Experimental applications of four possible substitution mortars were carried out on a battlement of the fortress. Some of the panels were painted with two types of paint hypothetically considered compatible with the renders: a silicate paint and a siloxan paint. The objective was to observe any defects or difficulties and to perform *in situ* tests on the different solutions, in order to choose the most adequate (fig. 4).

Fig. 4 – Experimental applications and tests in situ

All the substitution mortars applied, with the exception of the pre-dosed mortar, have been tested in laboratory in previous works (Veiga and Aguiar, 1996; Veiga et als., 2004; Velosa and Veiga, 2007a; Velosa and Veiga, 2007b).

The materials used were: hydrated air lime; cement CEM 32,5; industrial metakaolin of Caldas da Rainha region; expanded clay fines (industrial residues subjected to treatment); industrial pre-dosed render based on hydraulic lime; silicious river sand; pit sand of silicious nature with natural clay content; mineral paint for external use based in potassium silicate; aqueous paint based in a silicon resin.

Before the application of mortars the background was cleaned and wetted. For all the mortars with the exception of the industrial render, a fluid spatterdash was applied and it was let to cure for three days before the application of the next coat. In table 2 the different experimental applications and their composition (volumetric dosages) are presented schematically.

Table 2 – Composition of the experimental applications panels

Panel 1: air lime and cement	**Panel 2: air lime and metakaolin**	**Panel 3: Industrial pre-dosed mortar of hydraulic lime**	**Panel 4: air lime and expanded clay filler**
Spatterdash – 1:1:6 1st coat – 1:1:6 2nd coat – 1:2:9 Finishing coat – 1:2: (4+5) (lime: cement: fine sand of limestone + siliceous sand)	Spatterdash – 1:1:4 1st coat – 1: 1: 4 2nd coat – 1:1:4,5 Finishing coat – 1:1: (2+2,5) (lime: metakaolin: fine sand of limestone + siliceous sand)	Mortar applied in two coats following the manufacturer specifications.	Spatterdash – 1:1:4 1st coat – 1: 1: 4 2nd coat – 1:1:4,5 Finishing coat – 1:1: (2+2,5) (lime: expanded clay filler : fine sand of limestone + siliceous sand)
Rough finishing without painting	**Rough finishing** without painting	**Rough finishing** without painting; with silicate paint; with siloxan paint.	**Rough finishing** without painting
Flat finishing with silicate paint; with siloxan paint.	**Flat finishing** with silicate paint; with siloxan paint.		**Flat finishing** with silicate paint; with siloxan paint.

4.2 *In situ* tests on the existing renderings and on the substitution renderings

The experimental program was carried out with the aim of evaluating the mechanical strength, the water behaviour and the state of conservation of the existing renders and to verify the compatibility and efficacy of the new mortars chosen as possible substitution mortars.

One of the fortress battlements was selected for the *in situ* tests, both on the existing render – where zones with different deterioration degrees were chosen – and later on the experimental applications.

The test program included the following tests:

a) *In situ* stratigrafic identification of the renderings coats

This technique permits the observation of the existent renderings and identification of texture, thickness and colour of the composing coats (Tavares et als, 2005).

b) Permeability to water under low pressure (Karsten tubes)

This test consists in measuring the quantity of water absorbed by the wall surface, through the render or the painting, using small graduated tubes full of water applied on the wall (Magalhães et al, 2005).

c) Surface resistance by sphere impact

This test gives information on the render deformability. The impact resistance is evaluated through the diameter of the concussion and of the type of damage produced (Veiga and Carvalho, 2000; Magalhães and Veiga, 2006).

d) Pull-off adhesion test

This test evaluates adhesion of render to the background and the predictable rupture mode (Veiga et als 2004).

e) Controlled penetration test

This test, based on the penetration of a graduated nail by the impacts with known energy, gives information on the mechanical strength of the internal coats of the render permitting an assessment of their state of conservation (Veiga and Carvalho, 2000; Magalhães and Veiga, 2006).

f) Schmidt hammer and Shore A tests

These tests aim the evaluation of the strength of superficial render coats and of the painting capacity to improve the render cohesion. A type PM Schmidt hammer was used to give information on the external render coats; a durometer Shore A was employed to evaluate the most superficial thin coats and the effect of the painting (Tavares and Veiga, 2007). In both cases, higher values indicate higher superficial resistance.

