

COMPARATIVE EVALUATION OF LIME MORTARS FOR ARCHITECTURAL CONSERVATION

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Abstract: International bibliography on conservation usually refers that mortars made with lime putty with long extinction periods behave better than others made with the current dry hydrated limes. In order to evaluate this assess, an experimental study of lime mortars was carried out, using dry hydrated lime and two lime putties. It becomes clear that the use of lime putties with long extinction periods in mortars allow better performances, particularly in applicability and resistance to sulphates.

1. Introduction

The functional requirements of mortars for historic buildings depend on multiple conditions and require several characteristics that are not always easy to achieve and harmonize. Fundamentally these mortars should allow an efficient protection of the substrates on which they are applied, in order to avoid the development of processes that may lead to degradation. They should present good mechanical, physical and chemical compatibility with the masonries and simultaneously their characteristics should be enough to withstand their own degradation, particularly in the case of soluble salts [1].

Lime is used as a binder in architectural heritage mortars since ancient (even prehistoric) times. The selection and preparation of the binder and the execution and application of lime mortars was first carried out by trial and error and the acquired knowledge was transmitted over generations of craftsman [2].

Some decades ago the use of lime mortars fell into disuse and the traditional craftsman experience was almost lost, especially in developed countries. This situation was mainly due to changes in construction technology and the generalized use of cement as binder. During that time, the replacement of lime mortars with cement mortars in architectural heritage became common, creating new problems that were not foreseen at the time. In the last two decades the lime craftsmanship re-gained his important role in architectural heritage conservation.

Lime is obtained from calcination of calcareous rock with high percentages of calcium carbonate, from which calcium oxide (quicklime) is obtained. Quicklime is very reactive in the presence of water and cannot be used before being transformed to calcium hydroxide by reaction with water.

It is a long established tradition that slaked lime should only be used after a long period of water immersion. This tradition, however, was not compatible with modern practices of industrialization, thus allowing a progressive increase of ready to use dry hydrated lime (as a powder). In spite of this, the tradition of long extinction periods of quicklime was kept and can still be seen in several countries, such as Italy or the United Kingdom, where lime putty obtained after different periods of extinction is commercialized, mainly for use in conservation projects.

Whenever pure lime mortars were foreseen, international bibliography and practices recommend the use of lime putties with large periods of extinction. Better workability – in many cases really notable – and a better general performance are advantages currently attributed to these products due to the decrease of portlandite crystal dimensions, a subsequent increase of the specific surface and morphological changes upon ageing [3].

Lime production techniques lead to the production of $\text{Ca}(\text{OH})_2$ of different crystal size, depending on diverse factors as burning temperature, particle reactivity and slaking conditions. For conservation purposes, it is important to characterize different limes and the mortars made with them [4].

In some countries lime may be commercialised in different forms: ready to use dry hydrated lime (as a powder); finely crushed quicklime (as a powder) – which needs to be slaked *in situ* before being used; standard quicklime (in the form obtained after kiln firing) – to be slaked *in situ*; lime putty with different extinction periods.

The present paper evaluates the performance of mortars from a conservation point of view, prepared with dry hydrated lime and with a lime putty obtained from finely crushed quicklime, in comparison with mortars using standard lime putty as binder.

Nowadays, standards are mainly conceived for hydraulic mortars to be used in the broader context of the construction industry. This fact creates several problems when aerial binder mortars are to be evaluated. Hence the need for the development of test specifications that allows a comprehensive understanding of the performance of such mortars. Existing studies have shown how critical mixing characteristics, curing conditions and test methods can be when evaluating mortars [2, 5, 6]. With this in mind, the experimental study was developed using specific procedures that have been in use by the research team for more than a decade, concerning mortar preparation, curing conditions and test specifications that were designed specifically for this type of mortars.

2. Experimental study

Most of the standards for mortars have been developed for hydraulic mortars (namely EN standards), which means that frequently they are not adequate for testing non-hydraulic mortars. It is the case, for example, of the preparation of lime mortar prismatic samples, which cannot be de-moulded if the EN standard is followed [7], since the curing conditions are inadequate for aerial binder and do not allow an appropriate setting of the mortars. Due to the specificity of these types of mortars, the working team has developed test procedures specifically designed to suit the nature and specificities of non-hydraulic mortars [8]. Some of the tests were created by the team (as it is the case of the resistance to chlorides – see 2.3.4) and others have their origin on existing specifications that could be used as a base, as it is the case of those prescribed by the RILEM Commission 25 - PEM [9] and some later EN standards (mainly for natural stone testing).

