# Influence of Type of Air Lime and Curing Conditions on Lime and Lime-Metakaolin Mortars

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Abstract Air-lime mortars with or without pozzolanic components were largely used in the past. Due to natural or accidental degradation it is often necessary the application of repair mortars, durable and compatible with the masonries of historic buildings. Within this context and associating the improvement of mortars characteristics to the necessity of sustainable construction practices, mortars formulated with limes and the addition of pozzolans have been studied.

Each type of mortar presents its specificities. In pure lime mortars the setting occurs by carbonation and in lime-metakaolin mortars it occurs both by carbonation and hydration. A crucial question in order to optimize the characteristics of the mortars (and its applicability) is related with the curing conditions, which potentiate differently the reaction and consumption of the calcium hydroxide.

This article describes an experimental campaign with different pure air lime mortars and lime-metakaolin mortars, cured under different conditions of relative humidity and  $CO_2$  content. Properties of the mortars, mainly in terms of mechanical behaviour and open porosity, capillary water absorption, drying capacity and resistance to chlorides contamination, are obtained, compared and discussed. The benefits in some properties revealed by the different mortars are correlated with the laboratorial curing conditions and with *in situ* application possibilities.

# **1** Introduction

Air lime-based mortars are present in all Portuguese ancient buildings, in different types of application. The most common types of application in ancient buildings are as renders, plasters, ceramic glazed tiles adherence layers and masonry joint mortars.

Paulina Faria Nova University of Lisbon, 2829-516 Caparica, paulina.faria@fct.unl.pt Ana Martins Polyth. Inst. of Setubal, 2839-001 Lavradio, ana.martins@estbarreiro.ips.pt These mortars are composed by air lime - as unique or at least main binder -, sand and sometimes pozzolans.

An important role is played by the aggregates, as their mineralogical type, maximum size and gradation, influence the structure and the behaviour of the mortars [Konow 2003, Stefanidou & Papayianni 2005, Rato 2006, Faria et al. 2007].

Lime-based mortars are ecological mortars, in comparison with mortars with cement, because air lime is obtained by calcination at lower temperature - approximately half the temperature - than the one needed for cement production. Also they are compatible with historic masonries, what does not happened with cement-based mortars [Faria-Rodrigues & Henriques 2004].

Air lime can be purchased and used as a hydrated powder - after hydration of quicklime with a minimum of water - or as putty - obtained by hydration of quicklime with excess of water [Faria et al. 2008, Margalha et al. 2011]. The hydration of the quicklime occurs with rising temperature and traditionally can be held together with the addition of vegetal or animal fat, for water repellence of the air lime.

The pozzolans, fine materials rich in silicates and aluminates in amorphous form [IPQ 2010] – although not being a binder because pozzolans do not react alone with water -, can partially substitute the air lime. In the presence of water, the pozzolans react and combine with the calcium hydroxide of the air lime, developing calcium silicate and calcium aluminate hydrates that confer hydraulic properties to the mortars [Charola et al. 2005] and can also increment the mortar durability – but generally maintaining its compatibility with old masonry materials [Faria-Rodrigues 2009, Veiga et al. 2009].

An available and promising pozzolanic material is metakaolin, obtained by dehydrating kaolinitic clays at around 600°C, bellow temperatures that cause the formation of a vitreous phase and crystallization of other phases such as mulite [Velosa et al. 2009]. Kaolinitic clays are available in Portugal, although many quarries are no longer active due to lack of demand. Kaolin for metakaolin production can also be obtained from some industrial by-products or from kaolin rejected from other industries (as it is the case of kaolin rejected for fine ceramic production or kaolinitic sand washing). Metakaolin is an amorphous material, with high specific surface and also high content of acidic oxide (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> > 90%) [Fortes-Revilla et al., 2006]. Due to lack of other traditional pozzolanic materials, such as natural pozzolans or fly ash from thermoelectric plants, and the abundance of kaolins, the Portuguese industrial and research sectors are working towards metakaolin production [Ferraz et al. 2012] and optimization of application [Velosa & Veiga 2007, Andrejkovicová et al. 2011, Faria et al. 2012].

Pure air lime mortars harden by carbonation, while air lime-pozzolan mortars harden by carbonation but also cure by hydration. The carbonation process occurs by combination of  $Ca(OH)_2$  with  $CO_2$  from the environment and depends on the presence and transport of  $CO_2$  through the mortar. The carbonation of air lime mortars affect the pore structure of the mortars and in consequence its properties. There is a change in the volumes of pores associated with the transition of the

binder from calcium hydroxide to calcium carbonate. It seems that pores below 0.1  $\mu$ m are not involved in the carbonation process [Lawrence et al. 2007], what might explain why the carbonation of air lime mortars can continue for so many years.

In lime-metakaolin mortars the amorphous silicates and aluminates react with  $CO_2$ , producing CSH gel and several calcium silicate and aluminate hydrates (as  $C_2ASH_8$  and  $C_4AH_{13}$ ) [Fortes-Revilla et al., 2006]. This pozzolanic reaction is a slow process as well; depends on the presence of uncarbonated  $Ca(OH)_2$ , the reactivity of the pozzolan - which also depends on its specific surface - and the presence of water.

The presence of water, as moisture, is therefore important for the  $CO_2$  transport for carbonation and for the hydration of compounds by pozzolanic reaction.

The microstructure that is established and consequently the characteristics of lime-metakaolin mortars depend on which of the two reactions prevails [Fortes-Revilla et al. 2006] and that depend on the reactivity of the constituents, their proportion in the mortars and the curing conditions.

Further advantages of air lime-metakaolin mortars are their lower environmental impact, when compared to cement mortars. This is due to lower energy consumption during the air lime and the metakaolin production, the possibility of using kaolinitic by-products or kaolin rejected by other industries partially substituting binders [Tironi et al. 2012; Pontes 2011] and the absorption of  $CO_2$  by carbonation. Also an advantage can be the light colour of the mortars - that can be changed a little by the chosen sands or other aggregates -, important for joint repointing and to unpainted renders.

Since the beginning of the 20th century and until nowadays air lime mortars have been replaced in ancient buildings, mainly in plasters and renders, by cement mortars and due to this reason, the thousands of years knowledge of lime mortars craftsmen abruptly decreased. In the last decades, the origin of many defects that appeared in ancient buildings was correctly attributed to the cement mortars that have been applied. Many researchers, all over the world, have been trying to fundament the advantages of air lime-based mortars when compared with cement-based mortars. Fortunately also the knowledge of lime mortars craftsmen tends to be regained [Sandstrom-Malinowski 2009, Faria et al 2010].

