Physical and mechanical characterisation of ancient mortars. Application to the evaluation of the state of conservation

A. Magalhães*; R. Veiga

Buildings Department, National Laboratory of Civil Engineering, Av. do Brasil, 101, Lisboa 1700-066, Portugal

Resumen

El conocimiento de las características físicas y mecánicas de los morteros antiguos es muy importante a la hora de seleccionar morteros de reparación y de planear adecuadamente cualquiera intervención de reparación. Así, se hace necesario definir los métodos de ensayo de caracterización aplicables a las muestras irregulares y friables para evaluar dichas características.
En el presente trabajo son presentados y analizados algunos resultados de caracterización experimental de morteros antiguos portugueses. Métodos de ensayo utilizados para evaluar el comportamiento al agua y la resistencia a la compresión son descritos. La comparación con resultados de ensayos obtenidos para morteros nuevos, usando dichos métodos y también los métodos preconizados por la norma europea es usada para extraer conclusiones sobre las posibilidades de los métodos.
Los resultados experimentales son aún correlacionados con el nivel de la degradación inicial atribuido a los morteros antiguos con base en el análisis visual.

Palabras-clave: mortero antiguo; ensayo; resistencia a compresión; capilaridad; estado de conservación

Abstract

The knowledge of physical and mechanical characteristics of ancient mortars is very important to select repair mortars and to plan adequately any repair intervention. There is a need to define characterization test methods applicable to irregular, friable samples to assess those characteristics.
In the present work some results of experimental characterization of Portuguese old mortars are presented and discussed. The test methods used to evaluate the water behaviour and the compressive resistance are described. A comparison with results of compressive strength obtained for new mortars, using the same method and also the methods proposed by EN standards, is used to extract conclusions about the method's possibilities. A correlation of the experimental data with the initial degradation level attributed to the mortars by visual analysis is performed.

Keywords: ancient mortar; test; compressive strength; capillarity; state of conservation

1. Introduction

In general interventions on ancient building walls require the use of substitution or repair mortars durable and compatible with original structures; so, their physical and chemical behaviour must be similar to the existent ones. In this sense it is important to understand the chemical, physical and mechanical characteristics of old mortars [1, 2, 3, 4].

These characteristics are also relevant to assess the degradation level of the mortar, essential to define the repair strategies.

* Corresponding author. Fax: +351 21 844 3027.
E-mail address: anacristian@lnec.pt (A. Magalhães), rveiga@lnec.pt (R.Veiga).

Concerning chemical analysis of original mortars, several studies [2, 5, 6, 7, 8, 9, 10] have been mainly centred in the characterisation and identification of their components by sophisticated techniques which give rigorous data about mineral constituents and chemical compounds that cause deterioration. Nevertheless, the chemical and mineralogical characterisation is not enough to acquire the necessary knowledge to take fundamental decisions. Complementary information about physical and mechanical characteristics of mortars is indispensable, both to verify if they guarantee an adequate performance of the old mortar or to be used to design the new material, which must be compatible with the pre-existing materials in contact in aesthetic and functional - chemical, mechanical and physical - terms [2].

In old mortars (completely carbonated), the capillarity coefficient is a measure of the compacity of the rendering mortar and therefore of its strength, as in lime mortars, improved compacity is usually related with good strength; assuming the mortar is already completely carbonated, the low volume of voids, and consequently the capillarity coefficient and the strength, give an idea of the state of conservation of rendering mortar samples.

The study of physical and mechanical characteristics of pre-existing mortars allows the knowledge of the characteristics which must be expected to substitution mortars, as long as possible, and in that sense provides data for the formulation of new mortar mixes for repair.

However, there is some difficulty concerning their assessment as the extraction of sufficient amount of ancient mortar samples is not always possible. Additionally, the samples are often not suitable for standardised physical and mechanical tests due to their low cohesion and irregular shape [11, 12].

In the present work two test methods developed for these kind of samples are described and the obtained results for samples of old mortars extracted from site in several case studies are presented and discussed. In the case of the test method for compressive strength a comparison with results obtained for new mortars, using the same methods and also the methods proposed by EN standard (1015-11 or 1015-18) is used to extract conclusions of the methods' possibilities.

The analysis of the experimental data and a correlation with the initial degradation level attributed by visual analysis is performed and the utility of the physical and mechanical characterization to evaluate the state of conservation of ancient mortars is assessed.