2.1. Materials, preparation and proportions

Three different types of lime were used: dry hydrated lime (as a powder), and two quicklimes, one finely crushed (as a powder) and a standard quicklime (in the form obtained after kiln firing). These limes, all from the same Portuguese region, were used in different forms: dry hydrated lime used directly in powder (**al**);

finely crushed quicklime used as a putty after 10 months of extinction in water (**cq**); standard quicklime used as a putty after extinction in water for 16 months (**ql**). With the latter it was decided to prepare mortars with two different consistencies (**ql63** and **ql44**, see table 1).

All the mortars were prepared in laboratory conditions with a binder:aggregate proportion of 1:2 (in volume), using a common siliceous river sand as aggregate. Designations and proportions of the mortars (in volume) are presented in table 1, applying the type of lime used to designate the mortars (in the case of **ql** mortars the designation also included the flow table consistency).

2.2. Sample preparation and curing conditions

The amounts of water were designed so that each mortar could get comparable consistencies using the flow table test (see table 1). In the case of the mortars made with lime putties, workability was very good even with low consistency values. All the mortars were mechanically mixed in a laboratory mixer using a standard sequence of operations. The mortars were mechanically compacted in the moulds with twenty falls in each one of the two layers which completes the moulds.

In order to analyse the characteristics of the different mortars (at young and later ages), six 4 cm x 4 cm x 16 cm samples were prepared with each of the mortars. Metallic moulds were used with a minimum of grease to assure de-moulding. The samples were kept in a controlled dried ambience at a temperature of 23 ± 3 °C and $50\pm 5\%$ of relative humidity until the age of test (only the first three days inside the moulds).

2.3. Young age testing program and results

All the samples were dried to constant mass at 60°C just before being tested. The mortars were tested after 60 and 90 or 180 days, so that the evolution of their characteristics could be analysed. All the samples of each mortar were used for dynamic modulus of elasticity and flexural strength tests. Half of each sample (six half parts) were used for compressive strength and small portions of these were also used for bulk density and open porosity determinations. The other six halves were used for capillary water absorption; after being dried three of these samples were used to test for resistance to chlorides action and the other three for resistance to sulphates action determination.

2.3.1. Dynamic moduli of elasticity and flexural and compressive strength

The dynamic moduli of elasticity was obtained based on the determination of the longitudinal resonance frequency with an adequate apparatus, based on the european standard EN 14146: 2004 [10]. Flexural and compressive strength were determined based on the european standard EN 1015-11: 1999 [7], in an universal traction machine, following the classic method of performing the compressive test with half samples obtained from the flexural test. The average values and the standard deviation of each mortar at the ages of 60 and 90 days are presented in table 2.

2.3.2. Bulk density and open porosity

These tests were performed based on the european standard EN 1936:1999 [11] by total saturation with water under vacuum and hydrostatic weight. Results of each mortar at young ages (60 and 90 days) are presented on table 6, in terms of average values and standard deviation. Other samples from the same mortars have also been tested at the age of four years (see 2.4.2).

2.3.3. Capillary water absorption

These tests were conducted following test procedures that are close to those of the european standard EN 1925: 1999 [12]. The tests were conducted by placing the half samples in 2 mm of water (over absorbent paper) inside a covered box to maintain constant the hygrothermal conditions and to limit the water evaporating from the samples. The weight of the absorbed water per unit of the immersed surface, function of the square root of time (in seconds), is registered. The tests were carried out until the absorption reached an asymptotic value. The capillary absorption coefficient is given by the angular coefficient of the curve, while the asymptotic values correspond to the maximum absorption (successive weight variations of less than 1%). For the tested samples, these last values were obtained at 48 h of test. The obtained results at 60 and 180 days are presented in table 3 and in figure 1. The **cq** mortar samples were only tested at the age of 180 days. Figure 1 presents the test results during the first 6 h 15 min.

2.3.4. Resistance to chlorides

The samples were dried to constant mass (after being used in the capillary test) and then immersed in a sodium chloride saturated solution for 24 hours, after which they were dried again, at 105°C, until constant mass (requiring about a week to reach this point). The difference between the dry masses of each sample after and before immersion enables the determination of the amounts of retained chlorides, in terms of percentage of the initial dry mass. The samples were then placed in a climatic chamber where they were subjected to repeated cycles of 12 hours at 90% relative humidity (RH) and 12 hours at 40% RH, with a constant temperature of 20°C. Every week the samples were weighted to determine the mass variation. The deterioration of the samples generally occurred by development of superficial disaggregation of the material. The results of the resistance to chloride tests are presented in table 4 in terms of the percentages of retained chlorides and of mass variations after 30 and 50 cycles, at the ages of 60 and 180 days. The **cq** mortar samples were only tested at the age of 180 days. Figure 2 plots the percentage of mass variation as a function of the number of cycles.

