Abstract

Building with lime is an ancient construction technique. A thousand years of experience in building has proven us that lime still is a sane, durable and strong material. Nevertheless, the last 50-60 years a lot of new materials were introduced and they changed our way of thinking about construction. The knowledge of the right properties of traditional materials like lime diminished slightly through the years, which today sometimes leads to real problems in proper restoration works. An ancient building has its own way of behaving and reacting in different weather conditions. Our aim is to better understand those reactions and try to explain how we have to deal with them. Starting with a brief introduction about the production process of lime, emphasizing the importance of each stage, we would like to focus on the analysis of the behaviour of lime through some case-studies.

In the Low Countries several public heritage institutions nowadays even subscribe lime once more as the only option in some complicated cases. Most of the time the success of lime can be attributed to its permeability and its salt regulating characteristics, in combination with its adaptation to structural compression.

In many cases, the correct use of lime will determine the success and durability of a restoration.

History of Lime

Lime in construction is used as a ‘binder’. This means it is making part of a construction material, most of the time this is a mortar or a mineral limewash paint. The first binders in history were already used in prehistory, coming most of the time out of ‘plaster stones’ (gypsum), which doesn’t need high temperatures for processing the gypsum. 130°C are enough for gypsum to lose his water. The real functional mortars however appear during the fabric of lime. The first appearances date from Mesopotamia around 6000 BC. Egyptians knew the techniques of binders, but didn’t use them really for the making of mortars, due to their giant construction elements. The real use of mortars based on lime came through the Greeks and Romans. Step by step, the making of mortars knows an evolution. From the VI Century BC they already understood that the quality of lime based mortars increase by using lime stones with more silica, and addition of stone dust, marble, clay or volcanic stones pozzolan, broken clay tiles etc. Later on, the heating process will change too. Vitruvius already mentions that the composition of the mortars can differ, regarding to the type of construction (basin, aqueduct, coating for foundations,...). Till the Middle-Ages, the composition isn’t changing much. There will be more experiments with natural products like olive oil, oxblood, eggs, milk, casein, urine,...
In Mediterranean area a huge development of lime is becoming possible through decoration, such as in coatings, fresco paintings, stucco’s and ornaments. In Modern Times, starting from XVth Century AC, the notion of hydraulicity becomes an important part in further research, which will later lead us to the discovery of cements.

**Lime process**

a) The lime cycles

The binder “lime” is produced from limestone (rock). Limestone is mainly composed of the mineral calcite (with a chemical formula \( \text{CaCO}_3 \)). Under normal circumstances, calcite is a low to non reactive material and to reverse this limestone it must be burnt in a lime kiln at a temperature of \( \sim 900^\circ\text{C} - 1200^\circ\text{C} \):

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
\]

In this process, calcite (\( \text{CaCO}_3 \)) is transformed into calcium oxide (\( \text{CaO} \)) and carbon dioxide (\( \text{CO}_2 \)). Calcium oxide or quicklime is a volatile material, which will react in contact with water. Under controlled circumstances, the addition of water will lead to the transformation of quicklime into slaked lime also called calcium hydroxide or portlandite:

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2
\]

Industrial slaked lime is a white-coloured powder that is commercially available. To enhance the workability of this product a certain amount of water is added during the slaking process and shortly after brought at a high temperature again to let water evaporate again and stop automatically the slaking process. To produce lime putty the crushed \( \text{CaO} \) is left for quite some time (6 to 24 years and even longer) in a basin with plenty of water to become finally a very fine paste. In contact with the \( \text{CO}_2 \) in the atmosphere, lime putty will react following the carbonation reaction:

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]

The reacted product is calcite created in what is called the lime cycle. Most natural limestone contain the mineral calcite. The clay mineral content of limestones is at least 5% (Fig. 1). Limestones with clay contents between 10% and 30% are ideal for the production of natural hydraulic lime which hardens with air but also under water. Hydraulic hardening is created by a reaction between calcite and clay minerals during the burning process.
Clay minerals are mainly composed of the components SiO2 and Al2O3. By burning clay limestones at a temperature between 900°C and 1200°C, CO2 will be liberated. A part of the process calcium oxide will react with the components of the clay minerals:

\[ 2\text{CaO} + \text{SiO}_2 \rightarrow \text{C}_2\text{S} \]

Two reaction mechanisms are important for the hardening of a hydraulic lime mortar: a carbonation reaction similar to air-hardening lime, and a more important hydration reaction. The hydraulic hardening or hydration takes place by the reaction with water, and results in a complex molecular structure with the likelihood of higher compressive strength.