The main problems of cement mortars when applied as substitution renders in ancient buildings are their mechanical, chemical and physical incompatibility with the masonries and with other old mortars. In fact, cement mortars are much stiffer and stronger than the old masonry walls, and cement mortar renders induce stresses at the interface with those walls. Later on it tends to break by the wall that the render was supposed to protect.

Frequently cement mortar releases salts, namely sulphates, which also contribute to the contamination of those walls.

Many times the old walls have access to water, for instance by capillary rising from the ground, by problems in the roofs, by migration of the rain water through the porous structure of the exterior layers of the walls, by water vapour generated inside the building that migrate through the thickness of the walls, and its protective layers, towards the exterior. The water can transport salts from the outside and also salts that were already inside the walls. When the water front faces a layer that is much less permeable to water vapour in comparison to the wall materials some paint layers [Brito et al. 2011] or some substitution mortar layers, for instance -, the water, eventually transporting dissolute salts, concentrate in the previous layers, often the exterior surface of the original walls, weaker than the impermeable rendering layers.

In cold climates the water in the wall can originate problems of freeze/thaw, generating stresses and weakening the surrounding material. When salts like chlorides are involved, they can easily go through cyclic crystallization/dissolution processes, involving stresses that also weaken the old materials [Gonçalves 2007].

Even if the exterior rendering seems in good conditions, behind its thickness often there are voids, due to material that lost cohesion. Later on the apparently good substitution render detaches, showing a huge degradation in the wall itself

Nevertheless air lime mortars also have disadvantages mainly regarding actual construction constrains. In fact, in construction sites rapid construction schedules and fast resistant gains are often pursuit and these are not easily achieved with pure air lime mortar renders.

Frequently no one cares if cement renders will behave properly and if they will really protect the walls; the short term apparent resolution of the problem is generally the only constrain and that is why in some countries, cement mortar plasters and renders continue to be applied on interventions on ancient buildings.

But it should also be remarked the fact that lime renders need different application procedures. Sometimes lime renders are applied with the same techniques as if they were cement renders, what lead to new uses of lime mortars not always successful. Some of those different procedures are: the air lime-based mortars should be applied with low consistency compared with cement mortars because their workability is very good – if the water is added in order to achieve similar consistency to the one needed for cement mortars, it will be too much and the mortar layer will be to porous; the lime render have to be applied in separate thin layers, with about a week between them to achieve some carbonation; the lime mortar rendering layer should be re-tight over the base after suffering initial shrinkage to achieve better compactness and nullify that shrinkage.

The characteristics of the walls where the mortars are applied alter significantly the properties of the mortars and that should also be considered when formulating a mortar. But in the study that is presented here, the main focus is on the different properties obtained with air lime-based mortars cured in different relative humidity conditions and  $CO_2$  content.

In face of the results, several conclusions can be taken in order to optimize *in situ* curing conditions of pure air lime mortars and of air lime-metakaolin mortars, and to define possibilities to accelerate laboratorial curing of specimens.

# 2 Experimental Campaign

# 2.1 Preparation of the Material and of the Mortar Samples

For the preparation of mortars two commercial "washed" sands were used as aggregates: a 0/4 sand with coarser particles and a 0/2 sand only with finer particles; they were used in a mixture of one part of finer sand and two parts of coarser sand (Fig. 1). The mixture of sands intended to enlarge the grading curve of the mortar aggregate and to minimize the volume of voids (which was 35% for the 0/4 sand, 40% for the 0/2 sand and 32% for the mixture).



Fig. 1 - Grading curves of the sands and of the mixture of sands

Two calcium limes were used as binder in the different mortars: a powder hydrated lime EN 459-1 CL90-S commercialized by Lusical (designated in the following text as air-lime AL); a water repellent lime putty EN 459-1 CL 90-S PL commercialized by Fradical (designated as PL) [CEN 2010]. From what is known, as water repellent natural product, an olive oil by-product is incorporated in the lime putty production.

While a lime putty stays uncarbonated since always covered by a water layer, care should be taken to assure that a powder hydrated lime stays uncarbonated [Dheilly et al. 2002]. In fact, in Portugal is common that powder hydrated lime is commercialized in paper bags, not completely air and water vapour tight. Some samples collected from closed bags directly received by the factory and similar bags after being storaged at interior laboratory ambiance for some time showed a higher content of carbonated lime in the samples that have been storage. The hy-

drated lime that was used was recently produced and was storage carefully (the bags were kept inside other plastic bags).

A metakaolin was used as a pozzolan (Mk) produced from thermal and granular treatment of a Portuguese kaolin from Grupo Lagoa (Table 1). This enterprise was, by that time, still optimizing the product [Ferraz et al. 2012]. When the pozzolanic reactivity was tested by the Chapelle test determined by NF P 18-513 [AFNOR 2010] it did not tested "reactive" (a value of 265 mg Ca(OH)<sub>2</sub>/g metakaolin was registered while the reference value would be 700 mg Ca(OH)<sub>2</sub>/g metakaolin). Its specific surface by the Blaine method was 9310 cm<sup>2</sup>/g. Other metakaolins can be found with much higher specific surface and reactivity by the same tests, such as 33760 cm<sup>2</sup>/g and 860-1320 mg Ca(OH)<sub>2</sub>/g metakaolin for commercial metakaolin Argical M 1200 S [Pontes 2011, Ferraz et al. 2012].

Table 1 - Metakaolin characterization [Gomes 2010, Pontes 2011]

Mk	SiO <sub>2</sub>	$Al_2O_3$	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	TiO <sub>2</sub>	$P_2O_5$	CaO	LOI
[%]	52,17	44,5	0,45	0,15	1,42	0,12	0,01	1,42

All mortar volumetric compositions were 1:3 - 1 volume of binder (calcium lime (or calcium lime+metakaolin) and 3 volumes of sand (1 volume of finer sand and 2 volumes of coarser sand). The volumetric composition was chosen in order that the volume of binder would optimize the filling of the voids, left by the volume of sand. The volumetric compositions of the constituents were transformed in precise weight values by the loose bulk density [CEN 1998a], presented in Table 2.

Table 2 - Loose bulk density of mortar constituents

Material	AL	PL	Mk	Sand 0/2	Sand 0/4	
Loose Bulk Density [g/cm <sup>3</sup> ]	0,38	1,26	0,71	1,5	1,55	

The dried weight of a specimen of lime putty registered that the lime putty had 59% of water content. The lime content of the lime putty PL multiplied by its bulk loose density, compared with the loose bulk density of the hydrated lime AL, showed that the content of lime in the lime putty mortars was 30% higher than the one in mortars with powder hydrated lime.