2.3.5. Resistance to sulphates

The determination of the resistance to sulphates was carried out using samples that had been tested for capillarity. This test was developed by the research team, based on european standard EN 12370: 1999 [13]. The samples were immersed in a 6% anidrous sodium sulphate solution for 2 hours and dried for 21 hours at 105°C, after what they were weighted to determine mass variations and their integrity was visualised. These cycles of immersion, drying and weighing were repeated until the destruction of the sample or 25 cycles were completed. The destruction of some of the samples occurred by internal rupture of the mortar. The results in terms of the average percentage of mass variation after 5, 15 and 25 cycles and its standard deviation, at the ages of 60 and 180 days, are presented in table 5 and plotted in figure 3, as a function of the number of cycles. The **cq** mortar samples were only tested at the age of 180 days. When the total rupture of the mortar samples was achieved (100% mass variation), the number of the cycle is also registered (see figure 3).

2.4. Later age testing program and results

A second phase of the experimental campaign was carried out at a later age of the mortar samples to characterize the pore size distribution of the mortars, since it could assist in the analysis of the different behaviours observed.

The water content of lime putties was determined after a long period of four years of extinction. Samples that have been kept undisturbed in the controlled ambience were used for this new batch of tests, aimed at characterizing the pore structure of the mortars.

2.4.1. Lime putties analysis

Lime putties were preserved since slaking covered with a water film. The **cq** putty, when handled, presented a creamy consistency, while the **ql** putty consistency was harder and this material retained its shape when placed over a surface. However the water content of the lime putties registered 53% for **cq** and 60% for the **ql**.

2.4.2. Bulk density and open porosity

These tests were performed as referred in 2.3.2 with four years old mortar samples and the results are presented in table 6.

2.4.3. Mercury porosimetry

Pore-size distribution was performed with a mercury porosimeter with a sample from each mortar. Samples were dried to constant mass at 60°C. Two equivalent penetrometers were used with a 5 cm³ bulb and a total intrusion capacity of 1,716 cm³. Low pressure testing ranged from 0,0138 MPa (2 Psi) to 0,2068 MPa (30 Psi) and high pressure analysis from 0,2758 MPa (40 Psi) to 206,8427 MPa (30000 Psi). Equilibration times were 15 seconds for low pressure and 30 seconds for high pressure. As mercury parameters, the following were used: advancing and receding contact angle = 140°; surface tension = 0,485 N/m; density = 13,5335.

Cumulative and incremental curves are plotted in figures 4 and 5. These plots represent the pore size diameter in microns and each step of mercury intrusion in percentage of total intrusion.

Some images were collected with a binocular microscope in order to confirm the data obtained by porosimetry and are presented in figure 6.

3. Analysis of results

The results presented in table 2 show that the highest dynamic moduli of elasticity and flexural and compressive strengths are obtained by the mortar **cq** made with putty from crushed quicklime, followed by the ready to use dry hydrated lime mortar **al**. Mortars made with the putty from standard quicklime **ql** present the lowest mechanical resistances. In this last case the mechanical resistances are coherent with the water quantity of the mortars, since the results vary in inverse proportion of the flow consistencies. As expected, results obtained with longer cures (90 days) show an increase of mechanical resistances when compared with those obtained after 60 days.

Concerning density and open porosities at early ages (table 6), the mortar with the dry hydrated lime **al** is denser, followed closely by the lime putty **cq** mortar. Mortars with standard lime putty **ql** present the highest values in terms of open porosity and the lowest bulk densities. Again, the open porosity results are coherent with the consistencies of the mortars.

When comparing the mechanical resistances with the open porosities it can be noticed that the relation between the mechanical resistance of **al** and **cq** mortars can not only be explained by their densities, since the porosities are similar.

From table 3 and figure 1 it can be seen that at the age of 60 days, the capillary coefficients of standard quicklime mortars **ql44** and **ql63** are higher than those of the **al** mortar, which means that absorption occurs at a faster rate. The same occurs with the total amount of water absorbed by the mortars (asymptotic absorption). At the age of 180 days the **cq** mortar presents the lowest capillary coefficient and asymptotic absorption, followed by the **al** mortar. The **ql** mortars continue to register the highest values of capillary water absorption.