Portland cement is burnt at an even higher temperatures, >1450°C. As the elements of hydraulic components in cement are much higher (clay content, Fig. 1), the hardening is almost completely resultant from hydration. The rapid hardening time of cement is the reason that it became so popular during the last century.

The different types of building limes are classified according to their (CaO + MgO) content or, in the case of hydraulic limes, to their compressive strength, according to the norm “European Pre-standard ENV 459-1 “Building lime - Part 1 : Definitions, specifications and conformity criteria” (1994). The following terms are given:

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<th>Calcium lime 90</th>
<th>CL 90</th>
<th>Dolomitic lime 80</th>
<th>DL 80</th>
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<td>DL 85</td>
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<td>HL 5</td>
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Table 1: Classification of building limes, according ENV 459-1 (1994)
3) Properties of lime mortars, in relation to cement mortars

a) From binder to mortar

Most binders (lime, cement and others) cannot be used alone and the addition of an aggregate is required. The combination of binder and aggregate is defined as a mortar. The selection and the ratio of the aggregate is critical and determined by the type of application as it relied upon for: 1) counteracting shrinkage, 2) increasing the cohesion and the strength of the mixture, 3) accelerating the crystallisation of the binder, 4) as a filler.

The aggregate will be chosen by reference to:

- Purity: the aggregate must be free of clay and organic matter. These components will degrade to form molecules that are detrimental to the mortar.
- Angularity: angular aggregate fragments have a higher binding capacity than rounded.
- Granulation: the grain sizing of the aggregate must be well-balanced. Each mortar type and application requires a specific grain size distribution. Commonly the ideal distribution has the shape of a “Füller curve” (Fig. 2 below).

b) Compressive strength: factors

- Water/binder ratio

Generally, the higher the water content of a mortar, the lower the strength of the final product.
Binder/aggregate ratio

The role of the aggregate is to determine the strength of the set mortar. A shortage of the binder content will cause a poor final strength. The ideal proportion between binder and aggregate is approximately 1:3 by volume. Practically, 600kg of binder will be required for each m³ of aggregate.

Granulometry of the aggregate

An increase in the maximum grain size of the aggregate will have a positive influence on the final strength of a lime mortar and as a consequence it is very important to use a grain size as large as possible, during the preparation of the mortar. The pores between the large grains can then be filled with grains of a smaller diameter (see Fig. 2: Fuller curve) and the binder. It follows that the grain size will be dependent on the type of application with for example, bedding and pointing mortars requiring larger grain sizing than the restoration of a fresco in thin layers.

Figure 4: Influence of the maximum grain diameter of the aggregate on the final compressive strength of a lime mortar.

Aggregate type

An increase in the hardness of the aggregate, will lead to higher compressive strength of a lime mortar. Quartz sand (hardness 7) will have a much higher compressive strength than a dolomite sand (hardness 3).

c) Evolution of the compressive strength of lime mortars in time (>180 days)

Generally, the evolution of the compressive strength of a lime mortar will be expressed in periods of 7, 28, 60, 90 and 180 days. To understand well this statement, it’s interesting to compare this behaviour with that of cement. Since the hardening of cement is very fast, the final strength of a cement mortar will be reached in
a matter of days. After 28 days, the hydraulic reaction of cement will be completed. Thereafter cement cannot further develop in compressive strength.

The reaction of lime mortars (air-hardening and hydraulic) is much slower. Unlike cement, lime retains its reactive capacities and consequently the curve of the compressive strength will increase through years (Fig. 4). The standard curve between 7 and 180 day is actually (almost) worthless for the study of lime mortars.

The protracted reactivity of lime mortars promote an excellent performance in building movement and settlement. All structures will move during their life and lime mortar is an ideal product to withstand these stresses without cracking. Lime mortars allow each individual element of the brick or stone to move as a separate entity whereas cement sets as a mass and therefore requires expansion joints. The absence of these in our historic structures and their life span is evidence of the ability to build effectively with lime and avoid unsightly joints.

**Figure 5**: Evolution of the compressive strength of a natural hydraulic lime mortar in a period of 5 years. After 5 years, the compressive strength will be doubled, but even then, the strength evolution will show a positive trend.

d) Damp diffusion and hygroscopic salt content

One of the most important properties of lime mortars is found in its damp diffusion capacity. Lime mortar, either air-hardening or hydraulic, has an open pore structure. Here again we must make the comparison with cement. In cement the hydraulic components are abundant and create closed pores from which damp circulation is much inhibited and in some cases not possible. Consequently a build up of water and salts can occur in and behind a (hardened) cement mortar.
Daily experiences in the field

As mentioned above, the use of lime is not only a matter of aesthetics or a nostalgic feeling of re-using an ancient construction material, but many times it’s indeed the best option to be able to make a proper restoration. The specific properties of lime are the main reason why a lot of interesting and major historic buildings are still standing. Especially in areas susceptible to earthquakes for instance, lime makes a building able to withstand a certain amount of tensions. But other properties makes it also very suitable for other applications, like buildings with deformations and cracks, walls with high hygrometry and salt problems, as base coat for paintings and fresco’s,...