In lime-metakaolin mortars 20% of the mass of the volume of lime was replaced by identical mass of metakaolin. In terms of weight composition, it represented 25% of the mass of the remaining lime. In mortars with lime putty, once the volume of lime was heavier - compared with the same volume of powder hydrated lime -, the 20% mass content in metakaolin was higher but still 25% of the mass of the remaining lime.

Four different mortars were prepared: mortar AL with powder hydrated lime; mortar AL+Mk with the same hydrated lime and 20% of metakaolin substitution; mortar PL with lime putty; mortar PL+Mk with the same lime putty and 20% of metakaolin substitution (Table 3). By weight the mortar compositions were 1:12 for mortars with lime AL and 1:3,5 for mortars with lime PL – in this case, including the water of the lime putty. By weight but without considering the water content of the lime putty, the composition of mortars PL was 1:9 and of mortars PL+Mk was 1:11. As it can be seen, similar volumetric ratios of mortar constituents lead to different weight compositions and the lime putty mortar constitution (excluding the water) is stronger in terms of binder (Table 3).

Table 3 – Mortar and curing designation, volumetric and weight composition, water/binder ratio and flow table consistency

	Mortar/ Cur-	Volumetr. Comp.	Weight	Comp.	Water/binder Ratio		Flow
Mortar	tion	(Binder: Sand)	(Binder: Sand)	(Lime:Mk :Sand)	Added	Existent	[mm]
AL	AL_D AL_S AL_C AL_H	1:3	1:12	1:0:12	2,4		155
AL+MK	AL+Mk_D AL+Mk_S AL+Mk_C AL+Mk_H	1:3	1:12	1:0,25:15	2,4		154
PL	PL_D PL_S PL_C PL_H	1:3	1:3,5	1:0:3,5		0,6	151
PL+MK	PL+Mk_D PL+Mk_S PL+Mk_C PL+Mk_H	1:3	1:3,5	1:0,25:4,6	0,2	0,7	152

The mixture of the mortar components was mechanical and always identical: the water was added in the mechanical mixer tank, followed by the air lime and the sand (previously hand homogenized); mechanical mixture at low speed for 30 seconds; another 30 seconds to scrape the material inside the tank and mechanical mixture for three more minutes at high speed. The procedure was based on EN 196-1 [CEN 2005] and EN 1015-2 [CEN 1998b] but the period of mixture was enlarged because the one defined in the standard was considered inadequate for air lime-based mortars. In lime putty mortars PL no water was added and only a little amount was added for PL+Mk mortars; the other constituents were mixed similarly.

The water/binder ratio is registered in Table 3. The existent water was determined by the water content of the lime putty of mortars with PL.

The mortar samples were mechanically compacted in two layers inside prismatic metallic moulds 40 mm x 40 mm x 160 mm. The general samples of each mortar were subjected to four types of curing conditions until the age of test – at 7 days for shrinkage, from 30 to 120 days for carbonation, at 60 days for mechanical tests, at 120 days for capillary and drying tests -, at 20°C temperature, inside conditioned chambers: 50% relative humidity (RH) - cure identified by D; 65% RH – standard cure identified by S; 65% RH and 5% carbon dioxide – cure identified by C; 95% RH – cure identified by H (Table 3). Six samples of each mortar were subjected to each curing conditions. After tested at 60 days for mechanical characteristics, one half of each sample was kept in interior summer conditions until 120 days and tested for compressive strength, and after tested at 120 days for physical characteristics, also one half of each sample was kept in interior conditions and tested at 17 month for resistance to chlorides contamination.

# 2.2 Testing Program and preliminary results

For each type of mortar multiple mixings were made, due to the mechanical mixer capacity and the quantity of mortar samples required for the experimental campaign. For each type of mortar, when needed, always the same quantity of water was added. The quantity of water was added so that all the mortars seemed to provide good workability for application in real conditions. The influence of the amount of water in the fresh mortars was evaluated by the consistency flow table test [CEN 1999a].

The mortars shrinkage inside the moulds was evaluated, with six samples of each mortar/curing condition, before demoulding, at the age of 7 days - except for mortars cured inside the carbonation chamber (cure C) that could only be demoulded (without registering any visual shrinkage) at the age of 21 days.

At the age of 7 days those C samples were almost as soft as at the moment of moulding; at the age of 14 days the problem persisted and only at the age of 21 days, with particular care, they could be demoulded. A possible justification for this occurrence was a possible saturation of carbonate ions at the only exterior surface of the mortar samples (still inside the moulds), forming a solution rich in hydrogen carbonates - from the reaction of carbon dioxide with water - that strongly diminished the carbonation velocity or even stopped the carbonation front in the

mortar sample exterior face. It showed that confined rich CO<sub>2</sub> environments are not adequate for laboratory initial curing of lime-based mortars.

Nevertheless, and except for mortars C, shrinkage inside the moulds of the different mortar submitted to diverse curing conditions was registered, showing that shrinkage evaluation since moulding - and not only after demoulding - is important to lime-based mortars.

The carbonation velocity intended to be evaluated by the phenolphthalein method. A phenolphthalein solution at 0,5% in alcohol was applied in freshly cut surfaces - 2 cm thickness - of three samples of each type at the ages of 30, 60, 90 and 120 days. It was obvious that mortar C achieved complete carbonation during the test; for the other curing conditions the test colour change (and the carbonation) seemed to be very slow, generally a little faster in mortars D and S, and a little slower in those in cure H. For lime-metakaolin mortars, a trend could not be seen using this test and other method should be pursuit [Lawrence et al. 2006], especially taking into account the influence of the pozzolanic reaction on PH.

At 60 days of age, three samples of each mortar and curing were dried in an oven at 60°C until constant mass - weight variation in 24 h not higher than 0,1%. The mentioned drying of the samples intended to stop (or at least minimize) the curing at the age of test and to homogenize the mortar sample water vapour content conditions.

The mortar samples were used to dynamic modulus of elasticity determination by fundamental resonance frequency [CEN 2004] and three points bending flexural strength determination [CEN 1999b]. One half of each specimen from the flexural test were used to compressive strength determination at 60 days [CEN 1999b]. As mentioned before, from 60 to 120 days the other half of each sample was kept in interior summer environment at medium temperature of  $30 \pm 3$  °C and  $50 \pm 5\%$  RH. Those conditions were not particularly beneficial for the lime-based mortars curing, due to the lack of moisture for carbon dioxide transport and for pozzolanic reaction. At 120 days those half samples were used to compressive strength determination and afterwards the tops of those half samples - which were perfectly undamaged - were used for open porosity determination by vacuum and hydrostatic weighing [RILEM 1980, CEN 2006].

