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The role of aggregates on the structure and properties of lime mortars

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Abstract

Lime mortars have been used for centuries in civil engineering construction. Considering ancient monuments and historical buildings it seems that these mortars have proved to be durable and reliable materials although they are of low strength in comparison with cement mortars. Nowadays, they are used for the repair of monuments and for the manufacture of renderings and plasters.

In the present paper the role of aggregates on the structure and behaviour of lime mortars is examined by studying the influence of the aggregate content and the grain size on strength, porosity and volume stability of the mortars. Capillary porosity by suction was also measured as an indicator of resistance to weathering. It is shown that coarse aggregates contribute to the volume stability of lime mortars independent of strength enhancement when adequate compaction reduces the capillary pores. The highest strength values, and consequently, the low porosity, were attained by lime mortars of low binder/aggregate ratio which contained aggregates of maximum size 0–4 mm.

Keywords: Lime mortars; Aggregates; Grain size; Strength; Porosity; Compaction; Capillarity

1. Introduction

Lime-based mortars have been used for centuries, as joint material of historic monuments of masonry constructions. Such mortars consist of binders (lime or combination of lime and pozzolanic materials) and aggregates which are often coarse especially in the case of masonry with thick joints [1,2]. Old lime-based mortars with pebbles are also often found in the castle walls. Today, they are widely used for the repair or reconstruction of monuments and historical buildings. Furthermore, plasters and renderings are also based on lime but the aggregates used are usually finer particles of 0–4 mm. Addition of aggregates to a binding system have proved to confer technical advantages as they contribute to volume stability, durability and structural performance [3,4]. Apart from the different type of aggregates as their mineralogy is concerned, the volume content in the mixture, the maximum size and their gradation influence the structure of a binder–aggregate mixture [3,5].

Even in old mortars, which were designed rather empirically, aggregates were used in different sizes such as 0–4 mm, 0–12 mm, 0–16 mm and 0–40 mm [6,7] and in even gradation so as the mortars are often characterized as "concretes" [7]. In concrete, the interlocking of the aggregate–paste forms the transition zone, which is characterized as the "weak" phase due to the high porosity, and, because of the formation of micro-cracks and different crystal sizes of the binder [8–10]. The incompatibility between the modulus of elasticity of the aggregate and of the paste affects the development of micro-cracks at the aggregate–matrix interface. However, it is well recognized that coarse aggregate particles act as crack arresters, as they restrict the shrinkage of the cement, so that under an increasing load, extra energy is absorbed for the formation of a new crack. This results in the gradual failure of the concrete [3,9].

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Table 1
Mechanical and physical characteristics of mortars with different binding systems at the age of 90 days [11]

Binder	Compressive strength (MPa)	Open porosity (%)
Lime	0.25	22.81
Lime + pozzolan (proportion 1:1)	6.56	19.66
Lime + pozzolan + cement (proportion 1:0.5:0.5)	7.34	16.72

The matrix of a lime-based binder is characterized by high porosity and low strength in comparison with the cement matrix. For comparison, indicative values of strength and porosity of mortars based on cement, pure lime and lime–pozzolan combination are given in Table 1. Compressive strength was determined according to EN 1015-11:1999 and open porosity according to RILEM CPC11.3. The values both for compressive strength and for porosity are the average measurements taken after testing three samples. All mortar mixtures were prepared with the same binder: aggregate ratio (1:3) and they were of the same plasticity measured by flow table. In this paper, the role of aggregates in lime mortars is studied systematically by investigating the influence of mortar mixture characteristics such as the grain size of the aggregates, the binder to aggregate ratio, the compaction and the curing conditions on the long term behaviour of these mortars.

2. Experimental part

Fourteen series of lime mortar compositions were prepared. For each of them 21 mortar specimens, $40 \times 40 \times 160$ mm, were manufactured for testing compressive strength at 28, 90, 180, 360 and 730 days and for measuring volume change with time as well as water penetration by suction. The parameters studied were the binder/aggregate (B/A = 1:1.5, 1:2.5, 1:3, 1:4, 1:6) and aggregates of maximum grain size 0–2 mm, 0–4 mm, 0–8 mm, 0–16 mm. The gradation of the aggregates was selected to be even. Dry hydrated lime was used as binder. River sand and coarse aggregates of siliceous origin were used after testing their suitability. Some characteristics of the raw materials are given in Table 2. The aggregate fractions were selected to provide a mixed gradation of the maximum bulk density. For all mortar mixtures, the water content was controlled by keeping the flow table extension 15 ± 1 cm according to DIN 85555 so as the mortar mixtures have adequate fluidity for bedding. For the series with B/A 1:3 and for coarse aggregates (0–16 mm), the mortar mixtures were subjected to two different levels of compaction after molding according to pr EN 1015-6:1998. In the first case, the mixtures exerted no compaction and in the second, they were compacted by twenty strokes using a metal brake.