4.3 Results of tests

The test results are presented in tables 3 to 6 and in fig. 5

Table 3 – Stratigrafic identification of the wall coverings coats

Render	Coats	Identification	Chromatic identification (NCS index, edition 2)
Covering 1 (probably the oldest) (wall E)	0	Dark yellow render	S 1050 Y 20R
	1	Yellow ochre thin finishing render	S 2050 Y 30R
	2	Salmon colour painting	S 1030 Y 30R
	3	White painting	S0500 N
Covering 2 (probably from XVIII th century) (wall H)	0	Dark yellow render	S 1050 Y 20R
	1	Yellow ochre thin finishing render	S 2050 Y 30R
	2	Salmon colour painting	S 1030 Y 30R
	3	White painting	S0500 N
	4	Cement render (traces)	S1500 N
Covering 3 (the most recent) (walls A, B, C, D, F, G)	0	Dark yellow render	S 1050 Y 20R
	1	Yellow ochre thin finishing render	S 2050 Y 30R
	2	Cement render	S1500 N
	3	White painting	S0500 N

Table 4 – Results of the tests on the ancient wall surfaces (Magalhães et als, 2005)

Test (three measurements were carried out in each zone for each test)		**Zone A** (old lime mortar with apparent high deterioration degree)		**Zone B** (old lime mortar with apparent low deterioration degree)	
		Mean values	Standard deviation	Mean values	Standard deviation
Surface resistance by sphere impact (Ø, mm)		12	3.5	(*)	
Controlled penetration (mm)					
	1st. penetration	5.3	1.5	3.3	1.2
	2nd. penetration	2.3	1.2	2.3	1.2
	3rd. penetration	2.2	1.0	1.3	0.6
	Total	9.8	3.4	7.9	1.0
Permeability to water under low pressure (water absorbed, cm^3)					
	0 min	0	0	0 (**)	0
	5 min	0.03	0.06	0 (**)	0
	30 min	0.27	0.38	0 (**)	0
	60 min	0.77	0.75	0 (**)	0

(*) it was not possible to use the equipment

(**) no absorption was observed during the test

Table 5 – Results of the tests on the substitution renders without painting (about 3 months after application)

Test		PANEL 1 Air lime + cement	PANEL 2 Air lime + metakaolin	PANEL 3 Pre-dosed mortar	PANEL 4 Air lime + expanded clay filler
Surface resistance by sphere impact (Ø, mm)		10	14	14	13
Controlled penetration (mm)	1st. penetration	2.3	3.7	4.7	3.7
	2nd. penetration	1.3	2.7	1.7	2.0
	3rd. penetration	1.0	2.3	1.7	1.3
	Total	4.6	8.7	8.1	7.0
Adhesion to the background		0.38 (adhesive rupture between coats)	0.03 (adhesive rupture between coats)	0.11 (adhesive rupture between coats and cohesive in the render)	0.10 (adhesive rupture between coats)
Water content (%) (comparative values)		15 Slightly wet	19 Slightly wet	9 Dry	15 Slightly wet
Permeability to water under low pressure (water absorbed, cm^3)	0 min	0.00	0.00	0.00	0.00
	5 min	2.03	1.88	0.10	1.97
	30 min	> 3.70	> 3.24	1.15	> 4
	60 min	> 4.00	> 3.34	> 3.13	> 4

Table 6 – Results of the tests on the substitution renders with painting

Test	PANEL 1 Air lime + cement			PANEL 2 Air lime + metakaolin			PANEL 3 Pre-dosed mortar			PANEL 4 Air lime + expanded clay filler		
	0	1	2	0	1	2	0	1	2	0	1	2
Durometer (Average) (Shore A)	93	93	95	93	93	94	84	79	86	92	92	97
Schmidt hammer (Average) (kg/mm²)	39	34	40	23	23	31	31	31	29	30	30	33

0 – without painting; 1 – Siloxan painting; 2 – Silicate painting

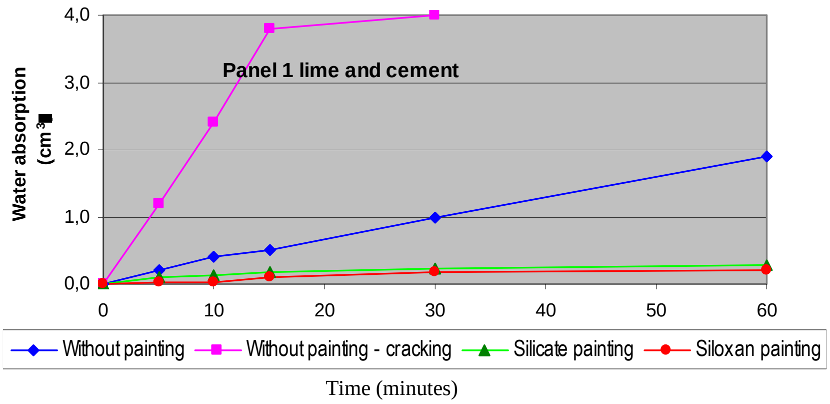

Fig. 5 - Graph of the Karsten tubes *tests on panel 1 with painting*

5. Discussion

Generally, the tests carried out *in situ* on the existing renderings and on the substitution mortars allowed for their characterization and for the evaluation of their state of conservation.