At 120 days, the half of three samples of each mortar and curing, resulting from the ones used before for the carbonation determination, were dried in an oven at 60°C until constant mass. After cooling in dry environment, they were used for capillary water absorption determination (Capillary Coefficient in terms of initial capillary absorption velocity and Capillary Absorption in terms of total adsorbed water) [CEN 2002, CEN 2009]. The lateral faces of the samples were not watertight and the test was held inside a box with saturated environment; the samples were placed over a geotextil with 2-5 mm water high.

When completely saturated by capillary water, the samples were directly used for the drying index determination [C.Normal 1991, Brito et al. 2011], also without faces been watertight. This situation allowed drying to occur over a large surface and without being unidirectional. During drying the mortar samples were kept in environmental conditions of  $20 \pm 3^{\circ}$ C temperature and  $50 \pm 5\%$  RH.

After this test the samples were kept in interior environment at medium temperature of  $25 \pm 3$  °C and  $57 \pm 5\%$  RH. At the age of 17 months the half samples of each mortar and curing that have been used in capillary and drying tests were dried in an oven at 60°C until constant mass and submitted to a resistance to chlorides contamination test [Faria-Rodrigues 2004]. After cooling in a dry environment, they were immerged in a sodium chloride solution for 24 h – 1000g NaCl in 3.4 liters of water – and dried again until constant mass. By the difference between the dry masses of each sample after and before immersion, the percentage of retained chlorides was determinate. The samples were then placed inside a climatic chamber where they were exposed to repeated cycles of 12 h at 90% RH and 12 h at 40% RH, with a constant temperature of 20°C. During those cycles the samples were weekly weighed to determine the mass variation that occurred and the type of degradation.

### **3 Results**

Results of flow table consistency are presented in Table 3. For all mortars preparation a comparable consistency flow of  $153 \pm 3$  mm was always reached. For mortars with lime AL the water/binder ratio and the consistency did not change with the metakaolin partial substitution; for mortars with lime PL the partial substitution of lime putty PL by powder metakaolin implied an increment on the total water/binder ratio (considering the existent plus the added water) for a similar consistency. That can be justified by the fact that the partial weight substitution of lime putty by powder metakaolin is indeed a big volume of powder instead of putty (calcium hydroxide plus water).

Mortar test results of mechanical characteristics (dynamic modulus of elasticity, flexural and compressive strength) and internal structure (open porosity) are presented in Table 4; total capillary absorption, capillary coefficient, drying index, retained chlorides and weight variation at 42 cycles after chlorides contamination are presented in Table 5.

It is expected that mortars cured with high  $CO_2$  optimize carbonation and cured with high RH optimize hydration. For that reason in pure air lime mortars curing with high  $CO_2$  is expected to be the most favorable; in air lime-metakaolin mortars the fact that curing with high  $CO_2$  content optimize carbonation, with calcium hydroxide consumption, can diminish the possibility of hydration because of lack of Ca(OH)<sub>2</sub>. That is why with air lime-metakaolin mortars the balance is unknown.

# 3.1 Mechanical Characteristics

## **Dynamic Modulus of Elasticity**

The dynamic modulus of elasticity  $E_d$  is associated to the deformability of the mortar; mortars with low  $E_d$  seemed to be more deformable than mortars with higher  $E_d$ .

As it can be seen in Table 4 and Fig. 2, mortars with powder hydrated lime AL present higher dynamic modulus of elasticity than mortars with lime putty PL, what may induce a higher deformability of lime putty mortars due to the decrease of portlandite crystal dimensions of the putty when compared to powder lime [Hansen et al. 1999]. Mortars with metakaolin AL+Mk and PL+Mk present higher  $E_d$  than similar mortars without metakaolin AL and PL - except in the case of mortars with powder hydrated lime cured with high CO<sub>2</sub> content AL+Mk\_C, with a very high standard deviation. With regard to mortars of each type (mortar and curing), the higher  $E_d$  is always registered by samples C cured with high CO<sub>2</sub> content; the following values of  $E_d$  are registered by samples cured at 50% or 65% RH (cure D or S) for mortars without metakaolin and by samples cured at 95% RH (cure H) for mortars with metakaolin.

**Table 4** Test results (average values and standard deviation) of dynamic modulus of elasticity, flexural and compressive strength and open porosity of mortars and curing

Mortar/ Cur- ing	$E_{d(60d)}$	StDv	$R_{f(60d)}$	StDv	$R_{c(60d)}$	StDv	R <sub>c (120d)</sub>	StDv	O.P.	StDv
[ID]	[M	Pa]	[M	Pa]	[M	Pa]	[MI	Pa]	[ó	%]
AL_D	2671	10	0,2	0,1	0,4	0,1	1,0	0,0	30	0,2
AL_S	2627	42	0,2	0,0	0,5	0,0	0,9	0,0	30	0,3
AL_C	5028	227	0,8	0,1	1,4	1,0	1,2	0,2	29	0,4
AL_H	2412	98	0,2	0,0	0,4	0,1	0,9	0,1	31	0,3
AL+Mk_D	3023	123	0,3	0,0	0,5	0,2	1,1	0,1	30	0,1
AL+Mk_S	2822	71	0,3	0,1	0,4	0,2	1,0	0,0	30	0,2
AL+Mk_C	3691	504	0,7	0,1	1,2	0,3	1,2	0,2	29	0,3
AL+Mk_H	3194	76	0,3	0,0	0,7	0,3	1,3	0,0	29	0,2
PL_D	1529	29	0,2	0,0	0,3	0,1	0,6	0,0	35	0,4
PL_S	1455	4	0,2	0,0	0,3	0,0	0,6	0,0	35	0,1
PL_C	4587	179	0,7	0,1	1,3	0,4	1,7	0,2	35	0,3
PL_H	1232	43	0,2	0,0	-	-	0,5	0,0	35	1,0
PL+Mk_D	2153	52	0,3	0,1	0,5	0,0	0,9	0,0	34	0,1
PL+Mk_S	2132	61	0,2	0,0	0,5	0,1	0,9	0,1	35	0,1
PL+Mk_C	4518	147	0,8	0,0	1,6	0,1	1,9	0,2	35	0,4
PL+Mk_H	2167	86	0,4	0,1	0,7	0,0	1,0	0,0	35	0,1

#### **Flexural Strength**

In what concerns flexural strength of mortars, higher values induce better resistance to cracking; but compressive strength values of rendering mortars should not be too high and do not overpass those of the wall where the mortars are to be applied.