For the mixtures with coarse aggregates, the water demand for the same workability was lower in comparison with the mixtures with sand as would be expected. The proportioning of the mortar mixtures is given in Table 3. The mortar specimens were kept in a room at 20 ± 1 °C and 85–90% RH up to 90 days, and

Table 2
Characteristics of lime and aggregates used for lime mortar mixtures

Properties	Dry hydrated lime	Sand (0–2 mm, 0–4 mm)	Coarse grains (0–8 mm, 0–16 mm)
Applied specific density	2.17	2.72–2.52	2.67–2.69
Content in available $Ca(OH)_2$	85%	–	–
Content in soluble salts (% by weight)			
Cl^-	0.02	0.003	0.003
NO_3^-	0.04	0.000	0.000
SO_4^{2-}	0.001	0.002	0.001

Table 3
Proportions of the mortar mixtures

Composition	Hydrated lime	Sand (0–2 mm)	Sand (0–4 mm)	Gravel (0–8 mm)	Pebbles (0–16 mm)	B/A	W/B
1	1	1.5	–	–	–	1:1.5	0.799
2	1	1.125	0.375	–	–	1:1.5	0.795
3	1	0.6	0.3	0.6	–	1:1.5	0.793
4	1	0.5	0.25	0.25	0.5	1:1.5	0.678
5	1	2.5	–	–	–	1:2.5	0.796
6	1	1.875	0.625	–	–	1:2.5	0.738
7	1	1	0.5	1	–	1:2.5	0.743
8	1	0.75	0.5	0.5	0.75	1:2.5	0.734
9	1	3	–	–	–	1:3	0.996
10	1	2.25	0.75	–	–	1:3	0.953
11	1	0.96	0.48	0.96	–	1:3	0.935
12	1	0.72	0.48	0.48	0.72	1:3	0.928
13	1	4	–	–	–	1:4	1.008
14	1	6	–	–	–	1:6	1.382

then exposed to indoor conditions at 20 ± 2 °C and 60–70% RH. Under these conditions the early hardening of pure lime mortars was very slow but it was purposely selected because they were compared with lime–pozzolan mortars, and because preliminary research had shown that early cracking of lime mortars with pebbles cured under the proposed standards of dry conditions (pre EN 459-2 "Building lime") was very intensive. However, it must be mentioned that in this preliminary research, the lime paste (without sand) cured at dry conditions (60% RH) developed lower porosity and higher strength (36.31% and 1.9 MPa respectively) compared with the same paste cured at 90% RH (53.93% and 0.5 MPa) [11]. For the determination of the compressive strength the pieces of the prisms remaining after flexural test were used. At each age, three samples (40 × 40 × 160 mm) were tested in order to find the average value for the flexural strength and then the six pieces were tested in compression. Volume changes were measured in three samples of 40 × 40 × 160 mm cured in stable conditions (20 ± 2 °C and 60–70% RH). The dimensions were measured periodically for almost a year. Water penetration by suction was measured according to NORMAL 11/85. Samples 40 × 40 × 160 mm were used (one in each case). The duration of the test was 24 h and the tests were performed at the age of 90 days.

3. The lime paste

The lime paste is formed when water is added to calcium oxide (CaO). The rigorous reaction renders a colloidal hydrated product the density of which depends on the water content. It shows very good adhesion and binding capacity, since it is carbonated in the air under natural environmental conditions. When hydrated lime in powder form is mixed with water, hydrated crystals are formed which later produce thick plates of carbonated lime. The structure of this matrix is not very condense. Many discontinuities are present. In the early stages, the hydrated lime pastes cured at high humidity are loose in comparison with those cured under dry conditions. However, at later stages the latter pastes show more intense cracking than those of the former wet cured lime pastes. SEM analysis of this paste showed crystals of size less than 10 μm at the age of 28 days (Fig. 1). The strength of lime pastes at that age ranges from 0.5 to 2 MPa. It is obvious that it is a soft binder of low strength capacity, very susceptible to cracking due to shrinkage because of the carbonation process and removal of the absorbed water from the capillary pores. The presence of autogenous stresses in the lime matrix is higher than its tensile strength capacity, and cracking easily occurs.

