Development of lime based mortars for repairing glazed tile coatings of historic buildings in the city of Ovar, Portugal

Desenvolvimento de argamassas de cal para reparação de revestimentos azulejares de edifícios históricos da cidade de Ovar, Portugal

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Abstract

Portugal is one of the European countries in which built heritage is a testimony of its history. In this context, the legacy of the decorative glazed tile coatings of facades must be preserved and restored.

This research is dedicated to the conservation of such facades in the city of Ovar, considered an example due to its rich heritage in glazed tiles, a high percentage of which requires a deep intervention. Therefore, this work is focused on the study of lime renders serving as a support for this type of tile facades. For this, samples were collected from several buildings in the city, targeting their mechanical and physical study with the aim of producing compatible mortars to be used for application of detached tiles in these buildings and generally for the repair of the facades with glazed tile coatings.

For this purpose, four lime mortar formulations with different volumetric ratios were composed. The aggregates used were: ordinary river sand and local gravel. In three of the mixtures, metakaolin was added, with the intention of acting as an artificial pozzolan and thus improving the performance of these mortars. The use of a pozzolanic addition promotes hardening of lime mortars in cases when the ingression of carbon dioxide is low as is the case of mortars placed below glazed tile coatings.

These mortars were also tested in the laboratory taking into account their physical and mechanical characteristics. The mechanical characteristics determined were: modulus of elasticity by two different methods, compressive strength and flexural strength. In turn, the physical characteristics determined were: water vapour permeability and water absorption by total immersion and capillary action. The best mechanical behaviour (compressive and flexural) was observed in the mortar with pozzolanic additions. Similarly, the value of the modulus of elasticity was better in mortars with pozzolanic additions. The performance of these mortars was also adequate in terms of water behaviour.

The mortars revealed suitable characteristics for application in building conservation situations concerning coating with glazed tiles.

Keywords

Conservation; glazed tiles; lime mortars; pozzolanic additions.

Resumo

Portugal é um dos países europeus em que o património construído é um testemunho da sua história. Neste contexto, o legado relativo aos azulejos de revestimento de fachada necessita de ser preservado.

A investigação desenvolvida foi dedicada à conservação destas fachadas na cidade de Ovar, considerada exemplar devido à riqueza do seu património azulejar, do qual uma percentagem considerável necessita de acções de intervenção profundas. Por este motivo, o trabalho desenvolvido focou-se no estudo das argamassas de assentamento para este tipo de fachadas. De forma a permitir o estudo das argamassas antigas, foram retiradas várias amostras de argamassa de diversos edifícios da cidade. Estas amostras foram ensaiadas para determinar as suas características físicas e mecânicas com o objectivo de produzir argamassas compatíveis, passíveis de aplicação em casos de destacamento dos revestimentos azulejares nestes edifícios e, de uma forma geral, em fachadas azulejadas.

Com este objectivo, quatro formulações de argamassas de cal, com diferentes traços volumétricos, foram efectuadas. Os agregados utilizados foram areia de rio siliciosa e uma areia local (saibro). Em três destas composições foi adicionado metacaulino, para que actuasse como uma pozolana artificial, melhorando o desempenho destas argamassas. A utilização de adições pozolânicas promove o endurecimento de argamassas de cal nos casos em que o ingresso de dióxido de carbono é baixo como é o caso de argamassas de assentamento localizadas sob uma camada de azulejo. Relativamente a estas argamassas, foram efectuados ensaios laboratoriais para testar as suas características físicas e mecânicas. Como características mecânicas, foi determinado o módulo de elasticidade utilizando duas metodologias diferentes, assim como a resistência à flexão e compressão. A determinação de características físicas incidiu na determinação da permeabilidade ao vapor de água, na absorção de água por imersão e na absorção de água por capilaridade. Verificou-se uma melhoria do comportamento mecânico (resistência à flexão e compressão) de argamassas com adição de pozolana. De forma similar verificou-se um valor mais elevado para o módulo de elasticidade destas argamassas. O comportamento destas argamassas relativamente à absorção de água revelou-se adequado.