Regarding the flexural strength at 60 days of age (Table 4 and Fig. 2), mortars with lime putty generally register a slight increase comparatively with mortars with powder hydrated lime. Except for mortar AL+Mk\_C, mortars with metakaolin present slightly higher values of flexural strength than similar pure lime mortars. In what concerns each type of mortar with different type of cure also mortars cured with high content of  $CO_2$  register the higher results of R<sub>f</sub>.



Fig. 2 - Dynamic elasticity modulus versus flexural and compressive strength of mortars

#### **Compressive Strength**

Respecting the compressive strength, an increase of the results generally occurs from 60 to 120 days of age of the mortars (Table 4 and Fig. 2), although the alteration of environmental condition where the samples were kept meanwhile. In terms of percentage, the increase was lower with curing conditions C because the acceleration of carbonation curing.

At 120 days mortars with powder hydrated lime AL register higher values than those with PL - except for mortar with lime putty PL cured with a high content of  $CO_2$ .

Mortars with metakaolin generally register an increase of compressive strength compared to the similar ones without this pozzolan. In what concerns each type of mortar with different types of cure, as for the case of  $E_d$  and  $R_f$ , also mortars cured with high content of  $CO_2$  register the highest results of  $R_c$ , except for AL+Mk\_C; as happened before for  $E_d$ , the following values of  $R_c$  are registered by mortars

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cured at 50% or 65% RH (cure D or S) among mortars without metakaolin and by mortars cured at 95% RH (cure H) among those with metakaolin.

# 3.2 Internal Structure

In terms of internal structure, mortars were tested for open porosity determination. It is higher for mortars with lime putty PL compared with mortars with powder hydrated lime AL; those last mortars are then denser than the previous. Results of similar mortars with or without metakaolin are almost the same. Regarding each type of mortar with different types of cure, only mortars with powder lime AL cured with high content of  $CO_2$  present a lower open porosity and a higher compactness; that can be related to a rapid carbonation evolution of this mortar.

Results of open porosity can justify some of the mechanical characteristics obtained although they cannot justify the higher mechanical characteristics of mortars cured with high  $CO_2$  content; but results underline the particularly different internal structure that may occur in mortars with lime AL compared with lime PL. One of the reasons can be due to the fact that the lime putty PL was water repellent. Further studies about the mortars microstructure need to be carried on.

# 3.3 Physical Characteristics

#### **Capillary Absorption**

As expected, there is a strong difference of capillary coefficient and total capillary absorption between mortars with powder air lime AL and with lime putty PL; the last mentioned mortars are much less absorbent than the others due to the water repellent natural product incorporated in the lime putty production – from what is known, an olive oil by-product (Table 5 and Fig. 3).

Mor- tar/Curing	Capillary Absorp.	Capillary Coef.	Drying Index	Ret.Chlor.	Weight Var. Cycle 42
[ID]	[kg/m <sup>2</sup> ]	[kg/m <sup>2</sup> .min. <sup>0,5</sup> ]	[-]	[%]	[%]
AL_S	13,21	1,14	0,25	2,6	-20,0
AL	13,90	1,20	0,23	2,6	-11,0
AL_C	12,42	1,17	0,24	2,2	2,8
AL_H	14,40	1,32	0,23	2,6	2,6
AL+Mk_S	13,85	1,07	0,15	2,5	-10,6
AL+Mk	14,47	1,12	0,21	2,6	-7,9
AL+Mk_C	16,91	0,96	0,13	2,6	4,1
AL+Mk_H	13,33	0,92	0,24	2,3	4,8
PL_S	4,08	0,09	0,35	1,4	-54,7
PL	3,27	0,03	0,33	1,4	-44,9
PL_C	1,54	0,01	0,27	0,2	-1,4
PL_H	3,28	0,05	0,42	1,8	-48,7
PL+Mk_S	4,11	0,13	0,56	1,3	1,7
PL+Mk	2,74	0,13	0,47	1,3	0,7
PL+Mk_C	6,49	0,03	0,25	1,7	-46,1
PL+Mk_H	4,40	0,07	0,51	1,7	0,3

**Table 5** Average values of total capillary absorption, capillary coefficient, drying index, retained chlorides and weight variation at 42 cycles after chlorides contamination of mortar/curing



Fig. 3 - Capillary absorption curves of mortars

Capillary coefficient of mortars with hydrated lime AL is lower for mortars with metakaolin; for mortars with lime putty PL, capillary coefficient is a little higher when metakaolin partially substitutes the lime. Regarding each type of mortar with different types of curing, generally mortars cured with high content of CO<sub>2</sub> register the lower capillary coefficient results - only mortar with powder lime with metakaolin cured in humid conditions AL+Mk\_H present a slightly lower value compared to AL+Mk\_C. But these results should be analyzed together with the total capillary water absorption.

In what concerns the total capillary water absorption, also the mortars with lime putty PL register very low absorption compared with those with AL. Comparing mortars with lime AL, there is an increase of total capillary water absorption when metakaolin is used, except with mortar with metakaolin and humid cure AL+Mk\_H.

These last mentioned mortar present the best behaviour in terms of capillary absorption test, among the ones with AL+Mk and particularly in terms of capillary coefficient among mortars with lime AL; mortar AL\_C present the best behaviour among the ones with AL without Mk, in terms of capillary absorption, and one of the best concerning capillary coefficient. Comparing mortars with lime PL, the best behaviour in terms of capillary absorption test is registered by mortar PL\_C. Among mortars with PL+Mk, the mortar with lower capillary coefficient register the highest values of total absorption and the mortar with lower total capillary absorption register the higher capillary coefficient.

#### Drying

Results of capillary absorption must be analyzed together with the drying capacity of mortars, fundamental for the elimination of water, once absorbed (Table 5 and Fig. 4).

Mortars with powder hydrated lime AL register lower values of drying index compared to mortars with water repellent lime putty PL, what means the moisture can be easily and faster eliminated from AL mortars than from PL mortars.

Among mortars with lime AL, mortars with metakaolin generally present lower values of drying index; between mortars with lime PL, mortars without metakaolin present lower values - except for mortar C cured with high  $CO_2$  content, with similar values.

