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DURABILITY OF AIR LIME MORTAR

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Abstract
This contribution deals with the physical and chemical reasons why pure air lime mortars used in masonry of burned bricks exposed to outdoor climate have shown to be durable from the Middle Ages to our days. This sounds strange in modern times where pure air lime mortars are regarded as weak materials, which are omitted from standards for new masonry buildings, where use of hydraulic binders is prescribed.
The reasons for the durability seam to be two:

1. The old mortars have high lime contents.
2. The carbonation process creates a pore structure with a fine pored outer layer and coarser pores inside. This difference in pore size will delay the capillary suction of rain from outside, while excess water inside can be sucked to the front and evaporate.

1. The high lime contents

The lime contents of mediaeval mortars are high, 25 - 40 % [1]. The reason for this fact is that the mortars were produced by the so-called hot lime technic. The burned lime (CaO) were mixed with gravel and water, and so it slaked to calciumhydroxid ($Ca(OH)_2$), ready to be placed in the building. (Lime mortar produced by wet slaked lime (kulekalk) can be produced with 13 % lime as maximum, because of the high water content of the lime dough.)

The carbonation of such lime rich mortars takes time, the higher the lime content and the thicker the wall, the longer the time. You can find very thick old walls, where the mortar is still uncarbonated after hundreds of years. Meanwhile, although the mortar is not carbonated, the load bearing capacity of the wall is present immediately after the construction. This is due to the capillary action in the pore water: During the brick laying the tiles suck up the excess water from the mortar. In this way a hydraulic under-pressure is created in the water. At moisture equilibrium at 80 % RH, 20 ^{0}C, the under pressure in the water is about 20 MPa.

This pressure secures the tiles in their places and forms the skeleton in the gravel to its load bearing duty. So, water is the binder in this situation, until the carbonation has taken place.

The load bearing effect of the water has been shown in experiments on our institute [6]. The cohesion of mortar in joints between two tiles was measured in a torsion test [7]. E.g. in a 9% air lime mortar the cohesion after 28 days was 0,17 MPa, while the value after 16 weeks, where the joints were fully carbonated, were 0,14 MPa.

2. The pore structure

When both calcium hydroxide and carbon dioxide are available, the carbonation process ($Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$) is a relative fast process. This can be seen on the surface of freshly poured limewater in a bucket. In less than a quarter of an hour a grey layer has been created. It consists of very small crystals of calcium carbonate reflecting the light. The crystals can be seen in polarised light (Figure 1). During a week the crystal layer gets a thickness of 0.03 – 0.04 mm.

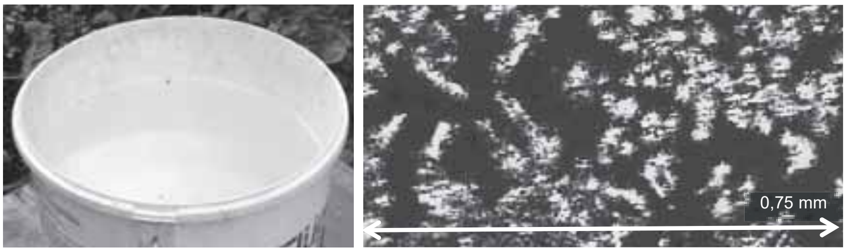


Figure 1. Carbonation on the surface of limewater. Crystals can be seen in the microscope.

This creation of small calcium carbonate crystals also takes place rather fast on the surfaces of freshly placed joints or plaster. (Von Balen et al [2] have shown that the take up of carbon dioxide in a mortar joint is two to three times faster in the first five minutes than after five hours.) The small crystals form a continuous layer on the surface. The carbon dioxide can still penetrate this layer and continue the hardening in the inner parts of the mortar. The final result is that we get a structure with a surface layer with much smaller pores than the bulk mortar (Figure 2).

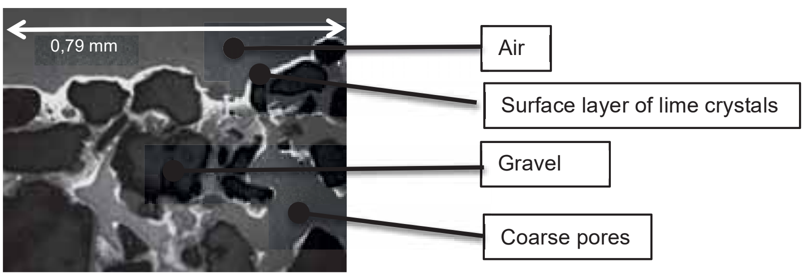


Figure 2. Cross-section of the outer layer of a 12 % lime mortar. Fluorescent light.

It is well known from the physics that a capillary tube with a small diameter is able to suck water from a tube with larger diameter, while the opposite cannot take place. For a mortar joint with a pore structure as described above this means that the suction of rainwater from outside is delayed in relation to the suction in a mortar without a crystal layer. On the contrary, an excess amount of water in the internal part of the joint will be sucked to the surface and evaporate. One can say that the mortar joint act as a hygrodiode. The positive effect of lime coatings on drying is shown in [9].