As argamassas testadas revelaram características apropriadas para a aplicação na conservação de edifícios no caso de utilização como argamassas de assentamento para revestimentos azulejares.

Palavras-chave

Conservação; azulejos; argamassas de cal; adições pozolânicas.

Introduction

Throughout its history, Portugal created a vast amount of heritage. The built heritage is a very important part of that collection, and also a visiting card of Portugal. In this context, the legacy of glazed tile facades marked an age in the country, so it must be respected and deserves to be taken care of. A fundamental aspect of the conservation and rehabilitation of glazed tile facades is the study of mortars used as a support for glazed tiles. These mortars are usually lime based mortars. In this context, Ovar is an exemplary case because it has an important glazed tile heritage, some of it very degraded and it is also considered the glazed tile museum city. Thus, the city of Ovar can be considered an "open sky laboratory" to be used for the preservation of its built heritage and to serve as an example for future studies and interventions.

This study focuses on execution, characterization and application of new compositions of lime based mortars with and without pozzolanic additions, compatible with the existing ones. Initially, in order to characterize the samples collected directly from the facades under study, several tests there were made to provide information about the desirable characteristics for the replacement mortars. So, old mortars were subject to mineralogical analysis by XRD (x-ray diffraction), and TGA analysis (thermo gravimetric analysis) to quantify the binder percentage in mortars. Concerning the mechanical characterization, the dynamic modulus of elasticity (E) by two different methods (ultrasound and by the resonance frequency) and compressive strength (Rc) were determined. Regarding the behaviour towards water, the following characteristics were determined: water absorption by capillary action and water vapour permeability.

Four mortar formulations were subsequently executed, three consisting of air lime and metakaolin (artificial pozzolan) and one consisting solely of air lime as binders. In these formulations two different sands were used. On these a series of mechanical tests were carried out in the laboratory: determination of the modulus of elasticity (E) by the method of the resonance frequency, determination of flexural strength (Rf), determination of compressive strength (Rc) and restrained shrinkage test. These mortars were also subject to tests such as capillary water absorption. In the end, "in situ" panels were executed in the facades of buildings targeted for intervention; these were subject to the determination of adhesive strength and water absorption tests using capillary Karsten tubes.

Requirements that repair mortars should fulfil

In an operation for conservation or in cases when it is necessary to replace the existing mortars the following must ensure mechanical, physical, chemical and aesthetic compatibility with the pre-existent materials. Functional characteristics and composition (constituents and type of mortar) of existing mortars should be reproduced as faithfully as possible, especially in cases of filling gaps or in historical monuments [1].

Air lime mortars usually ensure an adequate compatibility with old adjacent mortars. With the addition of metakaolin the general characteristics of mortars remain the same, following conservation practice requirements, but they attain higher mechanical strength, higher durability, higher resistance to salts and faster hardening even under wet environments or with low exposure to air.

Development of new lime based mortars

Table 1 shows the qualitative compositions of the developed mortars.

Table 1 Qualitative composition of the new mortars

Mortar	Materials			
	Lime	Metakaolin	Argillaceous sand	Ordinary river sand
COM	X	X	X	
CRM	X	X		X
CORM	X	X	X	X
COR	X		X	

Table 2 Water/binder ratio

Mortar	Water/binder
COR	1.38
CRM	1.21
CORM	1.21
COM	1.79

The volumetric ratio that was used in the studied mortars without metakaolin was 1:3, for mortars with metakaolin the ratio that was used was 1:0.5:2.5. The 1:3 ratio was chosen considering its current use, while the 1:0.5:2.5 ratio was chosen because of previous results obtained. It is important to refer that the amount of water used for mixing the mortar, shown in Table 2, was obtained in an experimental way assuming an adequate workability as the main goal.

Experimental procedure - Results and discussion

Historical mortars characterization

In this research, seven buildings were targeted for intervention, all of them located in the city of Ovar. The buildings object of intervention and the collected mortars are essentially from the nineteenth century [2].