All mortars AL without metakaolin cured in different conditions present very similar values; among mortars with the same lime but with metakaolin, mortar AL+Mk\_D and AL+Mk\_C register the lowest values, and humid cured mortar H present the highest drying index.

Among mortars with lime PL, also mortar with cure C present the lowest value and mortar with cure H register the highest value; among mortars with metakaolin PL+Mk, a low drying index is register by mortar C while the other mortars present the highest values.



Fig. 4 – Drying curves of mortars

Comparing the capillary coefficient with the drying index of mortars (Fig.5) it can be noticed that, in general terms, there is an inverse correlation between the capillary coefficient and the drying index, showing that with this type of mortars, faster capillary absorption is correlated with easier drying and *vice versa*.



Fig. 5 - Capillary coefficient versus drying index of mortars

## 3.4 Resistance to Chlorides Contamination

Table 5 presents the retained chlorides and the weight variation of mortars at 42 cycles after chlorides contamination. Weight variations due to humid and drying cycles after chloride contamination are presented in Figure 6.



Fig. 6 - Weight variation as a function of the number of cycles after chlorides contamination

The deterioration of the samples generally occurred by superficial disaggregation, as can be seen in Fig.7. But the degradation of lime putty mortars was much more visible and intense than the one that occurred in powder hydrated lime mortars. In Fig.7 some similarity can be observed between the PL mortar sample degradation and degradation that occurs in plasters and renders of buildings with problems of capillary raising and salts contamination.

At Table 5 it can be noticed that the percentage of retained chlorides is high for all the mortars with powder lime AL - only a little lower for AL\_C and AL+Mk\_H. It is much lower for all the mortars with water repellent lime putty PL. But the percentage of retained chlorides is particularly low for PL\_C mortar, showing that something enables the mortar with pure lime putty (with a water repellent agent) cured with high level of  $CO_2$  to retain chlorides and that cannot be justify by the measured open porosity.



Fig. 7 – General view of mortar samples at 42 cycles after chlorides contamination and zoom view of an AL mortar sample only with superficial disaggregation and a PL mortar sample with great mass loss

Observing Fig. 6, that presents the percentage of weight variation of the mortar/curing over the resistance to chlorides contamination test, the mortars behaviour can be divided in three groups: the mortars that suffers a huge degradation almost since the first cycles, losing a high percentage of mass – as the cases of PL\_D, PL\_H, PL\_Mk\_C and PL\_S; the ones that resist the first cycles but that begin loosing mass between the 14<sup>th</sup> and the 21<sup>th</sup> cycles – as the AL\_D, AL\_S, AL+Mk\_D and AL+Mk\_S; the mortars that maintain their integrity and mass over the multiple cycles – all the others. Between those last mentioned mortars there is the PL\_C mortar with very low percentage of chlorides retained. In general terms and except the PL\_C mortar, all the pure lime putty (with water repellent agent) mortars presented low resistance to chlorides contamination; the substitution by metakaolin seemed to improve PL mortars resistance to chlorides, except, in this case, for the PL+Mk\_C mortar. In terms of AL mortars, with or without metakaolin, the humid curing and curing with high CO<sub>2</sub> content (H and C) seemed to be most favorable in what concerns the chlorides attack.

# **4** Discussion

Before anything else, a remark in terms of the reactivity of the air lime itself. While the lime putty particles diminish their size and increment their characteristics while kept covered by a film of water for a long period, without carbonating [Faria et al. 2008], care should be taken with the powder hydrated lime, as mentioned at 2.1. In fact, these powder hydrated limes are commercialized in Portugal in paper bags and the contact with humidity and atmospheric  $CO_2$  is not totally prevented. It must be assured that the powder hydrated lime that is going to be used was not stored since production in humid and cold environments without the bags being completely covered by plastics, because if that does not happened, one

can be using powder hydrated lime partially carbonated and acting as a filler instead of a real binder - and without noticing the fact.

In what concerns the metakaolin, natural clays - other than pure kaolinite - or even industrial by-products can be interesting pozzolanic materials when thermal activated and the substitution of air lime by this type of material can result in energetic and environmental gains [Tironi et al. 2012, Pontes 2011].

The experimental campaign highlighted several aspects: the good workability of air lime-based mortars, even with relatively low flow table consistencies; the difficulty but the need on evaluating shrinkage since moulding in lime-based mortars; the phenolphthalein test inadequacy to evaluate lime-metakaolin carbonation due to changes registered on PH by pozzolanic reaction; the increase of mechanical characteristics when lime was partially substituted by metakaolin - although the metakaolin that was used was not chosen by its reactivity, but by the fact of being an available Portuguese metakaolin, and the lime-metakaolin proportion was not optimized; the good deformability, expressed in terms of the low dynamic modulus of elasticity, evidenced by all mortars but particularly by mortars with lime putty, with similar flexural strength results; the higher open porosity of mortars with lime putty compared to powder hydrated lime mortars, but with similar mechanical resistances when metakaolin replacement occurred; the low capillary water absorption of analyzed lime putty mortars, produced with a water repellent agent, but also the greater difficulty to dry of these mortars - while lime without water repellent agent mortars absorbed rapidly and more quantity of capillary water but could release that moisture more easily; an improvement of the behaviour of powder hydrated lime mortars to initial water capillary absorption and drying capacity when metakaolin was added and the inverse situation for lime putty with water repellent agent mortars; the improvement of the resistance to chlorides of powder hydrated lime mortars with and without metakaolin with humid and carbonated curing and the generally week resistance to chlorides attack of lime putty mortars without metakaolin - for curing other than C or with metakaolin with cure C.

Comparing the obtained values with the general requirements concerning some characteristics for rendering, plastering and repointing substitution mortars for ancient buildings [Veiga et al. 2010] it can be seen that all the mortars with powder hydrated lime AL satisfy those requirements in terms of mechanical characteristics, while the mortars with lime putty PL can only satisfy all those requirements when metakaolin is added. In fact the lime substitution for metakaolin and the optimization of curing conditions may increment the mechanical strength but mortars do not become strong enough to generate stresses that might lead to failure of the ancient walls; thus the mechanical compatibility is assured.

Concerning the behaviour in the presence of water, the comparison with mentioned general requirements can only be done in terms of the capillary coefficient and while all the mortars with AL lime satisfy the requirements, these may not be satisfied by the mortars with the PL lime because of the too low values that are presented by these mortars. Regarding the influence of different curing conditions, the most important aspects detected were: the initial difficulty of hardening of lime-based mortars inside the moulds when exposed to high levels of  $CO_2$ ; the increase of carbonation evolution and on mechanical characteristics, after the initial hardening, when cured with high level of  $CO_2$ ; also a different behaviour in terms of resistance to chlorides was highlighted especially with lime putty mortar with curing C. Although that cure situation is not reproducible *in situ*, the acceleration of cure of pure air lime mortars that, after initial hardening and demoulding, are submitted to higher  $CO_2$  environments during a defined period of time, can help in the preparation of lime mortar samples to be tested and characterized, but must be further studied to assure there are no important changes at microstructural level.