The effect can be seen on a piece of mortar from the outside of a joint. If water is dripped on the surface exposed to the weather, the water will lay as a pearl on the surface. If you turn the piece around and drip from the backside, the water is sucked up directly. In Figure 3 the effect is shown on a horizontally placed joint, where the surface layer has been damaged in two places.

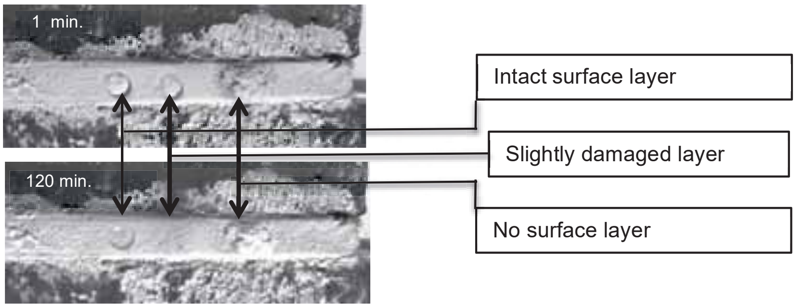


Figure 3. Joint of a 12 % air lime mortar placed horizontally. The mortar is of the same kind as shown in Figure 2. Three water drops are placed.

One may object that the surface layer will be dissolved by acid rain. This is correct, but it must be taken in consideration that the mortar joint is not a static system, where nothing more happens, when the first carbonation has taken place. Matter is transported back and forth in the pores. Calcium ions from the inner uncarbonated part of the joint may diffuse and meet carbon dioxide diffusing from the air. Anyhow, the surface layer continues to be there, as it can be seen on thin sections of old mortars. These transportation phenomena ought to be studied to increase our understanding of the influence of lime content and weather conditions on the thickness of the surface layer.

White wash and rendering with air lime mortars carbonate in the same way as described above. So the effect as a hygrodiode is also present in these structures. - Limewater, which is a saturated solution of calciumhydroxid, $Ca(OH)_2$, is often used as the last treatment of lime washed surfaces or renderings. (The solubility of $Ca(OH)_2$ is 0,16 g per 100 ml water at 23 ^{0}C.) The effect of this treatment is to thicken the crystalline surface layer. The outermost $Ca(OH)_2$ carbonates on the surface, and as the concentration of the $Ca(OH)_2$ decreases, new $Ca(OH)_2$ is drawn against the surface and carbonates there. The use of limewater is analysed and recommended in [8].

3. The church tower case

A case of damage shall be mentioned here as an illustration of the importance of the lime content and the surface layer. The church in Kirke Værløse had its tower built between 1400 and 1450. The mortar was produced as hot lime mortar and had a lime content of 25 - 40%. The original joints in the least exposed parts of the tower are still intact. In 1994 - 1998 the joints in the top of the tower were repaired. The medieval joints were removed to a certain depth by milling, and new material placed instead. One was aware that an air lime mortar should be used, but the lime content was obviously not considered, as a mortar with 6,6% lime was used (!)

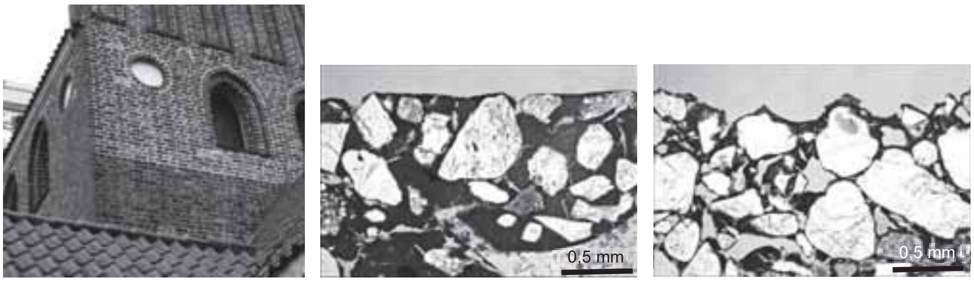


Figure 4. The church tower in Kirke Værløse.

Left: Both the tiles and the mortar in the top part were severely damaged by frost action.
Middle: Section of medieval mortar. See Figure 5. Right: Section of the 6,6% repair mortar.
Both micrographics: Transmitted light. No filters. Top of the picture is the outside surface. Dark colour is lime binder. (Photo: SEIR-materialeanalyse A/S)

Figure 5. Enlargement of the section of the medieval mortar. The "R's" show cracks.
Transmitted light. No filters. Dark colour is lime binder. Top of the picture is the outside surface with the dense calcium carbonate layer. (Photo: SEIR-materialeanalyse A/S)

After ten years the top of the tower suffered from severe frost damages, which turned the colour of the top from brownish to light red, as the outer layer of the tiles disappeared. A 6,6% mortar has not enough lime to fill the space between the gravel particles and the surface layer is not sufficient to avoid water penetration, cf. Figure 4. - In 2009 - 2015 the joints were repaired again with a mortar developed by master bricklayer Ole Jensen containing 25% lime produced as hot lime.