Sampling

Samples were taken from the following buildings:

- Ovar Musuem (MO)
- Residential building at Rua Visconde de Ovar (VO)
- Residential building at Rua Dr. José Falcão (JF)
- Residential building at Rua Camilo Castelo Branco (CCB)
- Residential building at Rua Dr. Cunha (DC)
- Residential building at Rua Dr. António Sobreiro (DAS)

Sampling in each building was performed at various heights taking into account different conservation states of the facade tiles. Sample location is identified taking into account the building where it was collected, the area from which it was taken (Z1, Z2,…), as seen in Figure 1, and the sample number (A1, A2, A3…) in the form of : House_Zone_Sample.

Fig. 1 Mortar sampling, showing different sampling areas

Mechanical characterisation

Figure 2 reflects the determination of mechanical characteristics of the historical mortars.

The determination of the elastic modulus (E) was performed in two different conditions, the first considering the distance covered by the probe through the average thickness of the sample (cross measurement) and the second considering the distance travelled towards the average length of the sample (longitudinal measurement).

Figure 2 shows that the JF building mortars have a better performance in terms of compressive strength (1.67 MPa) and the second largest value of modulus of elasticity (1785 MPa); the highest elastic modulus concerns the VO building, however in this case it was only possible to test a single sample so the result may not reflect the real performance of the building. Since all the buildings are located in the same geographic place, the average value of compressive strength of all samples is 1.38 MPa. In this way the MO building assumes the most distanced value from the average.

In the definition of the elastic modulus, the longitudinal measurement of samples led to values substantially higher (about twice) than the cross measurement. This discrepancy may be due to the fact that, in cross measurements, the heterogeneity of material that the probe crosses is greater than that in longitudinal measurements. The values for the longitudinal measurement are more reliable and consistent for this type of mortars.

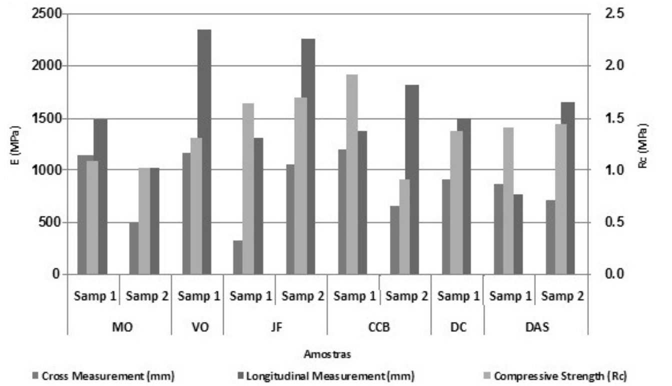

Fig. 2 Mechanical characterisation of the historic mortars

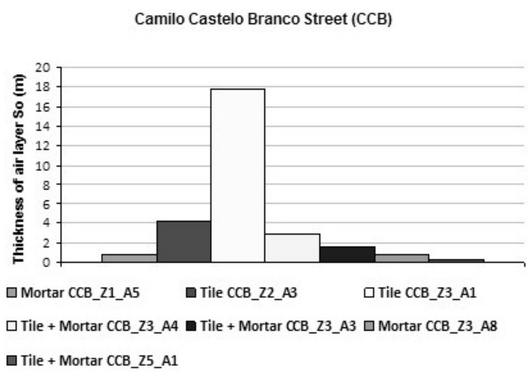

Fig. 3 Thickness of the equivalent air layers of mortar samples

Still, within the same building, the samples with lower compressive strength also have a low modulus of elasticity, with the exception of the CCB building.

It is possible to conclude that the JF building has the best average for mechanical behaviour [3]. On the other hand, the results of lime based mortars from the MO building show that the building has the worst mechanical behaviour. The discrepancy between the values of the elastic modulus and the compressive strength of samples collected in the same building is also relevant, leading to the conclusion that the area of sampling may greatly influence the mechanical characteristics probably due to changes in state of repair or due to the different degrees of exposure to aggressive actions.

