Lime mortars with brick dust and grounded particles for ancient masonry: development and evaluation

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SUMMARY: Lime mortars with brick dust and grounded particles have been largely used in many regions of the world as plasters, renders and in masonry joints and repointing. In Portugal this type of pozzolanic mortars has been introduced at least since the Roman period, particularly when hydraulic characteristics were needed. Brick dust, a source of silica and also of alumina, react with the calcium hydroxide of the lime, resulting on silicates and aluminates of calcium hydrates. The brick particles (grounded to appropriate dimensions) will act as a specific aggregate.

The lime mortars with brick material are supposed to achieve hydraulic characteristics and increment their mechanical resistances and durability, compared to pure lime mortars. Also the mortar behavior in face of water (liquid and vapor) will be changed. Lime mortars with brick material also present compatibility with ancient supports, what does not happened with cement mortars.

Within this context and associating the improvement of mortars characteristics to the necessity of sustainable construction practices, some mortars formulated with lime and the addition of industrial by-products have been recently studied by several researchers. To present pozzolanic reactivity, the brick material should be in an amorphous form, obtained from a low thermal industrial process. It also should be finely grounded, so that there is a big surface of pozzolanic particles to react.

The aim of this work is to present the evaluation of the influence of brick dust and of brick particles in lime mortars. Characteristics, particularly in terms of flexural and compressive resistances, capillary water absorption and water vapor permeability will be discussed. The repair mortars requirements of compatibility with the ancient masonries and their protection will be analyzed.

Considering the increase of some characteristics revealed by some mortars with brick dust and with brick particles, when compared with a pure lime mortar, it is possible to evaluate the benefits of the addition of this type of pozzolan and aggregates in lime mortars, and the viability of this industrial by-product reutilization.

KEY-WORDS: compatibility, lime, pozzolan, brick dust, brick particles

1 INTRODUCTION

The variety of materials used in mortars is conditioned mostly by its availability. In the past, the application of air lime mortars was frequent, especially when combined with substances that give mortars some required characteristics. These substances, also known as pozzolans, give mortars hydraulic properties.

Earlier, with the development of Portland cement, it was verified a decrease in use of air lime based mortars which is mainly caused by its economic advantages, such as its quicker set. However, the knowledge of ancient mortars has large importance, because lime based repair mortars effectiveness is conditioned by some properties such as strength, water vapor permeability and water absorption due to capillary action. When well choose and applied, repair mortars prevent severe pathologies that may cause high damages in constructions.

With the amount of materials with potential use in mortar composition, it is of the global interest the exploitation of industrial residues. It brings economic and environmental benefits.

Throughout time, it has been verified that the addition of small particles of brick residues confer lime mortars positive characteristics, mostly when the argillaceous materials has been submitted to specific temperatures (not very high so that the silica and alumina do not crystallize). It is also known that about 30% of the ceramic industry's resultant product is considered not usable, in the majority of the cases, being carried into landfills. Its great strength and resistance to degradation make the problem of waste conditioning unmanageable (Binici [1]).

This experimental work role intended to analyze lime based mortars behavior, with ceramic waste as artificial pozzolan and as aggregate. The studied compositions have brick dust as pozzolan that develops a reaction with the calcium hydroxide of the in air lime. They also have grounded brick particles in partial substitution of the aggregate, with particle size distribution similar to the one of the sand present in the mortars. The mortars behavior is analyzed, having common lime and cement mortar compositions as reference, as well as some bibliography related to this subject. Compressive and flexural strength, dynamic elasticity modulus, water vapor transmission properties and water absorption due to capillary action are determined.

This study intends to expand the knowledge about rehabilitation mortars, using some uncommon techniques and actual by-products as constitution materials, which might be useful in the future, and incite the reutilization of ceramic industry waste.

2 EXPERIMENTAL PROGRAM

2.1 Materials

River (washed) sand has been used in all mixtures and the particle size distribution has been determined according to EN 933-1 (1997) [2]. The distribution curve is represented in figure 1.

The brick by-product was grounded using a hammer mill and the material was separated by particle size distribution determination. The dust residue obtained was used as a pozzolan (particles with sizes under 0,075 mm), partially substituting the binder; the material with particle size distribution similar to the sand was used to partial substitution of the aggregate volumetric proportion.