Accordingly this study is being extended to further characterization of mortar samples submitted to carbonation curing and other curing conditions, combining some of the previous and different ones. The aim is to define cure conditions that potentiate pure lime mortars characteristics, in order to be able to prepare reproducible laboratory specimen that can be used as aged substrate to the application of other products to be tested (as the cases of paint systems and consolidants), but also trying to optimize curing conditions that can be reproduced *in situ*. The optimization of curing conditions, that can be reproduced *in situ* for lime-metakaolin mortars, will also continue to be tested, namely taking into direct consideration the substrate influence.

For the time being and from the obtained results of conditions reproducible on site, curing at 65% RH seemed to be the most appropriate for pure air lime mortars, but the resistance to chlorides attack – as well as to other salts, like sulphates - have to be deeply studied.

For lime-metakaolin mortars, and although the general improvement registered in the mortars characteristics with partial substitution of lime by metakaolin, the authors think that a substantial improvement can yet be achieved with the use of a more reactive metakaolin - especially with a higher specific surface that should lead to a higher reactivity - and a optimized proportion between each type of lime and the metakaolin [Gameiro et al. 2012].

In lime-metakaolin mortars the amount of calcium hydroxide must be able to react with the silicates and aluminates of the metakaolin but also to carbonate. It is important to be aware of the kinetic of both the pozzolanic reaction and the carbonation process, in order to potentiate the best conditions during mortar formulation and curing. It is expected that a richer proportion on binder, for instance a volumetric proportion 1:2 of binder:aggregate, may potentiate the pozzolanic effect, because although some calcium hydroxide became carbonated, it is more likely there would be some left (uncarbonated) to hydrate.

From the analyzed results, and although not reproducible *in situ*, curing with high level of  $CO_2$  generally potentiated the lime-metakaolin mortar characteristics - except for resistance to chlorides attack with the analyzed water repellent lime putty. Among the curing conditions that can be closer to *in situ* situations, humid curing can potentiate lime-metakaolin mortars characteristics. Humid curing

seems fundamental both for the continuity over time of the hydration - the pozzolanic reaction - and the  $CO_2$  transport - for the carbonation process.

In most Portuguese exterior environmental conditions, and even in summer time, cycles occur, between night and day, ranging from very humid to dryer conditions. That situation provides some level of humidity to the renders but may not be enough; nevertheless a geotextile covering, frequently wetted, could be recommended to be applied *in situ* over lime-metakaolin renders during the first ages, let say the two first weeks [El-Turki et al. 2010].

The addition of fine sepiolite to air lime-metakaolin mortars, acting as a water reservoir in pozzolanic systems, can also be a possibility for low-humidity applications [Andrejkovicová et al. 2011].

Non water repellent lime-metakaolin mortars may also be appropriate to walls with capillary rise problems.

For interior plastering of old walls in very humid environments, the application of lime-metakaolin mortars should be advantageous.

Lime-metakaolin mortars should also be advantageous for repointing masonries and substitution layers supporting ceramic glazed tiles in ancient buildings, as an alternative to substitute, when needed, old air lime pure mortars, as these are applications where the contact with  $CO_2$  is minimized.

# **5** Conclusions

In general terms it can be registered that:

- the partial substitution of air lime by metakaolin can be advantageous in terms of the characteristics of the mortars;

- the use of water repellent putty lime should be seen with care because its behaviour in face of water and moisture and in face of chlorides attack is not always the most appropriate for rendering mortars;

- the choice of the binder, considering the type of air lime mortar, with or without metakaolin, should take in to consideration the environmental conditions where the mortars will be applied;

- great care should be taken to the curing conditions in order to optimize and potentiate the mortars characteristics and their applications in ancient buildings.

## Acknowledgments

The authors acknowledge the support of the Polytechnic Institute of Setubal where the experimental work was conducted, the availability of limes Lusical and Fradical and of metakaolin from Grupo Lagoa, and the financial support from the Portuguese Science and Technology Foundation to projects LIMECONTECH (PTDC/ECM/100234/2008) and METACAL (PTDC/ECM/100431/2008).

## References

Andrejkovicová A, Ferraz E, Velosa A, Santos Silva A, Rocha F (2011) Fine sepiolite addition to air lime-metakaolin mortars. Clay Miner. 46: 621-635

Association Française de Normalisation – AFNOR (2010) Métakaolin, addition pouzzolanique pour bétons. Définitions, spécifications, critéres de conformité. Paris, NF P 18-513:2010

Brito V, Dias Gonçalves T, Faria P (2011) Coatings applied on damp building substrates: performance and influence on moisture transport. J. Coat. Technol. Res. 8 (4): 513-525

CEN (1998a) Tests for mechanical and physical properties of aggregates. Part 3: Determination of loose bulk density and voids. Brussels, EN 1097-3:1998

CEN (1998b) Methods of test for mortars for masonry. Part 2: Bulk sampling of mortars and preparation of test mortars. Brussels, EN 1015-2: 1998/A1:2006

CEN (1999a) Methods of test for mortars for masonry. Part 3: Determination of consistency of fresh mortar (by flow table). Brussels, EN 1015-3: 1999/A1: 2004/A2: 2006

CEN (1999b) Methods of test for mortars for masonry. Part 11: Determination of flexural and compressive strength of hardened mortar. Brussels, EN 1015-11: 1999/A1:2006

CEN (2002) Methods of test for mortars for masonry. Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar. Brussels, EN 1015-18: 2002

CEN (2004) Natural stone test methods. Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency). Brussels, EN 14146: 2004

CEN (2005) Methods of testing cement. Part 1: Determination of strength. Brussels, EN 196-1: 2005

CEN (2006) Natural stone test methods. Determination of real density and apparent density, and of total and open porosity. Brussels, EN 1936: 2006

CEN (2009) Conservation of cultural property. Test methods. Determination of water absorption by capillarity, Brussels, EN 15801: 2009

CEN (2010) Building lime. Part 1: Definitions, specifications and conformity criteria. Brussels, EN 459-1: 2010