Physical characterisation

Absorption of capillary water

Water absorption by capillary action test results revealed that the capillary coefficient of the two old tiles that were tested is very similar (MO_Z3_A9 - 4.69 $kg/m^2.h^{1/2}$ and CCB_Z3_A3 - 5.89 $kg/m^2.h^{1/2}$), however the capillary coefficient of the Camilo Castelo Branco building sample (CCB) is slightly higher.

Water vapour permeability of tiles, mortars and tile/mortar set

The determination of water vapour permeability was made according to EN 1015-19 [4].

Table 3 Characteristics of the developed mortars

Characteristics			Samples			
			COM	CRM	CORM	COR
Average consistence (mm)			133.25	124.50	124.00	119.50
Water/binder			1.38	1.21	1.21	1.79
Density (g/dm³)			1969.15	2001.65	2007.10	2037.60
E (MPa)	Resonance frequency	28d	3810	3300	2905	2970
		90d	2944	2448	1673	2995
	Normals	28d	3775	3639	3390	3092
		90d	2602	2280	1617	2570
	Exponentials	28d	2011	2495	2145	2226
		90d	2482	2035	1410	2482
Compressive Strength (MPa)		28d	2.78	2.63	2.18	0.62
		90d	3.15	1.82	1.66	0.65
Flexural Strength (MPa)		28d	0.52	0.42	0.37	0.20
		90d	0.79	0.41	0.26	0.20
Restrained Shrinkage		CSAF	-	-	3.70	1.60
		CREF	-	-	0.80	0.80
Capillary Coefficient ($kg/m^2.h^{1/2}$)		28d	8.01	8.71	8.64	10.94
		90d	12.93	13.04	13.73	10.15

Samples of several buildings were tested, with the following variations: only tile, only mortar and tile/mortar specimens.

From the analysis of Figure 3, it appears that the thicknesses of the equivalent air layers of mortar samples are similar, whilst tile samples have a greater difference of values. This variability may be due to the area of tile location. The sample of tile CCB_Z3_A1 which has the lower permeability was taken from an area without much effect from water action. Although the sample CCB_Z2_A3 is also from a tile, this already presents a much higher permeability than the sample above, but still lower than that of all other samples containing mortar. This sample is an area of deployment, as seen in Figure 2.

Relatively to samples of tile with mortar (2 layers), samples CCB_Z3_A2 and CCB_Z3_A4, they have a similar behaviour. Comparing them with the sample CCB_Z5_A1 of tile with mortar, but with a single layer, they have lower permeability. It should be noted that the sample containing only one layer of mortar had higher deterioration and it no longer had glaze. During the collection of samples it was found that in the area (Z5) the mortar was wet.

Characterisation of the new lime based mortars

Table 3 summarizes all determined characteristics of the developed mortars.

Concerning the determination of fresh mortars characteristics (consistence, water/binder ratio and density), it appears that COR is the mortar that has the lowest consistence of the studied mortars despite its higher water/binder ratio and density.

In fact, the characteristics of hardened mortars shown in Table 3 reveal that the mortar without metakaolin (COR) is the one that presents the worst results at all levels (modulus of elasticity, flexural and compressive strength).

It is still possible to see that the results for the modulus of elasticity determined by normal transducers are always higher than those determined by exponential transducers and look more alike the results for the modulus of elasticity by the resonance frequency.

In general the modulus of elasticity between 28 days and 90 days decreased in value. It is interesting to note that the variation in the mortars with metakaolin (CRM, COM, CORM) was higher than in the mortar without metakaolin (COR). The same is true in the case of compression and bending. Through the compression/flexural ratio, it can be seen that the mortars with metakaolin have higher relations than the mortar without metakaolin. Ideally, this ratio should be close to 1, indicating a lower cracking susceptibility, but this is not the case in the studied mortars [3]. Although relations are high, in CRM and COM mortars the same fell about 1.5 times with ageing, unlike the mortars CORM and COR that have a slight increase.