2. Case studies

The selected case studies are buildings from IV to XVIII centuries with ancient mortars based on air lime. In several cases, the ancient mortars show to be very resistant and durable to weathering factors either physical or chemical. The most serious defects of these mortars, present in some cases, concern loss of cohesion, efflorescences and criptoflorescences and loss of adhesion.
A level of degradation was previously attributed to each case study based on "in situ" visual analysis of visible mortars' damage, adjusted according to defect types and intensities observed.
The case studies and ancient mortars tested are identified on Table 1 and some of them are shown in figure 1. Some analysed ancient mortar samples with different deterioration degrees are presented in figure 2.

Figure 1 – Some case studies: a) Santa Marta Fortress; b) Elvas church; c) Nossa Sra. da Boa Nova Sanctuary – Flor da Rosa; d) Matriz church of Mértola

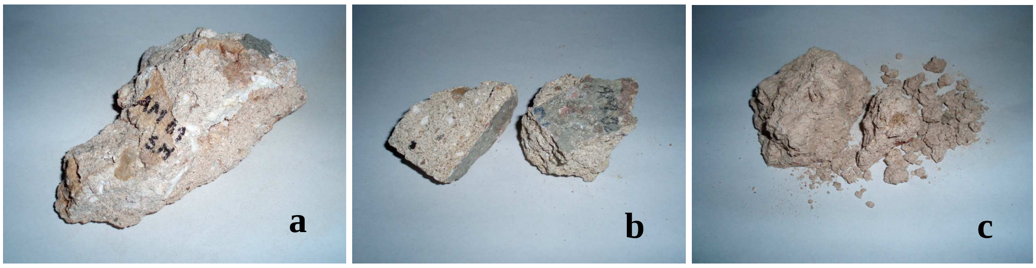

Figure 2 – Some samples of case studies with different deterioration degree: a) Low; b) Medium and c) High

3. Test methods

Render samples which can be extracted from site are usually small, irregular and sometimes with a low cohesion. Therefore, the direct application of existent standardised tests is seldom possible. In order to obviate this problem some special test methods have been studied and adapted to old mortar samples collected from site. Two tests – capillary absorption by contact and compressive strength – were prepared and experimented at LNEC together with other European Institutes within Research Projects[1]. These tests have been calibrated and described in previous works [11, 12] and here they are summarised:

Technique for capillary absorption by contact (fig. 3): the test consists on periodic weighing of samples which are put in a basket with wet geotextile gauze[2] placed in a transparent recipient with water. The specimen, which is in contact with water through the wet geotextil, is weighed together with the whole wire basket and wet gauze, every 5 minutes for the first 40 minutes and then within intervals of 60, 90, 180, 300, 480 and 1440 minutes. The absorbed water is determined through the difference between the weights measured periodically (basket + wet gauze + sample) and the initial weight. The capillarity coefficient obtained by this method is designed capillarity coefficient by contact (Ccc) and it is determined at 5 minutes and between instants 10 and 90 min (EN 1015-18 [13]) if the straight part of the absorption curve in function of the square root of time is prolonged.
Technique for compressive resistance test (fig. 4): the extracted mortar samples are arranged in a special mould within a strong mortar ("confinement mortar") in order to achieve the regular shape necessary for adaptation to the compression machine used on standardised method of EN 1015-11 [14] specification. The sample can protrude from the confinement mortar borders as it is shown in figure 4. This "confinement mortar", designed to be stronger than the extracted samples, is applied in fresh on the sample and it is normally composed by cement and siliceous sand with weight proportions 1:3 (CEM II, 32,5 : sand). An easily applied direct compression test is then carried out, giving compressive strength values (Sc_{cm}). An electromechanical testing machine ETIHM-S was used, with a load cell of 200 KN.

The mortar samples are submitted to the water absorption test and then dried and prepared to be submitted to compressive resistance test.