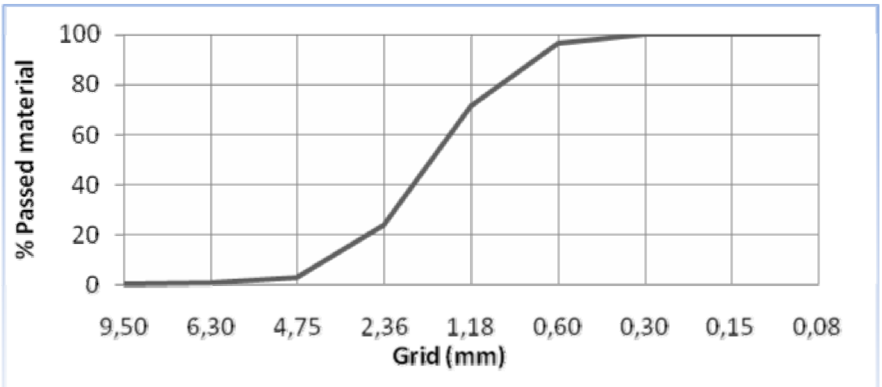

Figure 1- Particle size distribution curve

The air lime used was micronized quicklime, which was slaked immediately before mortars preparation and used as "hot lime".

Some mixtures with Portland cement have been developed as control specimens, using CEM II/B-L 32,5N type.

The loose bulk density of all materials was evaluated. The particle density, the percentage of voids of the sand, the water absorption and characteristics from the particle size distribution (fineness modulus and maximum dimension of the sand) were also determined. These properties are exposed in Tables 1 and 2.

Table 1 – Loose bulk density of the constituents

	Loose Bulk Density (g/cm^3)
Sand	1,56
Quicklime	0,76
Cement	1,18
Brick particles	1,04
Brick dust	0,87

Table 2 – Sand characterisation

Density (g/cm^3)	**Voids (%)**	**WA$_{24}$ (%)**	**FM**	**Maximum Dimension (mm)**
1,41	40	16,39	3,05	2,36

The low values of loose bulk density of the micronized quicklime and of the brick dust can be observed, denoting its fineness and probable high specific surface, compared with other materials.

2.2 Specimen preparation

The specimens of lime mortars were prepared using quicklime, slaked with water addition. Immediately after lowing temperature, other components were added (sand and brick residue). With the adoption of this method a better bonding between the lime and the other materials was attempted. If needed, more water was then added. The cement mortars were prepared mixing the cement and the sand, and only after adding the water.

The mixtures were manual and managed until adequate workability was percept. This procedure was applied to all specimens, and they were all submitted to the same chamber conditions during the curing process (temperature 22 ± 2°C and relative humidity - HR - 50 ± 5%).

Metallic moulds with 160 mm x 40 mm x 40 mm and circular plastic moulds with 106 mm of diameter and thickness of 15 mm were filled and manually compacted. The consistence of fresh mortar, by the flow table process (EN 1015-3:1999 [3]) and the retained water were determined from the water absorbed by filtering paper in contact with the fresh mortars (Faria [4]). However, these results were not reliable, because they were obtained with the slaking process very recent. As it is known, when air lime reacts with water, there is a volume increase, and high water consumption. This affects the fresh mortar's behavior and gives some uncertainty in volume proportions. In fact the resultant volume of calcium hydroxide is much higher than the initial volume of micronized quicklime, and the lime mortar compositions are "stronger" in lime proportions.

In Table 3 it is referred the proportions used in the mortars composition, and in table 4 the number of specimen applied in each test.

Table 3 – Proportions of the mortars

	Weight proportion	**Volume proportion**
A (ca:ar1,5)	1:3	1:1,46
B (ci:ar3)	1:4	1:3,03
C (ca:pt:ar1,5)	1:0,5:3	1:0,44:1,46
D (ca:gt:ar1)	1:1:2	1:0,73:0,98
E (ca:pt:gt:ar1)	1:0,5:1:2	1:0,44:0,73:0,98
F (ca:ar3)	1:6,14	1:3
G (ci:ar4)	1:5,29	1:4
H (ca:pt:ar3)	1:0,57:6,14	1:0,5:3
I (ca:gt:ar2)	1:1,37:4,10	1:1:2
J (ca:pt:gt:ar2)	1:0,57:1,37:4,10	1:0,5:1:2

ca – micronized quicklime; ci – Portland cement; pt – brick dust; gt – brick grains; ar – sand