In what concerns the resistance to chlorides at the age of 60 days (table 4 and figure 2) it can be seen that the percentages of retained chlorides are coherent with the open porosity of the mortars. But in spite of the higher retention of chlorides of the **ql** mortars, the losses of mass after 30 and 50 cycles are much lower than

those of the **al** mortar, showing the good behaviour of **ql** mortars in this test at early ages. At the age of 180 days the **cq** mortar retained less quantity of chlorides, followed by the **al** mortar. As it happened at the age of 60 days, the **ql** mortars retained the higher quantities of chlorides. The losses of mass after resistance to chloride cycles are now lower for the **al** mortar and higher for the lime putty mortars. It can also be noticed that the improvement of resistance to chlorides is not always associated with the mechanical resistances. That can possibly be explained by the different pore size distribution and connectivity of pores of the mortar samples and the possibility of having enough space to allow the formation and dissolution of halite crystals in the volume of the pores, without causing damages.

Concerning the resistance to sulphates at the age of 60 days (table 5 and figure 3) it can be noticed that the **al** mortar samples collapse prematurely, with total destructions at the 8th cycle, while in the **ql** mortars the deterioration occurred at a much slower rate until reaching an asymptotic loss around 40-50%. It was considered that this behaviour could be due to different chemical composition of the original limestones, particularly in what refers to magnesium content. But a chemical analysis for the magnesium content of the two types of lime (dry hydrated lime and standard quicklime lime putty) showed very low and similar values, so that hypothesis was excluded. The same test after 180 days showed that the **ql144** and **ql163** mortar samples went over all the 25 cycles of the resistance to sulphate test without any mass losses. At this age the **al** mortar also presented a good behaviour, while the **cq** mortar presented mass losses that stabilized at around 50%. The resistance to sulphates increases observed in the mortars from 60 to 180 days could be explained by the longer periods of cure and the higher carbonation rates.

The hypothesis that the different behaviour of mortars could be justified by distinguish pore size distributions lead to a second phase of the experimental campaign.

The consistency of the 4 years old putties when handled was quite different and it was the one which seemed more liquid that presented the lower water content. That shows that for the case of this two lime putties made from calcium oxide from the same region but commercialized in different forms (finely crushed quicklime and standard quicklime – in the form obtained after kiln firing), the characteristics of aged putties are still different.

The bulk density and open porosity results at the age of 4 years of the mortars confirmed the trend obtained at younger ages – the **al** mortar is the denser, followed by the **cq** mortar. The **ql** mortars present higher values of open porosity, what is coherent with the flow consistency of these mortars when in a fresh stage. It seems that the evolution of carbonation attained at the age of 4 years had no influence on the open porosity trend.

Mercury intrusion curves (figures 4 and 5) clearly show that these mortars have a bimodal pore size distribution. This characteristic is typical of lime mortars and has been reported by several authors [14, 15, 16]. This type of distribution is the result of the well-known retraction phenomena that induces the formation of an interconnected macropore network with a fissure-like shape.

In the incremental curves (figure 5), a significant distinction can be observed in the first intrusion. In the tests performed, the first intrusion corresponds to all the accessible and interconnected pores which diameter is above 108 μm . Mortars **ql63** and **ql44** have the greatest values, respectively 46,0 % and 30,0 %, while mortar **al** presents a percentage of 6,1 % and mortar **cq** register 16,5 %. The incremental curves also denote that mortars **al** and **cq** have an important threshold diameter of around 43 μm (15,3 % intrusion for **al** and 20,0 % intrusion for **cq**). It may be then concluded that the fissure-shaped macropores have larger diameters on the **ql** mortars. The images of the four mortars obtained with the optical microscope (figure 6) confirm this distinction. Finally, in what concerns the finer pores, it can be observed that **al** and **cq** mortars have a threshold diameter of around 0,54 μm (22,4 % intrusion for **al** and 7,0 % intrusion for **cq**) while the corresponding value for **ql** mortars is 0,36 μm (nearly 4 % intrusion for both).

Porometry data may contribute to explain the results of the capillary water absorption. The interconnected macropore network of the **ql** mortars, with larger diameters, naturally leads to higher water absorption rates in the initial phase of the tests, thus resulting in higher values of the capillary absorption coefficients.