In short, mortars with metakaolin, in a 60 days period, reduced their mechanical properties in a relevant way. The air lime mortar without metakaolin had a behaviour without large fluctuations, as the values determined at 28 days were very similar to those obtained after 90 days. It is also clear that the mortar with a mixture of sands (CORM) has a worse mechanical behaviour than the mortars with only one sand type.

Regarding the susceptibility to cracking, according to Rosário Veiga [5] the COR and CORM mortars belong to the same class (average) of susceptibility to cracking. This test also indicates that the maximum force developed by restrained shrinkage is similar and relatively low in the two tested mortars, indicating good compatibility of these mortars with old supports and with old glazed tiles [6].

The adhesion test was not possible to execute as during the initial drilling procedure glazed tiles came off. Therefore, the test was performed without drilling. However, in this variant of the test, all the strength of the glazed tile was mobilized. The new tiles tested higher than the old.

From this experience it is possible to see that there is a fragility of the system, in which there is a low adhesion between the tile and mortar.

Table 3 also indicates that the mortar with the largest spread is CRM (lime, river sand and metakaolin) although the water/binder relationship, in weight, is the lowest, due to lower absorption of river sand when compared with sand of Ovar, which has more clay. The mortar COR (lime, sand of Ovar and river sand) is the mortar with less spread, higher density and greater water/binder ratio. This presents the higher capillary coefficient at 28 days, when compared with the other mortars and at 90 days it shows a lower capillary coefficient.

By comparison, it is evident that the mortars with metakaolin at age 90 days increased their capillary absorption rate and those containing no metakaolin slightly decreased the value obtained at 28 days. This decrease can be explained by the influence of carbonation, because there is a differentiation of the porous structure. The mortars with metakaolin have fibrous CSH and do not have pores filled with calcite crystals, whilst mortars with no metakaolin have carbonated producing calcite crystal and thus filled the porous structure.

Compatibility between historical and new mortars

Table 4 has the purpose of allowing the comparison between the several determined mechanical characteristics (E and Rc) common to both historical and new mortars. Regarding the comparison between the modulus of elasticity (E) of old and new mortars at 90 days it is evident, in general, that in the new formulations the value is higher than in the old mortars (about 1.5 times higher). However, it is pointed out that the mortar CORM assumes values similar to those of ancient mortars and mortar of VO building takes values similar to the new mortars.

Regarding compressive strength of old and new mortar, the obtained values are similar. Despite this similarity, it is interesting to note that the COR mortar, without metakaolin, has about half the value obtained in the old mortars. This may be due to the fact that the carbonation process of the lime has already been completed in the old mortars while in the new mortars the same process is still under way. It also possible to raise the issue if in the old mortar there is some material that works as a pozzolanic binder, such as metakaolin, because CRM and CORM mortars contain metakaolin and have very similar values to Rc.

Regarding COM mortar, its compressive strength is about twice that of old mortars. This would be expected because the mortar contains argillaceous sand and metakaolin. Thus, the last mortar can be little compatible

Table 4 Mechanical behaviour of mortars (historical and new)

Mortars		E (MPa)		E (MPa) 90d			Rc (MPa)
				Ultrasounds		Renossance Frequency	
		Long. M.	Cross M.	Normal	Exponencial		
Historical mortars	CCB	1593	917	-	-	-	1.41
	MO	1250	818	-	-	-	1.05
	JF	1785	684	-	-	-	1.67
	DC	1489	907	-	-	-	1.37
	VO	2338	1159	-	-	-	1.30
	DAS	1206	858	-	-	-	1.42
New Mortars	COM	-	-	2602	2482	2944	3.15
	CRM	-	-	2280	2035	2448	1.82
	CORM	-	-	1617	1410	1673	1.66
	COR	-	-	2570	2482	2995	0.65

with other materials from the old buildings studied. However, the moderate modulus of elasticity of this mortar shows that it has a deformation capacity closer to that of other compositions which reduces the risk of incompatibility.

From the analysis of figure 4, the difference between old and new tiles is evident in terms of capillary absorption but not in terms of the capillary coefficient. New tiles have a lower absorption of water in comparison with the old, while the value of the capillary coefficient is similar between tiles 5 and 6 and the old tiles. The new tile 4 shows the greatest difference in capillary coefficient, with lower water absorption.