• The survey of the façades and the stratigraphic analysis identified the existence of diversified old render coats, finishing thin coats and paintings, with varied colours produced by natural pigments, pointing out to different application periods and possibly to different interventions. New cement mortars have been applied in recent interventions in most walls (table 3).

• The analysis of the *in situ* tests carried out on the existing renderings showed they presented good cohesion and good ability of protection to water. Zone B presented high repair ability and Zone A medium repair ability according to the definition established for old mortars by (Magalhães and Veiga, 2006) (table 4).

• Considering the substitution mortars, panel 2 (air lime + metakaolin) presented loss of cohesion in the internal coats, verified by the cuts for the adhesion test. This panel, as well as panel 3 (pre-dosed mortar), presented mechanical strength lower than the old lime mortar considered in good conservation conditions. Further work on lime and metakaolin mixes seem to point out that the dosage 1:1:4 (volume) is not the best for the kind of metakaolin employed and this could be the reason for bad behaviour of panel 2. Panel 1 (air lime + cement) presented high mechanical strength and good adhesion to the background. Panel 4 (expanded clay filler) presented mechanical characteristics similar to the old lime render of zone A and favourable general characteristics measured in laboratory (Velosa and Veiga, 2007), however it presented some surface cracking, specially when applied with flat finishing. This defect was probably due to particularly severe climatic conditions during the application (wind and hot dry weather). Concerning water behaviour, the Karsten tubes test revealed that all the solutions tested have higher permeability than the old lime mortar of zone A, probably due to being much more recent and consequently with a smaller degree of carbonation. Panel 3 (pre-dosed mortar) shows lower permeability to water than the other substitution mortars tested, which evidence similar behaviour in this test (table 5).

• The results obtained and the observations of the panels pointed out to the exclusion of solutions of air lime + metakaolin (panel 2) and pre-dosed mortar (panel 3). Due to a short term of the works the solution air lime + expanded clay filler (panel 4) had to be excluded, as it proved to need a very careful application in order to avoid cracking.

• Therefore, in this particular case, it was decided to recommend the application of a render based in air lime + cement, with the composition of panel 1. As a matter of fact the results *in situ* were positive and it is easily applied by the current workmanship. The results of laboratory tests in previous studies (Veiga et als, 2004) were also acceptable, as well as previous application in real work (Veiga and Aguiar, 1996).On the other hand, materials with cement present known disadvantages, related with a certain degree of incompatibility with old background, namely concerning salt contents that can contaminate the support. However, in this Fortress, some solutions that imply a rupture with the original work have already been used, including structural concrete elements.

• The analysis of the test results on the paintings (table 6 and fig. 4), together with data from previous studies (Tavares et al, 2002; Veiga and Tavares, 2002) pointed out to the recommendation of the silicate paint. This paint seems to present a consolidant effect on the render, evidenced by slightly higher values of durometer and Schmidt hammer measures, and it contributes for water protection favouring simultaneously an easy drying. Concerning the siloxan painting, the results of the tests *in situ* were not unfavourable, although the consolidant effect was not noticeable, but the inexistence of laboratory studies for now was considered a negative factor.

6. Conclusion

Santa Marta Fortress is a significant military building of the XVII th century, placed in a coastal zone nearby Lisbon, with aggressive climatic conditions. The survey of the building showed structural good conditions. Nevertheless, the option of the owner institution was to substitute the rendering mortars which were superficially deteriorated and with very heterogeneous appearance.

To recommend adequate solutions of rendering and painting, experimental applications of some solutions were carried out and a test program was accomplished.

The final recommendation took into account the test results, the observation of the solutions appearance and the confront of the conditions needed for the good behaviour of each solution and the real conditions in the work.

The lime and artificial pozzolan mortars solutions tested (air lime + metakaolin and air lime + expanded clay filler) were considered the most compatible but they proved to need controlled application conditions, in terms of climatic conditions during and after application and of workmanship, which could not be assured in this case, due mainly to very short time for the applications. Thus, a render based in air lime and cement, applied in several coats, was recommended. Although this is not considered a thoroughly compatible mortar, it was considered a reasonable solution for this situation. The silicate painting was selected as a good solution to cover the new render, due to favourable test results and appearance.