As for the asymptotic values, it may be generally observed that the higher values of **ql** mortars are a consequence of the smaller micropore diameters. Mortars **al** and **cq** deserve a more detailed analysis. Their micropore threshold diameter is similar and the latter has a higher open porosity. These facts should suggest that **cq** mortar would absorb a higher quantity of water, which does not occur (table 3). However, the higher percentage of mercury intrusion of **al** mortar in this type of pores (22,4 % versus 7,0 % for **cq** mortar)

indicates that there is an important micropore network giving access to the macropores. As it is known, capillary water absorption rises higher in smaller diameters porous networks. The image of figure 6 clearly shows these denser micropore areas in the **al** mortar.

4. Discussion

When dealing with mortars for architectural heritage, four main characteristics should be considered:

- Absorption and evaporation of water (this last issue is currently analysed by the determination of either the water vapour permeability or the drying index; it was not analysed in this study because it is well-known that lime mortars present appropriate values on this issues);
- Mechanical resistances (including adhesion, that was not considered in this study);
- Resistances to soluble salts;
- Amounts of released salts (this issue was not considered in this study because it is known that lime mortars do not release damaging salts, when compared with hydraulic binder mortars).

These four issues should be considered in two different ways:

- a) Characteristics needed to protect the walls in which the mortar is applied (avoiding the degradation processes)
 - absorption and evaporation of water
 - mechanical resistances
 - release of soluble salts
- b) Characteristics needed to prevent the degradation of the mortar (increasing durability)
 - resistance to soluble salts
 - evaporation of water
 - mechanical resistances

The relative performance of the mortars analysed in this study should be conducted in accordance with the previous general concepts.

- a) Characteristics needed to protect the walls

The water capillarity absorption presents two types of behaviour: the initial water absorption (measured by the capillary coefficient) and the total amounts of adsorbed water (measured by the asymptotic values). Pure lime mortars generally present high capillary coefficients and low asymptotic values. From this point of view, and considering that all the analysed mortars present good water vapour permeability, the best balance is achieved by mortar **cq** and mortar **al**.

The analysis of the mechanical characteristics should be carried out from the point of view of the compatibility with old walls, which are characterized by having low mechanical resistances and high levels of deformability. The results in terms of mechanical resistances and moduli of elasticity of lime mortars are not high, and this question of compatibility is assured.

b) Characteristics needed to prevent the degradation of the mortar

Within this context the mechanical resistances should be analysed in a different way from the one expressed previously. In fact, if the mortar is to be durable it should have enough mechanical resistances to withstand the aggressions it will inevitably face. This means that the compressive and particularly the flexural strengths should not be too low (and should be achieved in a reasonable amount of time). From this point of view it should be emphasized the better performance of mortars **cq** and **al**.

The resistance to the action of salts was carried out considering the chlorides (which mainly introduce a mechanical action) and the sulphates (which combines a chemical with a mechanical action). As for the resistance to chlorides, the best performance was achieved by mortar **ql63**, which presented the lowest losses of mass (a result that should not be related to the low mechanical resistances showed by this mortar at ages of 2 and 3 months). In terms of resistance to sulphates, the best performance was achieved by mortars **ql** (**ql44** and **ql63**).

From the previous analysis, mortars **ql** and **al** are those complying better with the purpose of protecting the walls (mainly in terms of capillary action); in particular mortars **ql** are those assuring the best performance in what concerns their own durability.

Once the effects of a higher capillary absorption can be compensated by a good evaporation of water (through an adequate water vapour permeability), it seems that the preferable mortars to be applied are those of type **ql**.

5. Conclusions

Good correlations were established between the properties of the porous network of the lime mortars and the capillary water absorption.

The ready to use dry hydrated lime mortar presented a good behaviour, particularly in terms of capillary absorption, what assures very good characteristics as far as historic masonry protection is concerned.

The laboratory analysis of lime mortars made with putties with long slaking periods evidenced the improvement of the obtained characteristics, comparatively with the ones registered with dry hydrated lime, in terms of workability (and the consistency to assure applicability) and in what concerns resistance to chlorides and particularly to sulphates. Concerning this last aspect, although losses of mass of 40% to 50% are high, it is relevant the fact that after that loss, standard quicklime mortars of very young ages will remain in a stationary stage, assuring more satisfactory durability.

This type of mortars should present an increased durability, contributing to prevent degradation caused by salts attack (very frequent in historic masonries), without jeopardizing the necessary protection of the architectural heritage.