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Charola E., Faria-Rodrigues P, McGhie A, Henriques F (2005) Pozzolanic components in lime mortars: correlating behaviour, composition and microstructure. Restor. Build. Monum. 11 (2):111-118

Commissione Normal (1991) Misura dell'indice di asciugamento (drying index), Roma, CNR/ICR, Doc. 29/88

Dheilly R., Tudo J, Sebau Bi Y, Quéneudec M (2002) Influence of storage on the carbonation of powdered Ca(OH)<sub>2</sub>. Constr. Build. Mater. 16 (3): 155-161

El-Turki A, Ball R, Holmes S, Allen W, Allen G (2010) Environmental cycling and laboratorial testing to evaluate the significance of moisture control for lime mortars. Constr. Build. Mater. 24 (8): 1392-1397

Faria-Rodrigues P (2004) Mortars for ancient masonry renderings. The influence of binders (in Portuguese). PhD thesis Civil Eng., Nova University of Lisbon

Faria-Rodrigues P (2009) Resistance to salts of lime and pozzolan mortars. In: RILEM Proc. PRO 067 - Repair Mortars for Historic Masonry: 99-110

Faria-Rodrigues P, Henriques F (2004) Current mortars in conservation: an overview. Restor. Build. Monum. 10 (6): 609-622

Faria-Rodrigues P, Henriques F, Rato V (2007) Current mortars: influence of the type of binder and aggregate (in Portuguese). In: 2° Congresso Nacional de Argamassas de Construção, APFAC. Lisboa, LNEC

Faria P, Henriques F, Rato V (2008) Comparative evaluation of aerial lime mortars for architectural conservation. Cult. Herit. 9 (3): 338-346

Faria P, Tavares M, Menezes M, Veiga R, Margalha G (2010) Traditional Portuguese techniques for application and maintenance of historic renders. In: HMC2010 - 2<sup>nd</sup> Historic Mortars Conference & RILEM TC 203-RHM, Repair Mortars for Historic Masonry Final Workshop, Prague

Faria P, Silva V, Flores-Colen (2012) Mortars of natural hydraulic lime and artificial pozzolans: laboratorial evaluation. In: 4° Congresso Português de Argamassas e ETICS, APFAC, Coimbra

Ferraz E, Andrejkovicová S, Santos Silva A, Rocha F, Velosa A (2012) Use of modified Chapelle test to evaluate pozzolanic reactivity of metakaolins (in portuguese). In: 4° Congresso Português de Argamassas e ETICS, APFAC, Coimbra

Fortes-Revilla C, Martínez-Ramírez S, Blanco-Varela MT (2006) Modelling of slaked lime-metakaolin mortar engineering characteristics in terms of process variables. Cem. Concr. Compos. 28: 458-467

Gameiro A, Santos Silva A, Veiga R, Velosa A (2012) Hydration products of lime-metakaolin pastes at ambient temperature with ageing. Thermochim. Acta (accepted for publishing)

Gomes A (2010) Renderings with fibers for rehabilitation (in Portuguese). MSc Thesis Civil Eng., University of Aveiro

Gonçalves T (2007) Salt crystallization in plastered or rendered walls. PhD thesis Civil Eng. LNEC and Technical University of Lisbon/IST

Hansen E, Tagle A, Erder E, Baron S, Connell S, Rodríguez-Navarro C, Van Balen K (1999) Effects of ageing on lime putty. In: RILEM Proc. PRO 012 - Historic Mortars. Characteristics and Tests: 197-207

Instituto Português da Qualidade (2010) Pozzolans for concrete, mortars and grouts. Definitions, requirements and evaluation of conformity (in Portuguese). Caparica, NP 4220: 2010

Konow T (2003) Aggregates grain size distribution. A major influence on many properties of lime mortars for restoration. In: EUROMAT 2003 – European Congress on Advanced Materials and Processes, EPFL, Lausanne.

Lawrence R, Mays T, Walker P, Ayala D (2006) Determination of carbonation profiles in non-hydraulic lime mortars using thermogravimetric analysis. Thermochim. Acta 444 (2):179-189

Lawrence R, Mays T, Rigby S, Walker P, Ayala D (2007) Effects of carbonation on the pore structures of non-hydraulic lime mortars. Cem. Concr. Res. 37 (7):1059-1069

Margalha G, Veiga R, Santos Silva A, Brito J (2011) Traditional methods of mortar preparation: the hot lime mix method. Cem. Concr. Compos. 33: 796-804

Pontes J (2011) Reactivity of artificial pozzolans for mortar and concrete (in Portuguese). MSc thesis Civil Eng., Nova University of Lisbon

Rato V (2006) The influence of morphologic microstructure on the performance of mortars (in Portuguese). PhD thesis Civil Eng., Nova University of Lisbon

RILEM Commission 25 PEM 1980 Essais recommendés pour mesurer l'alteration des pierres et évaluer l'efficacité des methods de traitment. Matér. Constr. 13 (75)

Sandstrom Malinowski E (2009) historic mortars revived. Developing local materials and crafts for restoration. In: RILEM Proc. PRO 067 - Repair Mortars for Historic Masonry: 328-338

Stefanidou M, Papayianni I (2005) The role of aggregates on the structure and properties of lime mortars. Cem. Concr. Compos. 27: 914-919

Tironi A, Trezza M, Scian A, Irassar E (2012) Kaolinitic calcined clays: factors affecting its performance as pozzolans. Constr. Build. Mater. 28: 276-281

Veiga R, Velosa A, Magalhães A (2009) Experimental applications of mortars with pozzolanic additions: characterization and performance evaluation. Constr. Build. Mater. 23: 318-327

Veiga R, Fragata A, Velosa A, Magalhães A, Margalha G (2010) Lime-based mortars: viability for use as substitution renders in historical buildings. Archit. Herit. 4 (2): 177-195

Velosa A, Veiga R (2007) Lime-metakaolin mortars: properties and applications. SB07 – Sustainable Construction, Materials and Practices. Challenges of the Industry for the New Millenium, Lisbon

Velosa A, Rocha F, Veiga R (2009) Influence of chemical and mineralogical composition of metakaolin on mortar characteristics. Acta Geodyn. Geomater. 6, 1 (153): 121-126

In Durability of Building Materials and Components (Vasco Peixoto de de Freitas, J.M.P.Q. Delgado, eds.), Building Pathology and Rehabilitation, vol. 3, VIII, 105-126. ISBN: 978-3-642-37474-6 (Print) 978-3-642-37475-3 (Online). Springer-Verlag Berlin Heidelberg. DOI: 10.1007/978-3-642-37475-3 [.