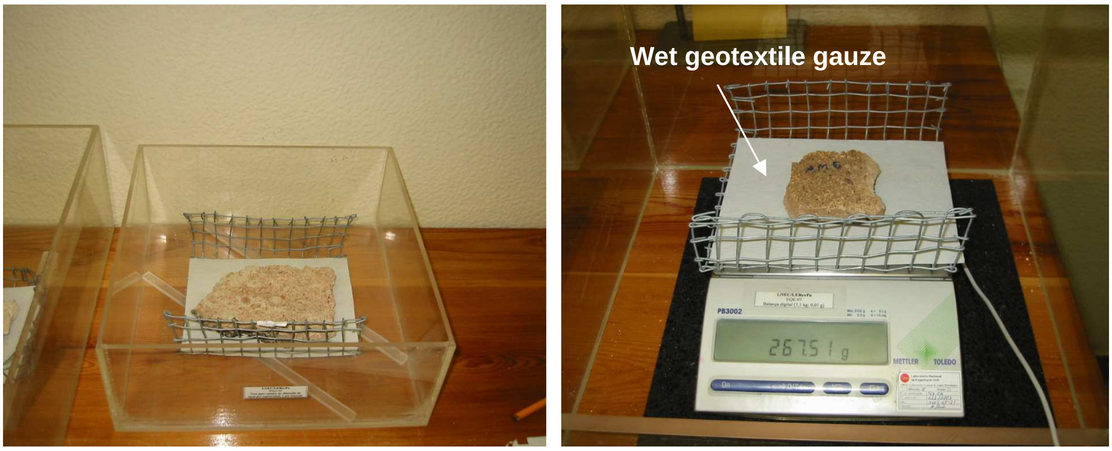

Figure 3 – Capillary absorption by contact test

[1] Project *Historical mortars*, engaging Laboratório Nacional de Engenharia Civil (Portugal), University of Ljubljana (Slovenia) and Institute of Theoretical and Applied Mechanics (Czech Republic).
[2] As the samples are superficially friable, the standard method by direct immersion in water is unfeasible so, geotextile gauze is used to avoid loosing the fine particles which are soluble in water.

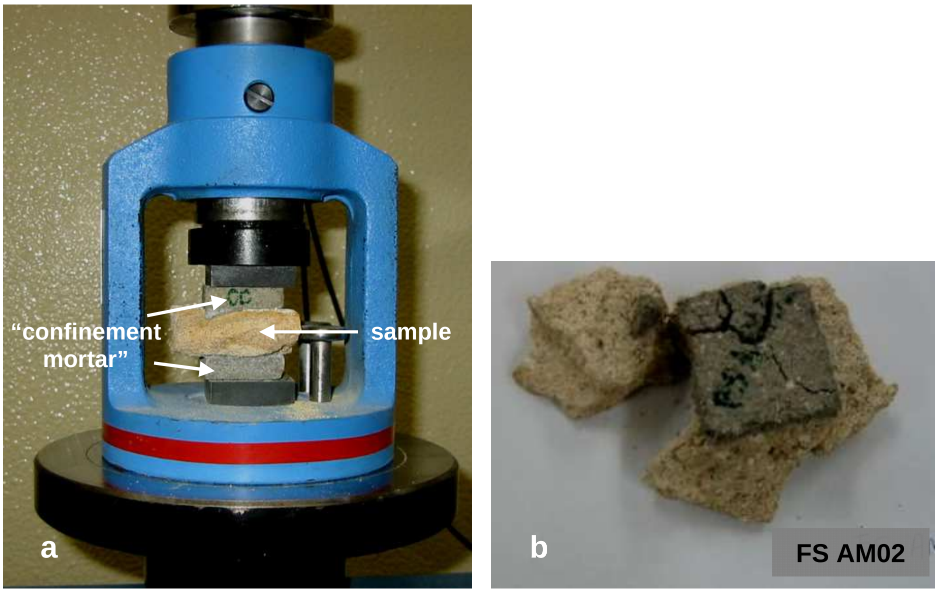

Figure 4 – Ancient mortars: a) compressive strength test; b) sample after compressive strength test

4. Test results

In order to assess the influence of the “confinement mortars” on the ancient mortars results, tests with cement and siliceous sand mortars with two different weight proportions – 1:2 and 1:3 – were performed. The results at 28 days show compressive strength values of these cement mortars are of higher magnitude respect to ancient mortars values (CEM 1:2 – 21N/mm^2 and CEM 1:3 – 11N/mm^2), confirming that confinement mortars are stronger than the extracted ancient samples. The results obtained with both compositions also confirm that they have no influence on the old mortars results.
The comparison mortars (new mortars) prepared on laboratory are identified and the test results of compressive strength by standardized and adapted methods are presented in Table 2. To take into account the representativity of the new mortars and to show more conclusive results, several different compositions of mortars – considered as possible solutions for wall rendering’s repair – were tested (figure 5).