6. References

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Table 1

Mortar designation, constitution (in volume) and consistency by the flow table test

Constituent/Mortar	al	cq	ql63	ql44
al	1			
cq		1		
ql			1	1
river sand	2	2	2	2
Consistency (flow table) [%]	68	72	63	44

Table 2

Dynamic moduli of elasticity, flexural and compressive strength (average values and standard deviation) of mortars aged 60 and 90 days

Mortar	E (Mpa)		Rt (Mpa)		Rc (Mpa)	
	60 d	90 d	60 d	90 d	60 d	90 d
al	2050 ±77	2100 ±53	0,29±0,04	0,32±0,01	0,46±0,04	0,75±0,03
cq	2450 ±56	3100 ±93	0,39±0,02	0,63±0,02	0,70±0,02	1,09±0,11
ql63	1150 ±10	1600 ±39	0,15±0,01	0,23±0,03	0,24±0,02	0,35±0,02
ql44	1250 ±66	1700 ±23	0,17±0,04	0,25±0,04	0,34±0,02	0,47±0,04

Table 3

Capillary water absorption coefficient and asymptotic water absorption (average values and standard deviation) of mortars aged 60 and 180 days

Mortar	Capillary Coef. (kg/m ² .s ^{1/2})		Asympt.Abs. (kg/m ²)	
	60 d	180 d	60 d	180 d
al	0,43±0,08	0,39±0,05	20,7±0,8	18,8±0,6
cq	-	0,26±0,02	-	16,9±0,7
ql63	1,27±0,01	1,10±0,09	22,3±0,2	21,0±0,5
ql44	1,17±0,04	1,08±0,05	21,2±0,9	20,5±0,3

Table 4

Chlorides retention and mass variation after 30 and 50 cycles of resistance to chlorides test (average values and standard deviation) of mortars aged 60 and 180 days

Mortar	Retained chlor. (%)		Chlorides - mass variation (%)			
			30 cycles		50 cycles	
	60 d	180 d	60 d	180 d	60 d	180 d
al	4,4	4,4	-13,9±6	-20,4±2,5	-33,4±5,9	-43,2±4,2
cq	-	4,0	-	-22,1±5,2	-	-67,0±1,3
ql63	5,2	5,1	0,9±1,1	-31,3±3,1	-10,3±7	-58,4±2,9
ql44	5,0	4,8	-1,0±4,5	-46,1±0,4	-9,2±6,7	-73,4±0,6

Table 5

Mass variation after 5, 15 and 25 cycles of resistance to sulphates test (average values and standard deviation) of mortars aged 60 and 180 days

Mortar	Sulphates - mass variation (%)					
	5 cycles		15 cycles		25 cycles	
	60 d	180 d	60 d	180 d	60 d	180 d
al	-3,0±2,6	3,5±0,1	100(c.8) ±0,0	-9,4±24,9	-	-19,7±45,6
cq	-	1,1±0,3	-	-26,1±2,2	-	-51,6±0,7
ql63	0,3±0,8	2,7±0,1	-50,4±4,0	4,3±0,4	-54,1±3,9	5,4±0,4
ql44	1,1±0,7	2,8±0,1	-41,1±2,6	4,6±0,0	-43,3±3,1	6,1±0,1

Table 6

Bulk density and open porosity (average values and standard deviation) of mortars aged 60 or 90 days and 4 years

Mortar	Bulk dens. (kg/m ³)			Open poros. (%)		
	60 d	90 d	4 y	60 d	90 d	4 y
al	1720 ±7	1690 ±9	1730 ±4	34 ±7	35 ±1	34 ±0
cq	1670 ±7	1640 ±18	1652 ±19	35 ±0	37 ±1	37 ±1
ql63	1550 ±8	1560 ±9	1544 ±8	40 ±1	40 ±1	41 ±0
ql44	1590 ±10	1600 ±7	1582 ±9	39 ±0	37 ±1	39 ±0