Table 4 – Tests of hardened mortars and number of specimens tested

Tests/Mortar	A	B	C	D	E	F	G	H	I	J
Water vapour permeability (30 days)	3	3	3	2	2	-	-	-	-	-
Water vapour permeability (60 days)	5	5	5	5	5	5	5	5	5	5
Flexural strength (60 days)	3	3	3	5	3	3	3	3	3	2
Compressive strength (60 days)	3	3	3	5	3	3	3	3	3	3
Dynamic elasticity modulus (60 days)	3	3	3	5	3	3	3	3	3	2
Water absorption due to capillary action (60 days)	3	3	3	5	3	3	3	3	3	2

2.3 Experimental description and results

Dynamic elasticity modulus and compressive and flexural strength

The specimens used to these tests were the ones with prismatic shape. For each one, the dynamic elasticity modulus was first determined, followed by flexural strength determination. One of the half part of each sample remaining from the flexural strength test was used to evaluate the compressive strength.

The dynamic elasticity modulus was calculated by an equipment based on the ultra-sounds propagation through materials principle (Montoya [5]). The apparatus determines the period of time each impulse takes to go through the mortar sample, from one top to another. The results appear in Table 5, in terms of average value and standard deviation.

To compressive and flexural strength evaluation the procedure indicated in EN 1015-11 (1999) [6] was followed.

Except the ones with cement, all mortars present reduce values of flexural and compressive strength. Compositions C, D and E were the ones that possessed the lesser values of flexural strength and C, E and J the ones that have minor value of compressive strength. The mortar with lower dynamic elasticity modulus is D, although it is consider that all air lime mortars analyzed present extremely high values to this type of mortars.

Water absorption due to capillary action

Water absorption due to capillary action was determined using a half of each specimen of the flexural strength test. The procedure followed some indications of EN 1015-18 (2002) [7]. The specimens were kept in a ventilated oven capable of maintaining a temperature of 60ºC, until constant mass is reached. The specimens were then placed with the cut surface downwards in a 5 mm water layer, inside a large covered container, where a saturated environment was guarantee in its interior (with RH of approximately 95 ± 5%). The specimens mass was determined after 5, 10, 30, 60, 90 and 180 minutes of immersion in the water layer. After that, the mass was determined every 24 hours. The results are presented in terms of average values and standard deviation in Table 6 and graphically in Figure 2.

Table 5 – Dynamic elasticity modulus and flexural and compressive strength results

Mortar	Dynamic elasticity modulus		Flexural Strength		Compressive strength	
	MPa	stdev	MPa	stdev	MPa	stdev
A (ca:ar1,5)	6150	62	0,55	0,05	0,55	0,05
B (ci:ar3)	11944	215	2,64	0,35	6,48	0,54
C (ca:pt:ar1,5)	6186	53	0,33	0,05	0,30	0,00
D (ca:gt:ar1)	5738	120	0,34	0,02	0,45	0,02
E (ca:pt:gt:ar1)	6090	59	0,34	0,04	0,32	0,03
F (ca:ar3)	7317	95	0,34	0,04	0,44	0,10
G (ci:ar4)	12212	658	2,13	0,13	5,47	0,77
H (ca:pt:ar3)	7021	13	0,43	0,06	0,66	0,03
I (ca:gt:ar2)	6370	126	0,36	0,03	0,48	0,01
J (ca:pt:gt:ar2)	7144	24	0,48	0,04	0,23	0,01

Table 6 – Water absorption due to capillarity action and capillary coefficient

Mortar	C		CA	
	$kg/(m^2.min^{0.5})$	stdev	kg/m^2	stdev
A (ca:ar1,5)	6,05	0,38	22,69	0,65
B (ci:ar3)	1,29	0,08	17,79	1,07
C (ca:pt:ar1,5)	6,12	0,12	29,26	2,31
D (ca:gt:ar1)	6,41	0,29	26,73	0,74
E (ca:pt:gt:ar1)	6,75	0,08	30,17	1,46
F (ca:ar3)	5,38	0,13	18,10	1,12
G (ci:ar4)	1,02	0,05	14,48	0,89
H (ca:pt:ar3)	2,45	0,18	24,00	1,96
I (ca:gt:ar2)	2,91	0,15	19,72	0,89
J (ca:pt:gt:ar2)	3,45	0,35	20,13	1,52

C – Water absorption coefficient; CA– Capillarity water absorption.