Figure 5 – Lime mortar specimens prepared to compressive strength test (method for irregular samples)

Values of compressive strength obtained for laboratorial mortars by standardized method show low standard deviations (SD < 0,11) while higher dispersion of results for the different specimens of the same mortar were verified for values obtained by confinement method. However, even in these cases SD values are < 0,4, with exception of one case (ALB950) which SD is 0,6.
In general, the collected samples show variable thickness and in some cases they are composed by more then one layer. In some cases it was not possible to collect more than one sample due to the weak cohesion, which restricted the representativity of the obtained results in these case studies.
The capillarity coefficients by contact and the mechanical strength results obtained for the old mortars' samples are shown in Table 5.

5. Discussion

5.1 Compressive strength determined by standardised method and by the confinement mortar method

Figure 6 exhibits the correlation between the compressive strength obtained by standardised method (Sc_s) and compressive strength determined by the method for irregular samples (Sc_{cm}), showing a ratio Sc_s / Sc_{cm} varying from 0,6 to 1,0 with exception of two cases (AL2, HFLM3) which ratios were 1,1(Table 3). This variation seems acceptable, considering the previsible render strength increasing in time. In fact, it is likely that when the new compressive strength test was applied to those samples, one or three years after the test accomplished by the standardised method, the samples' degree of carbonation had already increased and therefore their resistance was higher, producing a ratio Sc_s / Sc_{cm} lower than one.

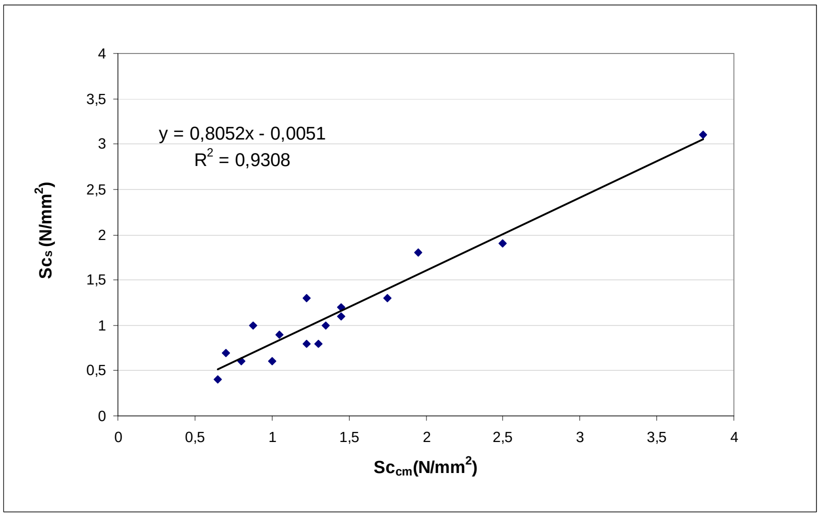

Figure 6 – New mortars. Correlation between compressive strength by standardised and new method (confinement mortar samples)

5.2 Ccc and mechanical characteristics

The interrelation between capillary coefficient at 5 minutes (Ccc 5 min) and compressive strength (Sc_{cm}) obtained for both new and ancient mortars has been plotted in figs. 7 and 8, respectively.
Hydrophobic lime mortar's values were not included in figure 7 as the lower capillarity of these mortars is not related with their compacity, thus it not possible to correlate it with the mechanical strength.
The graphics show that the mortars prepared in laboratory, which are probably not completely carbonated, present values of capillary coefficients between 10 and 20 $Kg/m^2.h^{1/2}$ and great part of compressive strength values lower than 3 N/mm^2.

A part of studied ancient mortars with different degradation levels shows a broader velocity of absorption distribution and compressive strength values. These results were expected for these heterogeneous mortars with different characteristics of age, deterioration level, climate conditions, strength requirements, etc.
A careful analysis should be performed in order to correlate the deterioration degree with capillarity coefficient and compressive strength values. The obtained information should be useful to establish intervention recommendations.