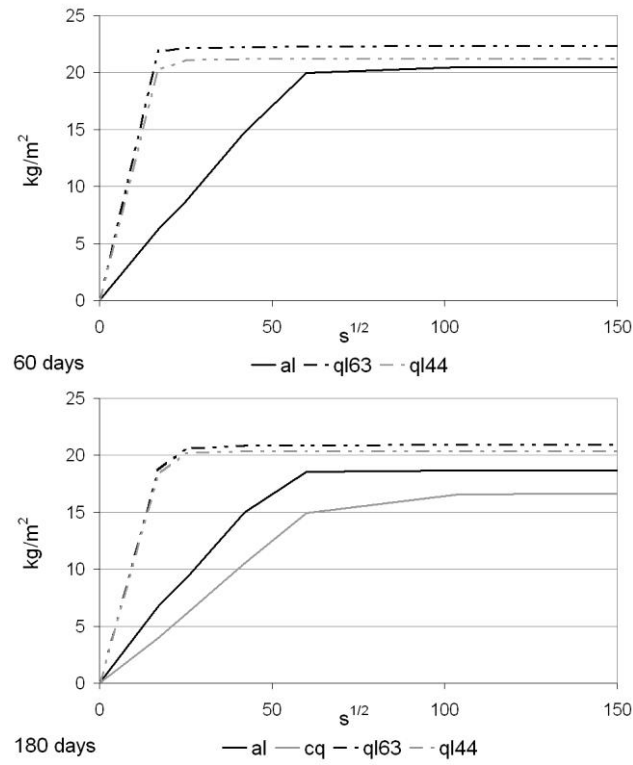


Fig. 1. Capillary water absorption test curves at ages of 60 days (**al**, **ql63** and **ql44** mortars) and 180 days (**al**, **cq**, **ql63** and **ql44** mortars)

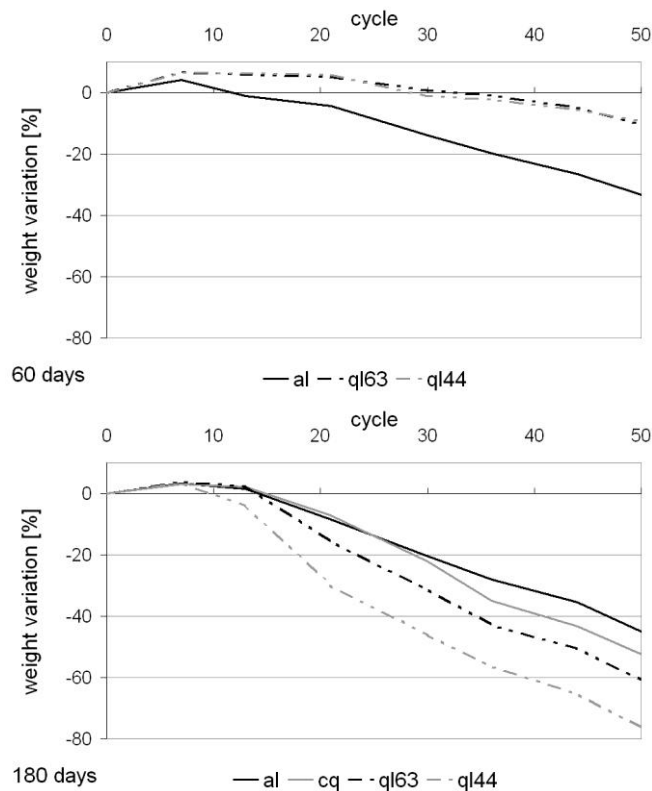


Fig. 2. Weight variation of sodium chloride contaminated samples at ages of 60 days (**al**, **ql63** and **ql44** mortars) and 180 days (**al**, **cq**, **ql63** and **ql44** mortars) upon cycling at 40% and 90% RH

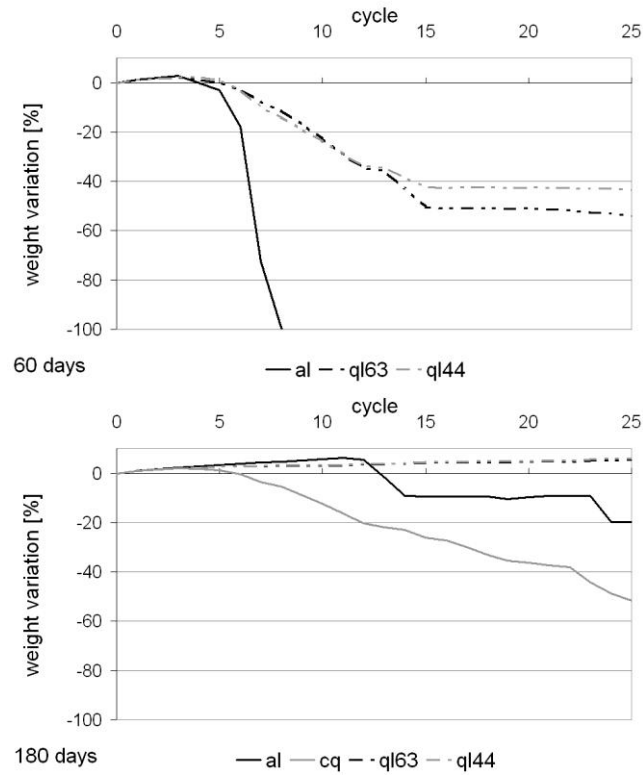


Fig. 3. Weight variation of sodium sulphate contaminated samples at ages of 60 days (**al**, **ql63** and **ql44** mortars) and 180 days (**al**, **cq**, **ql63** and **ql44** mortars) upon wet and dry cycling