According to the results, the mortars E and D have a higher water absorption coefficient. G and B mortars present the lowest results, which were expectable for cement mortars. The mortar that absorbed more water due to capillary action was C, containing brick dust. Cement mortars present a lower rate of water absorbed.

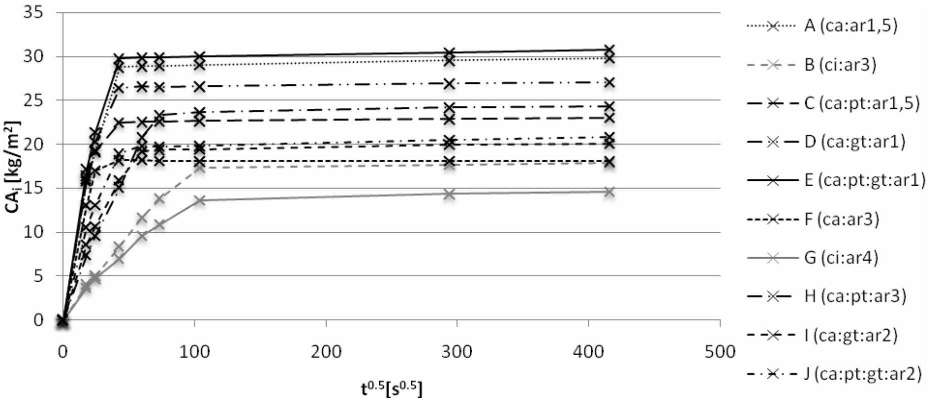

Figure 2 – Water absorption due to capillary action

Water vapor permeability

The water vapor permeability was determined according to EN ISO 12572 (2001) [8], because there were no conditions to develop the assay in accordance with norm EN 1015-19 (2000) [9], related to the water vapor permeability of hardened mortars. However, some of the aspects mentioned in the last one were taken as reference, as well as information of the assay procedure (Faria, [4]). The circular specimens were used.

By the options indicated in EN ISO 12572 (2001) [8], the wet cup assay was taken for conditions of RH between 50% and 100%. The role is to create two distinct environments in each side of the surfaces of the specimen, with distinct relative humidity and, therefore, with different partial vapor pressure, in order to generate a constant water vapor flow, through the specimen. In this case, the vapor flow establishes itself from the cup's interior to its exterior (from the zone of superior relative humidity to the zone of inferior relative humidity). The results for 30 and 60 days are presented in Table 7 and 8.

Table 7 – Water vapor permeability and water vapor resistance factor (30 days)

Mortar	δ ($x10^{-11}$)		μ	
	kg/(m.s.Pa)	stdev		stdev
A (ca:ar1,5)	1,76	0,09	11,09	0,57
B (ci:ar3)	0,98	0,14	20,15	2,58
C (ca:pt:ar1,5)	1,74	0,03	10,99	0,18
D (ca:gt:ar1)	1,90	0,12	10,30	0,64
E (ca:pt:gt:ar1)	1,99	0,26	9,90	1,28

δ - water vapour permeability; μ – water vapour resistance factor; stdev – Standard deviation.

Mortars D and E are distinguished with a superior value of water vapor permeability, although E presents a high standard deviation. The worse behavior is relative to the cement mortar, B, whose water vapor resistance is approximately the double of the other mortars.

Table 8 – Water vapor permeability and water vapor resistance factor (60 days)

Mortar	δ (x10^{-11})		μ	
	kg/(m.s.Pa)	stdev		stdev
A (ca:ar1,5)	1,62	0,00	12,06	0,58
B (ci:ar3)	1,08	0,01	18,08	0,11
C (ca:pt:ar1,5)	1,60	0,03	12,23	0,27
D (ca:gt:ar1)	1,74	0,15	11,29	0,96
E (ca:pt:gt:ar1)	1,85	0,19	10,62	0,98
F (ca:ar3)	1,54	0,04	12,70	0,30
G (ci:ar4)	1,21	0,03	16,12	0,47
H (ca:pt:ar3)	1,64	0,05	11,90	0,36
I (ca:gt:ar2)	1,59	0,05	12,24	0,36
J (ca:pt:gt:ar2)	1,41	0,03	13,82	0,22

δ - Water vapor permeability; μ – water vapor resistance factor; stdev – Standard Deviation

The mortars D and E present the highest values of water vapor permeability. With the exception of the cement mortar, all the mortars tested at 30 and 60 days tend to reduce the water vapor permeability through time and consequently its water vapor resistance factor tends to increase.