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References

Boiça, Joaquim; Barros, M.ª de Fátima; Ramalho, Margarida de Magalhães, *As Fortificações Marítimas de Cascais*. Lisboa : Livros Quetzal, 2001.

Coutinho, A de Sousa, *Betões com Pozolans e Cimento Pozolâncios*. Lisboa, LNEC, 1958.

Fragata, A.; Paiva, H.; Velosa, A.; Veiga, R., Ferreira, V., *Application of crushed glass residues in Mortars*, in Sustainable Building - SB07, Lisboa, IST; 2007.

Magalhães, A.; Veiga, R.; Costa, D., *Caracterização do Estado de Conservação de Revestimentos de Paredes Antigas através de Ensaios in* situ - *Dois Casos de Estudo.* In: VI SBTA - Simpósio Brasileiro de Tecnologia de Argamassas. Florianópolis: ANTAC, 2005.

Magalhães, A.; Matias, L.; Vilhena, A.; Veiga, R.; PIna dos Santos, C., *Non-destructive Testing for the Assessment of Moisture Defects on Ancient Walls. Some Case Studies.* In 8th Int. Conference on Non-destructive Investigations and Microanalysis for the Diagnostics and Conservation of the Cultural and Environmental Heritage, Lecce (Italy), 2005.

Magalhães, A.; Veiga, R., *Comparison of in-situ Mechanical Tests on Masonry Mortars: Sphere Impact and Controlled Penetration Test.* In HWC 2006, Madrid, June 2006.

Sanchez, F. J., *Historia, Caraterización y Restauración de Morteros*, Sevilla, Univ. Sevilla, 2002.

Tavares, M., Veiga, R., Eusébio, I. *Uma Solução actual para Acabamento de Paramentos Exteriores de Edifícios Antigos: As Tintas de Silicatos*. Lisboa: LNEC, Novembro, 2002, Relatório 311/02-NA.

Tavares, M., Magalhães, A., Veiga, R., Aguiar, J., *Métodos de Diagnóstico para Revetimientos de Edificios Antiguos. Importância y Aplicabilidad de los Ensayos in situ*. In: Boletin del Instituto Andaluz del Património Histórico, PH nº 53, Sevilla, Abril de 2005.

Tavares, M.; Veiga, R., *A Conservação de Rebocos Antigos - Restituir a Coesão Perdida através da Consolidação com Materiais Tradicionais e Sustentáveis*, in: VII SBTA – Seminário Brasileiro de Tecnologia de Argamassas, Recife – Pe, ANTAC, Maio de 2007.

Velosa A., *Argamassas de Cal com Pozolanas para Revestimento de Paredes Antigas*. Aveiro: Universidade de Aveiro, Julho de 2006. Tese de doutoramento.

Velosa, A.; Veiga, R., *Utilização de um Sub-produto Industrial como Aditivo em Argamassas de Cal.* In VII Seminário Brasileiro de Tecnologia de Argamassas, Recife, Brasil, Maio de 2007.

Velosa, A.; Veiga, R., *Lime-metakaolin Mortars – Properties and Applications*. In Portugal SB07: Sustainable Construction, Materials and Practices. Challenges of the Industry for the New Millennium. A realizar em Lisboa, IST, September 2007.

Veiga, R.; Aguiar, J., *Reabilitação do Forte de S. Bruno. Notas sobre os Resultados da Colaboração Prestada pelo LNEC à CMO*. In IV Encontro Nacional de Municípios com Centro Histórico, Oeiras, Novembro de 1996.

Veiga, R.; Carvalho, F., *Experimental Characterisation of Lime based Rendering and Repointing Mortars. Definition of Relevant Laboratorial and in situ Tests*. Athens, National Technical University of Athens, December 2000.

Veiga, R.; Tavares, M., *Características das Paredes Antigas. Requisitos dos Revestimentos por Pintura.* In Encontro A Indústria das Tintas no início do Século XXI. Lisboa, APTETI, Outubro de 2002.

Veiga, R. et als., *Conservação e Renovação de Revestimentos de Paredes de Edifícios Antigos*. Lisboa: LNEC, Julho de 2004. Colecção Edifícios, CED 9.

Vitrúvio (Trad. Port. do latim de M. Justino Maciel), Vitrúvio, *Tratado de Arquitectura*, Lisboa, IST, 2006.