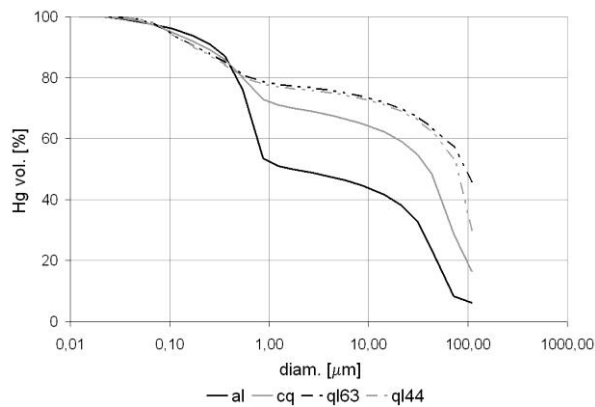


Fig. 4. Mercury intrusion cumulative curves of 4 years old mortars **al**, **cq**, **ql63** and **ql44**

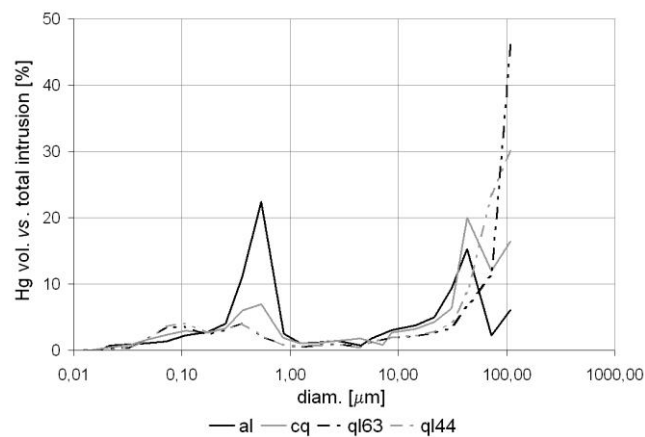


Fig. 5. Mercury intrusion incremental curves of 4 years old mortars **al**, **cq**, **ql63** and **ql44**

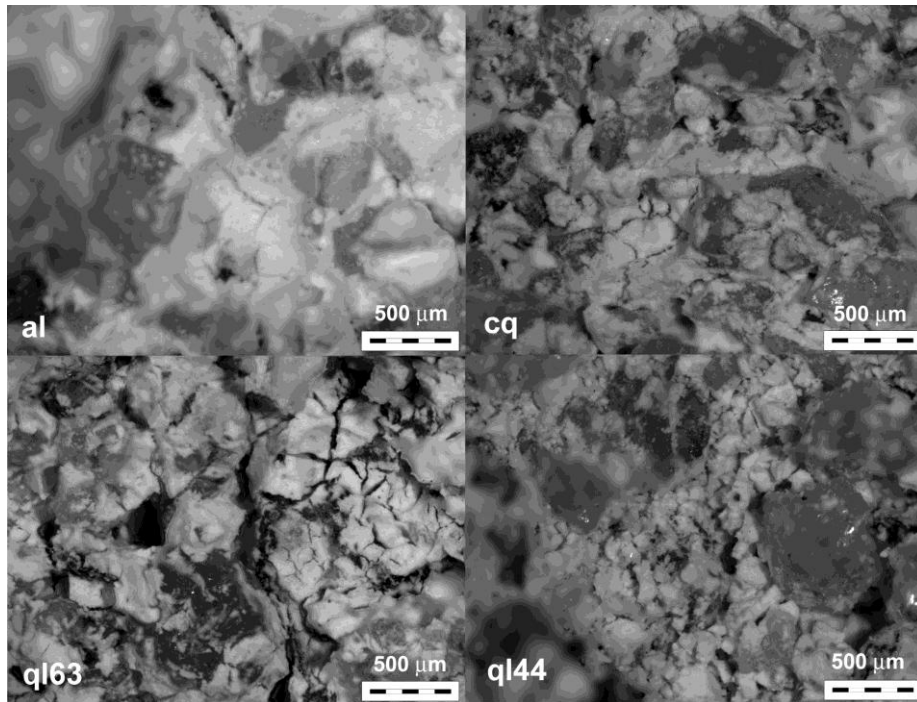


Fig. 6. Images from optical microscope of 4 years old mortars **al**, **cq**, **ql63** and **ql44**

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