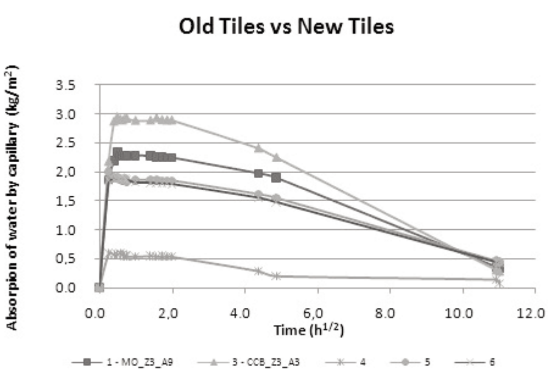

Fig. 4 Water absorption by capillary action (kg/m²)

Through the figure above it is evident that the old tiles behave better in terms of drying. The tile CCB_Z3_A3 is the one with a greater absorption of capillary water with a maximum absorption of 2.95kg/m^2, for 15 minutes. The new tile 4 has the lowest capillary absorption values, and its maximum of 2.00 kg/m^2 is, immediately, reached at 4 minutes after the start of the test.

Conclusions

Historical mortars characterization

The mechanical characteristics analysis may indicate that the area where the mortars were sampled can influence their mechanical behaviour; as an example, in one of the analyzed buildings, the samples analyzed provided the lowest and highest compressive strength values. This may be due to differences in the state of conservation, related to greater or lesser exposure to aggressive actions (water pollution).

It is noted that the modulus of elasticity determined by measuring the longitudinal length of the sample is more consistent with the values generally obtained for this type of mortar instead of the modulus of elasticity determined by measuring the cross length of the sample.

Likewise the compressive strength values are congruent with the values normally obtained for this type of mortars.

Water absorption by capillary action tests showed that the absorption of water from old tiles was higher than that of new tiles, but they also had a better drying ability.

The results obtained with water vapour permeability tests of old mortars, showed huge variations depending on various sets (tile, tile + mortar, mortar) and the different areas where they were sampled.

Results of water vapour permeability for mortars were, however, similar. There is a high influence of tiles in this parameter, and variability factors of the composition and conservation status of the tiles.

New mortars characterization

The mechanical characterization of mortars developed allowed the conclusion that the mortars with pozzolanic additions (metakaolin) have a better mechanical behaviour in comparison to the mortars without metakaolin for the ages of 28 and 90 days.

Despite the best behaviour of these lime/metakaolin mortars it should be enhanced that from 28 days to 90 days of age, in general, the mortars with metakaolin present a relevant decrease in their mechanical behaviour.

It may also be concluded that the studied mortars formed only with a single type of sand have better mechanical behaviour than the mortars studied with two types of sand (gravel and ordinary river sand), probably due to the chemical and mineralogical nature of the gravel.

Regarding the "in situ" tests it is possible to infer that there is a problem to be solved concerning the mortar / tile interface.

Compatibility between the new and historic mortars

After a comparative examination of historic and developed mortars, concerning their mechanical behaviour it may be concluded that the determined characteristics are similar.

Regarding the results for the modulus of elasticity, the new studied mortars tend to converge to the values obtained for the old mortars.

Concerning the compressive strength there is also a similarity of values, with the exception of COM mortar.

Consequently there is compatibility between the old and new mortars regarding the type of binder and mechanical behaviour. It is estimated that there is chemical compatibility between them, given the similarity of compositions.

After the development of new mortars, they were subjected to tests to characterize their behaviour towards water.

Applications like salt analysis, water absorption and adhesion were performed.

The results obtained in this study suggest that the lime based mortars with metakaolin might be good solutions for use as tile support mortars in the building facades of Ovar in conservation interventions.

It will be important to continue with this work in order to carry out more detailed characterization of old mortars of glazed tiles facades of the city of Ovar (Tile Museum City), because of the wide range of the heritage that exists.

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