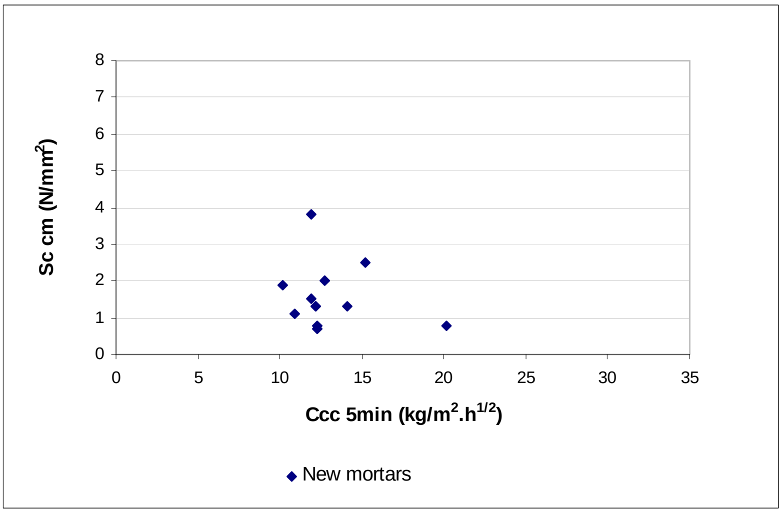

Figure 7 – New mortars. Relationship between compressive strength and capillarity coefficient by contact

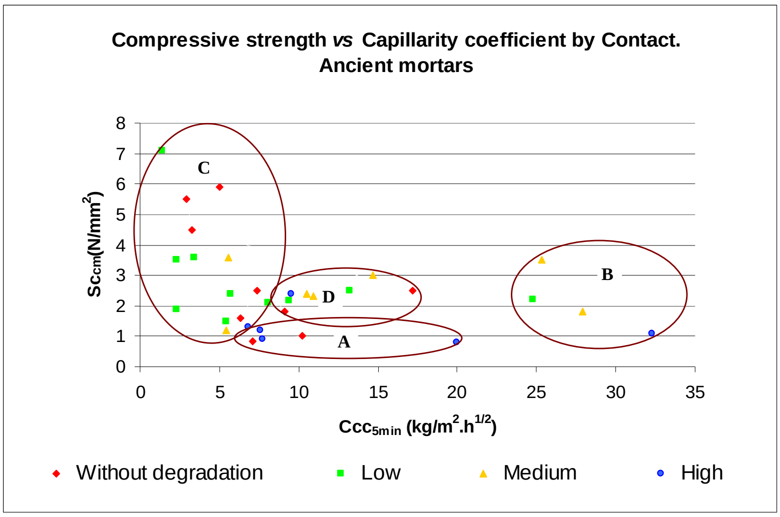

Figure 8 – Ancient mortars. Relationship between compressive strength and capillarity coefficient by contact

5.3 Degradation level, Ccc and mechanical characteristics

Figures 9 and 10 shows schemes of the relationship between the initial degradation level classifications considered for the several cases (table 1) and the minimum and maximum values of analyzed parameters: compressive strength and capillarity coefficient by contact at 5 minutes (table 3). Values of Average (AV), Standard Deviation (SD) and Variation Coefficient (VC) are also included.
The different degradation degrees of mortars and the high coefficient variation for both methods – capillary absorption and compressive strength – prove the low homogeneity among the analyzed samples. This

conclusion was in part predictable considering the diversity of samples characteristics both of mortar's origin and mortar's composition.
Medium to high degradation degree mortars show more homogeneous values concerning the compressive strength. Concerning the capillarity coefficient, the correlation between deterioration degree and this characteristic is hard, taking into account the high (> 57%) variability of the results for all level of deterioration.
The analysis of figures 9 and 10 also allows for the following observations: mortars with high deterioration degree show the higher Ccc5 and the lower compressive strength; mortars with low deterioration degree show the lower Ccc5 and the higher compressive strength.

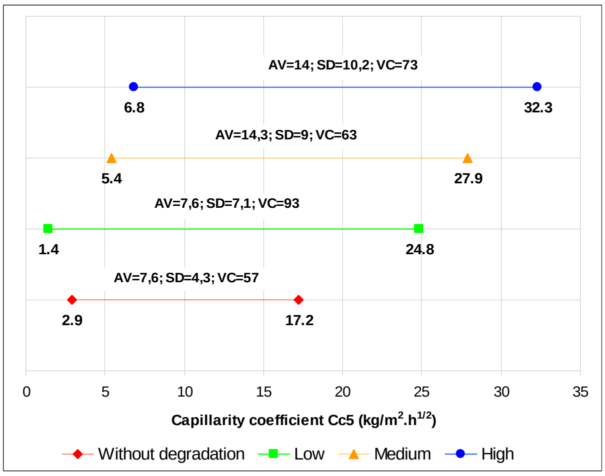

Figure 9. Schematic representation of the relationship between degradation level and capillarity coefficients by contact (Ccc5)