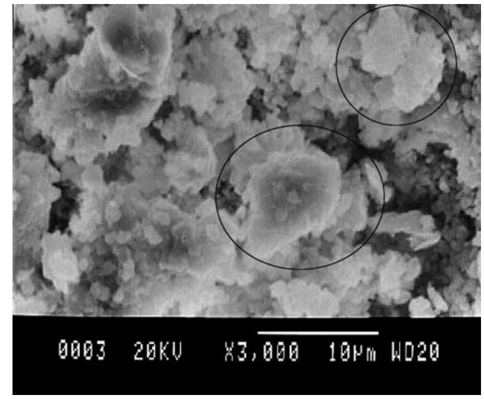

Fig. 1. Calcite crystals in a lime paste.

4. Test results and discussion

The strength development of mortar compositions with different binder/aggregate (B/A) ratio and grain size are given in Figs. 2–4. It seems that at relatively early ages, up to 90 days, where the lime mortars were kept in humid climate, the strength value is low (around

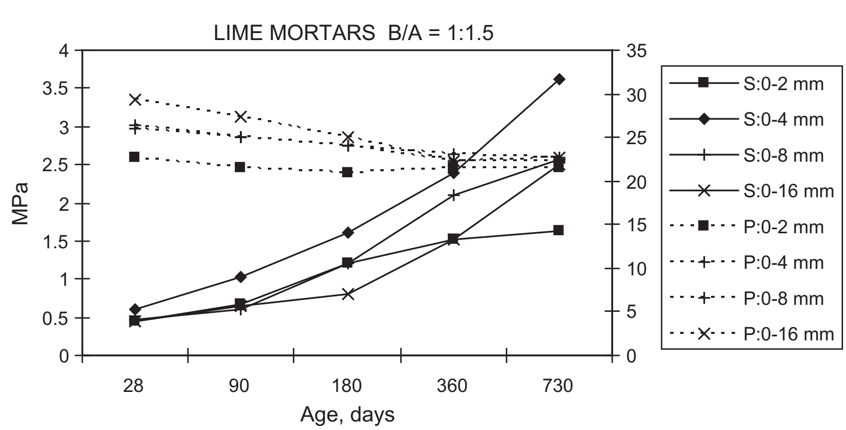

Fig. 2. Development of strength and porosity in lime mortars with B/A 1:1.5 (S = strength, P = porosity).

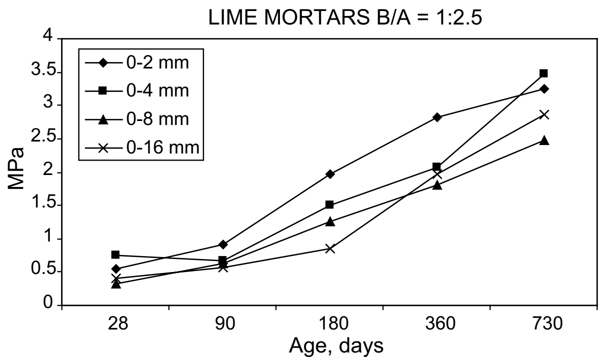

Fig. 3. Development of strength in lime mortars with B/A 1:2.5.

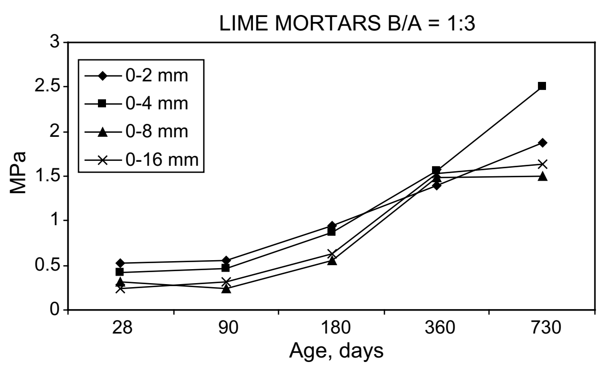

Fig. 4. Development of strength in lime mortars with B/A 1:3.

0.5 MPa) from 0.3 to 0.7 MPa. The lowest values were presented by mixtures with coarse aggregate >8 mm. However, after exposure to dry conditions, the strength of the compositions with coarse aggregate was noticeably increased, and was competitive to the highest observed ones. This means that the inclusion of coarse aggregates is advantageous for long term strength. Microscopic observations of mortar structure shown in Fig. 5 that at early ages, in the case of lime and fine sand mortar, pores and cracks are located in the lime matrix, while in the lime and coarse aggregates, the voids appeared preferentially at the boundaries of the pebbles (Fig. 6). At later ages, cracks appeared to be blocked by the coarse aggregate (Fig. 7). The highest strength values were developed by lime mortars with sand (0–4 mm). Regarding the influence of the aggregate volume content on mortar strength with sand (0–2 mm), it could be said that the lower ones 1:1.5, 1:2.5 exhibited the highest strength values such as around 2.5 MPa at the age of one year (Fig. 8). Volume changes measured are shown in Figs. 9 and 10. They are higher in mortars with the lowest B/A ratio, 1:1.5. The presence of coarse aggregate contributed to the lowest volume change (0.8%) independently of the strength enhancement (Fig. 10).