4. Capillarity

The mortars from Kirke Værløse and Farum churches were included in a project, where the moisture properties of different air lime mortars were examined [3]. The capillary suction capacity was measured by means of the so-called Karsten tube.

Figure 6. The 25% mortar developed by Ole Jensen was also used by the repair of a wall around the churchyard at Farum church. Picture is taken during measuring of capillarity with the Karsten tubes. (Photo: Martin Jensen)

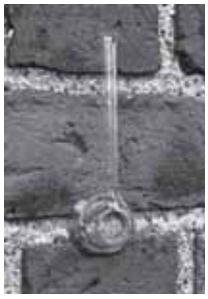
The coefficients of capillarity were calculated from the measurements by means of a method invented in [5]. In laboratory measurement were taken on platens of 6,6%, 9% and 13,5% air lime mortar. Specimens of the in Denmark very common used lime-cement mortar KC50/50/700 (50 kg air lime, 50 kg Portland cement, 700 kg sand) were included for comparison. The results are seen in Table 1 and Figure 5. - In a textbook [4] the coefficient of capillarity for lime mortar can be read as 0,25 $kg/m^2s^{1/2}$ and for concrete to 0,01 - 0,3 $kg/m^2s^{1/2}$.

Measurement of capillarity is a tool in the evaluation of the frost resistance of the mortars. Porous building materials are frost-resistant as long as the water saturation degree, S, is lower than the critical degree of water saturation, S_{krit}, for the material in question. The reason why the medieval air lime mortars are frost-resistant seems to be that the combination of the high lime content together with the fine crystalline surface layer is able to keep $S < S_{krit}$. In the church tower case mentioned above the lime content in the old mortar was good, while 6,6%

lime was not enough to secure against frost damage. This finding coincides with the capillarity seen in Table 1 and Figure 5. Which lime content is enough to secure frost resistance should be cleared out in further research.

Table 1: Coefficient of capillarity of lime mortars [3]. To the right is shown the Karsten tube.

Mortar type	Coefficient of capillarity, $kg/m^2s^{1/2}$
6,6% Kirke Værløse church	0,38
6,6% Laboratory specimens	0,41
9,0% Laboratory specimens	0,28
13,5% Laboratory specimens	0,16
KC 50/50/700 Lab. specimens	0,12
25% Farum church	0,01



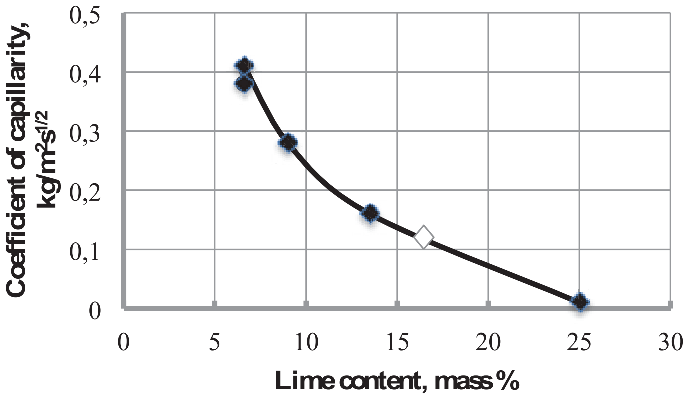


Figure 5. Coefficient of capillarity of air lime mortars. Measured by means of the Karsten tube. The white mark is the result from the very common lime-cement mortar KC50/50/700. From [3].

5. Discussion

The protecting effect from the inhomogeneous pore structure occurs not only in pure air lime mortars. Mortars with hydraulic binders containing a certain amount of air lime also create the crystalline surface layer of calcium carbonate. In [3] it is seen on a thin section of a KC50/50/700 mortar. How much “a certain amount of air lime” is needs more research to be cleared out. - A practical example of the durability of a lime-cement mortar is seen on the yellow masonry buildings on DTU, which were erected in 1963 - 1971 using a mortar much like KC50/50/700. To my knowledge now frost damages have been reported.

The hardening of a pure cement mortar is quite different from the hardening of a lime mortar: Firstly after the brick is placed the tiles suck up the excess water, and the tiles are kept in place by the under-pressure in the water. During the following hours the mortar sets in bulk. The hardening continues in the whole volume during the next days and months. This gives a homogeneous microstructure in the whole volume. Further, the pores in the hardened cement binder are much smaller (10 - 100 nm) than the pores between the carbonate crystals in the lime mortar (100 - 1000 nm). The homogeneity and the smaller pores in the cement mortar will give a worse drying potential to the surroundings, as related to a lime mortar. Maybe a surface layer is created as the cement-binder carbonates, but the pore size may be of a magnitude, which cannot draw water from the fine pores in the binder. More research is needed to elucidate the connection between pore structure and the drying potential and the effect that additives have on this.

6. Conclusion

Air lime mortar in joints and rendering exhibits a good frost resistance in spite of the rather poor mechanical strength. This is due to a certain amount of binder and to an inhomogeneous pore structure, where a surface layer of fine calcium carbonate crystals acts as a hygrodiode, which keeps the coarse pored bulk material dry, and in this way protect the structure from frost damage. - More research is needed to elucidate the phenomenon.

Acknowledgement
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