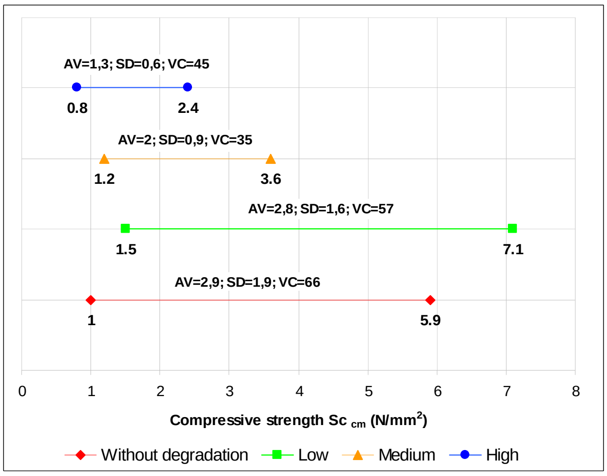

Figure 10. Schematic representation of the relationship between degradation level and compressive strength (Sc_{cm})

5.4 Global analysis

As it was referred before, a careful analysis of case studies and the obtained information are useful to give a key for possibilities of intervention recommendations.
In figure 8, four regions – A, B, C and D – were defined according to groups of physical and mechanical results.

The lower compressive strength values were obtained for the "Pombalina" wall and for the Misericórdia church of Viana do Alentejo. In both cases they are interior plaster mortars, with lower strength requirements than external renders or joints' mortars. However, in the second case it is a sample classified visually with a high deterioration degree. Figure 8 shows the referred cases which are placed in region A. Amieira do Tejo exterior mortars are also included in this region, as they have low resistance and they are classified with high degradation degree.
The render samples FSAM02, BIM, AAL and AAM06, show rather high capillary coefficients. This characteristic should be studied more carefully to evaluate the need of complementing those renders with protection additional finishing coats. Nevertheless, as the referred mortars present good enough resistance, this kind of measure must be adopted only if problems are noticed in the building clearly related to lack of water protection. These mortars are illustrated in region B of figure 8.
In region C of figure 8, the majority of cases are related to mortars without degradation or with low degradation level, which assessment of conservation state may lead to their maintenance.
The other cases, included on region D, assemble mortars with medium characteristics, similar to the performance found for substitution mortars. For these cases, maintenance is also a logic decision.

6. Conclusions

Information about physical and mechanical characteristics together with chemical characteristics is necessary both to adjust the formulation of repair mortars and to assess their state of conservation.
The analysis of their application to an extensive number of cases allowed evaluating the suitability of two adapted test methods applicable to irregular and friable samples concerning their use as auxiliary techniques to evaluate old renders conservation state.
According to the experimental results, the following conclusions can be drawn:

(1) Although the determination of compressive strength of irregular mortar samples using the referred method clearly does not furnish an exact absolute value it permits a comparative evaluation of this characteristic.

(2) There is no influence of the "confinement mortars" composition on the results. Nevertheless, a further calibration is necessary, namely to assess the influence on the results of the sample's thickness.

(3) Together with the capillarity coefficient by contact at 5 minutes the compressive strength can contribute to the characterization of the state of conservation of ancient mortars complementing the results of visual analysis.

(4) It should be noticed the importance of performing physical and mechanical characterization tests in order to assess objectively the conservation state as in some cases the visual analysis leads to incorrect classifications.

(5) Most of the samples analysed here presented results of compressive strength and capillary coefficients considered acceptable for their use, when compared with mortars formulated for use in ancient buildings' interventions and prepared in laboratory. The values obtained, together with the visual assessment point out to the conservation of the mortars studied, with possible localised repair works, with the possible exception of the Misericordia church mortars. In this case, it must be considered the hypothesis of consolidation treatments or of partial substitution by compatible new mortars.

(6) The comparison between results obtained for substitution mortars and the regions (A, B, C and D) obtained for ancient mortars corroborates to the decision of ancient mortars preservation located in C and D regions. In effect, the opposite decision probably leads to substitution by mortars either incompatible or with lower or similar performance.