Compaction, although is not prescribed as necessary in relevant regulations, is essential in the case of lime mortars with coarse aggregates. Its influence in strength

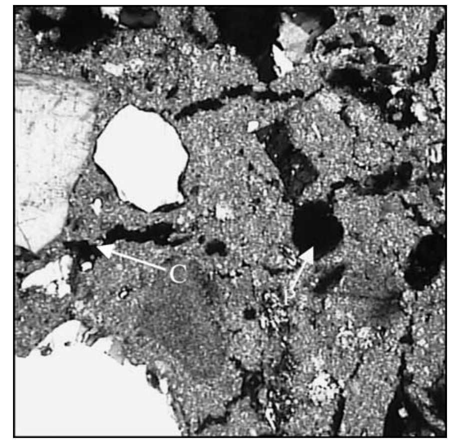

Fig. 5. Structure of lime mortar with fine aggregates. Pores and cracks net into the binder (polarized microscope crossed nicols, ×65, P = pore, C = crack).

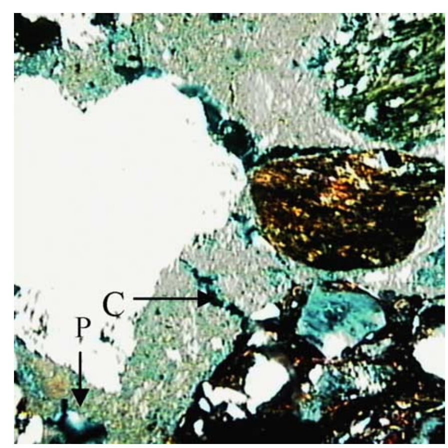

Fig. 6. Pores and cracks in the structure of lime mortar with coarse aggregates (stereoscope, ×15, C = crack, P = pore).

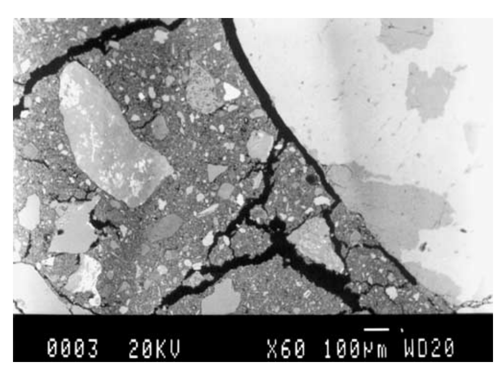

Fig. 7. SEM analysis of the structure of lime mortar with coarse aggregates.

is given in Fig. 11. It seems that the strength increase is around 10–15% at early ages but later, at 180 days, it amounts about 30% at higher values. Open porosity measured at the age of 90 days for low compacted mortars is 18.45% (measuring according to RILEM

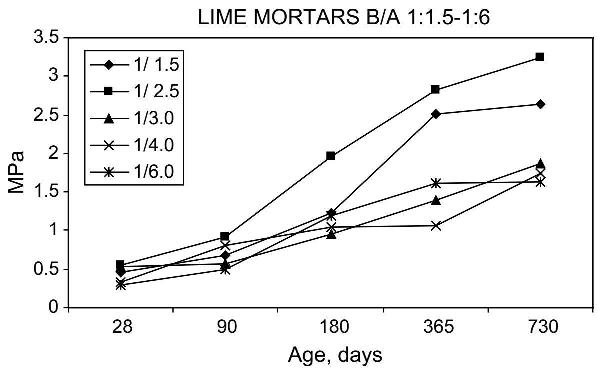

Fig. 8. Development of strength in lime mortars with different B/A ratio.

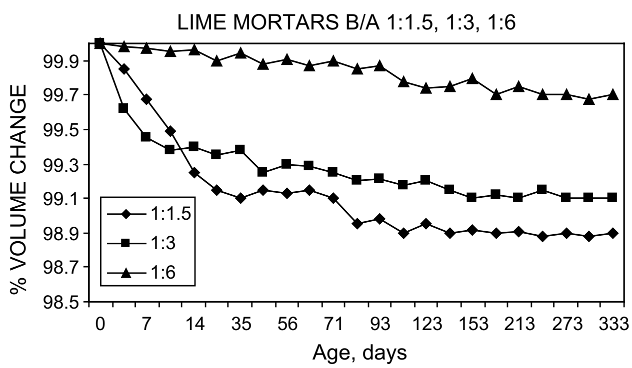

Fig. 9. Volume change measurements for lime mortars with different B/A ratio.