By means of practical case-studies the different ‘unknown’ properties will be treated below.

**Figure 6 :** St Pancras London (United Kingdom)

In this case of a brick structure built and pointed with a lime mortar, the damp diffusion capacity of the lime mortar is normally higher than that of the brick. In dry weather conditions, the humidity level of the interior will be higher than that of the exterior. Vapour will migrate from the inside of the building to the outside. As the damp diffusion capacity of the lime mortar is higher than that of the brick, vapour will migrate primarily through the lime mortar joints. Since a lime mortar is also a barrier to water, rainy conditions externally will not influence the migration pattern. A small amount of water will however penetrate into the bricks and the joints. In dry conditions, the migration pattern will be reversed from the bricks towards the joints and the moisture will be evaporated through the joints.
In the case of a brick building, bedded and pointed with a cement mortar the porosity and the damp diffusion of the brick are low, but generally higher than those of the cement mortar. In dry weather conditions, the humidity level inside will be higher than outside, and the moisture will migrate to the exterior. Moisture and salts will be trapped behind the cement mortar and will accumulate with the result that the brick and cement mortar can, in time, disintegrate.

Lime mortars are flexible and capable of repairing themselves. This means they will follow the deformation of a building/arch under stress. No cracks will appear, which will contribute to an extremely stable structure.
Due to their particular conical shape, façades of mills have to deal with a huge amount of water, especially in the climatic conditions of the Low Countries. Painting coats, for example, could help to protect the surfaces, but can’t avoid the appearance of small cracks. A mill structure is continuously under tension because of its turning sails.

In the beginning of modern architecture, when concrete became a great opportunity to make new shapes, most of the time builders didn’t consider the problem of inner condensation. This is one of the reasons rust started to damage the steel structures in the outer sides of the wall. Today, new additives make it possible to have insulation lime based mortars (still breathable). As a result, dew points (responsible for inner condensation) will be located much closer to the outer surface, i.e. the mortar, and as such protect the steel structures.
In modern restoration techniques craftsmen and suppliers are more and more using lime based mortars for the reparation of stones and the making of moulds. Because of its flexibility, different shapes are becoming possible, and, even more important, the product remains natural, without synthetic additives. Behaviour and aging are more similar to those of their mineral support (natural stone).

On ancient walls it's important to work with breathable finishes. Again, due to inner condensation and damp transfusion, one must be sure the outer layer, like fresco’s, remains sane. Thanks to this property, a lot of old paintings on buildings are still visible.
Figure 13: Underground ice storage VUB Brussels (Belgium)

Research has been done by KIK on this particular site. The caves have to deal with a very high degree of humidity, because of their underground location. The inner wall surfaces are full of salts coming from the sand of the earth on the other side. The salts are no problem at this moment, as with the amount of moisture, they can’t crystallize. They can’t be taken out, though, and there is no alternative but to leave them on the surface. Lime mortars are the only possible way of restoration, thanks to their regulation capacities. Other mortars will change the humidity level of the site, and the salts would start to crystallize and damage the masonry.

Figure 14: Cathedral of St John ‘s-Hertogenbosch (the Netherlands)

Masonry of heavy structures, like supporting walls of cathedrals, can be composed of inner brickwork and finished with an outer natural stone wall. The two materials have different reactions against humidity and salt migration, and against tensions. Restoration of this kind of structures must be executed with a lime based mortar, again to avoid all problems of extra tensions and a possible vapour barrier.
An ancient masonry in brickwork, especially in huge supporting structures such as castles, or, in this case, a sluice, have a lot of small cracks and loss of inner composition of the wall. Injection grout with lime will assemble all the different inner materials (not always of good construction quality). Thanks to its flexibility it will take into account all the different stresses.

Research was made by the University of Padova, together with HD Systems, about this kind of injections in areas where earthquakes are taking place. Measurements were made on different constructions, and it turned out that all structures with concrete beams and floors presented a different behaviour than a construction built in a traditional way (lime based). Collapse happened as a ‘card play’, this means all concrete and cement based structures reacted as one huge structure, with a much greater damage than in lime based structures.

Bibliography