(7) Further development of this study will hopefully permit to examine thoroughly the influence of the porous structure and the porous diameter distribution on the strength and on the water behaviour of ancient mortars and to establish a correlation between the porous structure characteristics and the physical and mechanical characteristics.

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Table 1. Characteristics of old mortars

Case studies	Sample	Type	Age of Building construction	Deterioration degree*	Main defects found in wall mortars
Sacavém Fortress	FSAM01 (1A) FSAM02 (1FT) FSAM07 (2FT)	Militar	XIX century	Medium	Stains, biological colonization, superficial cracks
Santa Marta Fortress	FSM AM01		XVII century	Low	Stains, localized loss of cohesion
	FSM AM02b			High	Erosion, loss of cohesion, pulverulence, detachments
	FSM zona1			Low	Stains, localized loss of cohesion
São Julião da Barra Fortress	FSJB		XVI century	Medium	Superficial cracks, biological colonization, dirt. High erosion on walls in contact with the sea
São Bruno Fortress	FSB		XVII century	Low	Superficial cracks, biological colonization, dirty
Bugio Fortress	BSM		XVI century	-	Erosion, loss of cohesion, pulverulence, detachments
	BIM			High	Erosion, loss of cohesion, pulverulence, detachments
Evoramonte Castle	EMT2		XII century	Low	Signs of biological colonization
Amieira do Tejo Castle	AAM02		XIV century	Medium	Erosion
Viana do Alentejo Castle	AAM01		XIV century	Medium	Erosion, loss of cohesion pulverulence, detachments
Mértola Cryptoportic	AAM05		IV-V century	Low	Dirt, pulverulence
Mértola Tower's River	AAM07		IV century	Low	Erosion, pulverulence
Santa Casa da Inquisição (Holy Home of Inquisition) - Monsaraz	SCI AM06	Religious	XVII century	Low	Erosion, pulverulence
Elvas church	AAM04		XVI century	-	-
Amieira do Tejo Chapel	ATe - ATi		XVI century	High	Moist stains, subflorescences, loss of cohesion and adhesion, dirt
Matriz church of Viana do Alentejo	MAT1A - MAT1B		XVI century	-	-
Misericórdia church of Viana do Alentejo	MIS3A-MIS1		XVI century	High	Plaster heterogeneity, loss of cohesion and adhesion, moist stains, efflorescences
Nossa Sra. da Boa Nova Sanctuary – Flor da Rosa	AAM03		XVII century	Low	Dirt, biological colonisation
Matriz church of Mértola	AAM06		XII century	Medium	Moist stains
Maiorca Palace	PMAM04	Palace	XVIII century	Low	Salts contamination, biological colonization
"Pombalina"[3] Wall	P7	Dwelling building	XVIII-XIX century	-	-
	P5		XVIII-XIX century	-	-
Queluz's Windmill	MSO AM03	Industrial	Unknown	Low	Stains, superficial cracks, without chemical or biological colonisation
Cetaria of Troia	CT1 CT2 BCT		I - VI century	-	Superficial stains
"Águas Livres" Aqueduct	AAL		XVIII century	Low	-

* Classification based on visual analysis.

(-) without degradation

[3] "Pombalino" is a building construction method developed and used in Lisbon after the severe earthquake that took place in 1755 on that town, characterized by walls with wooden crossed frames linked to wooden pavement's structures. These constructions are rather resistant to earthquakes, due to their ductile and solidarised structure.