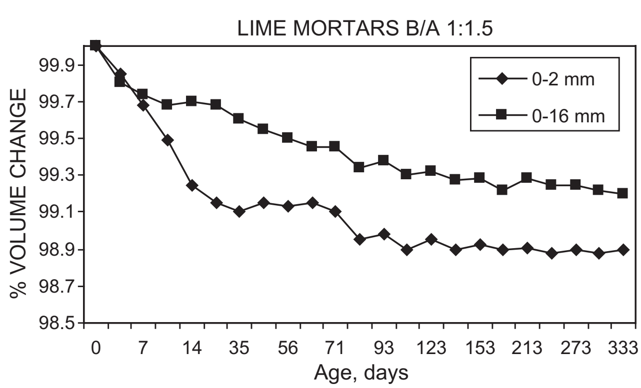

Fig. 10. Volume change measurements for lime mortars with B/A 1:1.5 and different grain sizes.

CPC 11.3 method—water absorption under vacuum) while for high compacted mortars at the same age is 17.91% [11].

Capillary suction measurements are shown in Fig. 12 measured at 90 days. It is obvious that the rate of water penetration as well as the final water absorption is higher in the case of lime mortars with coarse aggregates. It means that capillary porosity developed in the microstructure, was higher than that of lime–sand mortars.

Fig. 11. Impact of compaction on the strength of lime mortars with coarse aggregates (L-Compac. = low compaction, H-Compac. = high compaction).

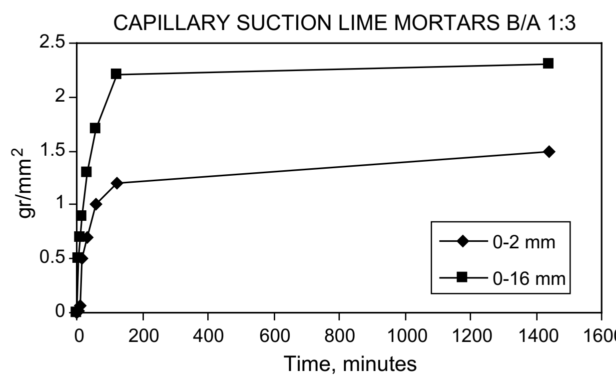

Fig. 12. Capillary suction measurements at 90 days.

However, for lime mortars with coarse river aggregates (0–16 mm) for which extra compaction was applied, the amount of water penetration is comparable to that with sand (Fig. 13). It is obvious that in the case of the addition of coarse aggregate in lime mortar mixtures, compaction is necessary for the benefit of long term strength and weathering resistance.

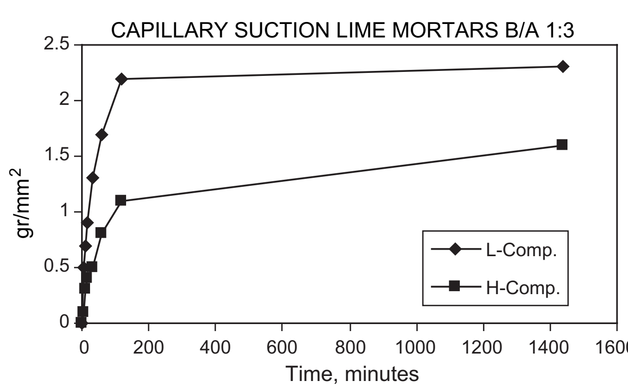

Fig. 13. Capillary suction measurements for lime mortars with coarse aggregates (0–16 mm) differently compacted at 90 days (L-Compac. = low compaction, H-Compac. = high compaction).

5. Conclusions

Taking into account all the results presented, it seems that higher strength values are attained for lime mortars of low B/A ratio (1:1.5, 1:2.5 and 1:3) which contained sand 0–4 mm. Coarse aggregates have contributed positively to volume stability of lime mortars since the volume changes were noticeably restricted. This has a positive impact on long-term strength, and explains why in the old days, masons have used pebbles for the construction of tall masonry structures.

It seems that, when coarse aggregates are used, strong compaction of the mortars is necessary to reduce the voids and increase the bond of lime paste with pebbles. Although this is not prescribed in regulations, compaction is also advantageous for reducing water penetration and consequently increases the resistance of mortars to weathering.

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