As expected, the highest values of water vapor resistance factor refer to cement mortars and among mortars with brick residues, the ones with brick grains seemed to register better behavior.

2.3 Discussion

It was considered that the results from fresh mortars consistence determination were not reliable and that no clear connection could be established with other test results.

The dynamic elasticity modulus obtained with all the analyzed lime mortars is considered too high. However, this factor might be conditioned for some irregularity of the specimens' bases and by the method of test itself.

It was considered that acceptable values of flexural strength for substitution mortars varies between 0,2 and 0,7 MPa. Therefore, all air lime mortars studied present acceptable values. In what concerns compressive strength, the interval generally indicated corresponds to values between 0,4 and 2,5 MPa. Lime mortars C, E and J register inferior values then those considered acceptable. However, in general all lime mortars present low values of compressive strength. The extremely low value of the compressive strength of mortar J is distinguished. It is possible that this result was influenced by some unknown irregularity during the specimens' production or the test procedure itself, once the flexural strength is higher than the compressive strength.

Analyzing the composition analysis, it is verified that in general, lime mortars with 1:3 (binder : aggregate) proportion present better behavior (exception for control mixture A).

As expected, cement control specimens possess higher dynamic elasticity modulus, as well as flexural and compressive strength.

Globally and in relation to mechanical properties, it is considered that mortars presenting better global results are A, H and I.

In terms of water vapor permeability, it is verified that it tends to diminish in time, except for cement mortar, B. Generally all mortars present good behavior in terms of permeability. In this subject, mortars D and E demonstrate better global behavior, and both contain brick grain residues in its composition. It is considered, however, that this assay is not determinative at 30 days because the lime carbonation process is slow. From mortars with brick residues, the one that possess better behavior had in its constitution brick grain and brick dust, with less amount of aggregate (mortar E).

Lime mortars possess, generally, a bad behaviour to water absorption due to capillarity. They register a very high initial absorption speed. However, mixtures H and I are distinguish, because they demonstrate to have good behavior. This mortars possess in its composition respectively brick dust and brick grains, showing that these type of materials can have an important role in what concerns capillary action. In this analysis, cement mixtures present better results related with the coefficient of capillarity and water absorbed by capillary action. In the specimens group, it is verified that water absorption speed increases with the increment of cement proportion.

In relation to the total amount of water absorbed, lime mortars F, I and J register a better performance, which might be related to brick grain or brick dust in larger proportions (I and J) and with a larger aggregate proportion (F). Mortars with greater cement or lime proportions present a worse behavior.

In global behavior terms, it is verified that mortars H and I register a better performance among the studied characteristics. Therefore, it will be correct to affirm that, in adequate amounts and traces of approximately 1:3 of lime and aggregate, with brick dust or brick grain in aggregate substitution, mortars could be viable as substitution mortars.

3 CONCLUSIONS

This experimental work allowed the acquisition of some knowledge about actual brick residues as lime mortar components. Through the tests results, it was possible to realize that the use of brick residues will not only bring advantages in an economic and environmental level, but also reveal an industrial by-product with which good technical characteristics can be implemented as lime mortar components, and that can be applied in buildings rehabilitation.

Mortars with a correct proportion of lime and aggregate, that possess in its composition brick dust and/or brick grains, according to elaborated tests, seems to present a quite appropriate behavior.

However, an adjusted substitution mortar does not only depend on the most common characteristics. Simultaneously, the support conditions, the climatic ambiance and other items on which application depends are also very important. So it is necessary to evaluate all situations.

It is considered that the characteristics evaluated are not enough to define mortars behavior and that other parameters determination should be required. A complementary evaluation of the mortars characteristics would be recommended.

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