Table 2. Compressive strength values of laboratorial mortars

Mortar	Volumetric dosage	Constituents	Compressive Strength (N/mm^2)								Capillarity coefficient ($kg/m^2.h^{1/2}$)
			Standardised method			Confinement mortar method				Sc_s / Sc_{cm}	Contact method
			Age	Sc_s	S.D.	Age	Sc_{cm} 1:2 [(2)]	Sc_{cm} 1:3	S. D.		Ccc $_{(5min)}$
AL1	1:3	Air lime: well graded river sand	90d	1,3	0,04	3 years	1,5	2,0	0,4	0,7	12,7
AL2	1:3	Air lime: mixed sand from the Lisbon region	1 year	1,3	0,15	1 year	1,2	1,3	0,2	1,1	12,2
AL3	1:3	Air lime: river sand	90d	0,8	0,05	4 years	1,5	1,1	0,3	0,6	10,9
ALCe	1:3:12	Cement: air lime: well graded river sand	90d	1,9	0,07	3 years	n.d.	2,5	-	0,8	15,2
ALPZ	1:0,5:2,5	Air lime: pozzolan: graduated river sand	90d	1,8	0,07	3 years	2,0	1,9	0,1	0,9	10,2
ALB950	1:1:4	Air lime: brick (950º): river sand	5 years	0,8	0,07	5 years	1,7	0,8	0,6	0,7	12,3
ALB750	1:1:4	Air lime: brick) (750º): river sand	90d	1,0	0,02	5 years	1,4	1,3	0,1	0,7	12,2
ALM	1:3	Air lime: river sand: 10% metakaolin (of lime weight)	2 years	0,4	0,04	2 years	n.d.	0,7	-	0,6	12,3
AHL1	1:3	Artificial hydraulic lime : mixed sand from the Lisbon region	90d	3,1	0,11	2 years	n.d.	3,8	-	0,8	11,9
AHL 2	1:1:6	Artificial hydraulic lime: air lime: mixed sand from the Lisbon region	90d	0,6	0,02	1 year	n.d.	0,8	-	0,8	20,2
HFL	1:3	Hydrofobic lime: mixed sand from the Lisbon region	90d	0,6	0,04	2 years	n.d.	1,0	-	0,6	1,4
HFLM1	1:2,5	Hydrofobic lime: river sand: 10% metacaulin (of lime weight)	2 years	0,7	0,00	2 years	0,7	0,7	0,0	1,0	0,3
HFLM2	1:2,5	Hydrofobic lime: river sand: 25% metacaulin (of lime weight)	2 years	1,0	0,06	2 years	0,9	0,9	0,0	1,1	1,9
HFLM3	1:2,5	Hydrofobic lime: river sand: 20% metacaulin and 5% silica fume (of lime weight)	2 years	0,9	0,10	2 years	1,2	0,9	0,2	0,9	1,5
PD1	-	Pre-dosed mortar	90d	1,2	0,10	2 years	1,4	1,5	0,1	0,8	11,9
PD2	-	Pre-dosed mortar	90d	1,1	0,01	3 years	1,6	1,3	0,2	0,8	14,1

[(2)] Comparison values; S.D. – Standard deviation; n.d. – not determined

Table 3. Capillarity coefficient and compressive strength values of samples extracted from site

Case studies	Type	Sample	Capillarity coefficient Ccc5 ($kg/m^2.h^{1/2}$)	Compressive strength - Sc_{cm} (N/mm^2)
Sacavém Fortress	Militar	FSAM01	5,4	1,2
		FSAM02	27,9	1,8
		FSAM07	14,7	3,0
Santa Marta Fortress		FSM AM01	5,7	2,4
		FSM AM02b	6,8	1,3
		FSM zone1	3,4	3,6
São Julião da Barra Fortress		FSJB	10,9	2,3
São Bruno Fortress		FSB	1,4	7,1
Bugio Fortress		BSM	9,1	1,8
		BIM	32,3	1,1
Evoramonte Castle		EMT2	nd	1,6
Amieira do Tejo Castle		AAM02	5,5	3,6
Mértola Cryptoportic		AAM05	5,4	1,5
Mértola Tower's River		AAM07	2,3	3,5
Santa Casa da Inquisição (Holy Home of Inquisition) - Monsaraz	Religious	SCI AM06	13,2	2,5
Elvas church		AAM04	5,0	5,9
Amieira do Tejo Chapel		ATe	7,6	1,2
		ATi	9,5	2,4
Matriz church of Viana do Alentejo		MAT1B	7,4	2,5
		MAT3B	6,3	1,6
Misericórdia church of Viana do Alentejo		MIS1	7,7	0,9
		MIS3A	20,0	0,8
Viana do Alentejo Castle		AAM01	10,5	2,4
Nossa Sra. da Boa Nova Sanctuary – Flor da Rosa		AAM03	2,3	1,9
Matriz church of Mértola		AAM06	25,3	3,5
Maiorca Palace	Palace	PMAM04	8,1	2,1
"Pombalina" Wall	Dwelling building	P7	7,1	0,8
		P5	10,2	1,0
Queluz's Windmill	Industrial	MSO AM03	9,4	2,2
Cetaria of Troia		CT1	17,2	2,5
		CT2	3,3	4,5
		BCT	2,9	5,5
"Águas Livres" Aqueduct		AAL	24,8	2,2

Nd – Not determined