LIME IN MORTARS

HYDRATED LIME
– BENEFITS OF USE IN MORTARS

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Content

Summary

Building lime (Calcium Hydroxide or air lime) has been used in construction for thousands of years as a binder. The Romans were using air lime in combination with natural and artificial pozzolans in their buildings. Mortar formulations have developed over time and it was common practise in the last century to combine air lime and cement. In this way, lime has been used extensively as a component of masonry mortars and renders in order to provide the mason or bricklayer better mortar workability in the fresh state. These benefits essentially relate to the development of better water retention and air entrainment. In addition, as a result of the reaction with carbon dioxide from the air, the lime hardens and contributes to the overall strength of the mortar.

Although widely used, there is only a limited scientific or technical literature base that supports the beneficial attributes either in the fresh or hardened state. This paper reviews what literature is available and the types of benefits that lime brings to the performance of cement based mortars, not only in the fresh state, but also in the hardened state. This paper explores what evidence is in the literature and highlights the benefits of the use of lime in mortars.
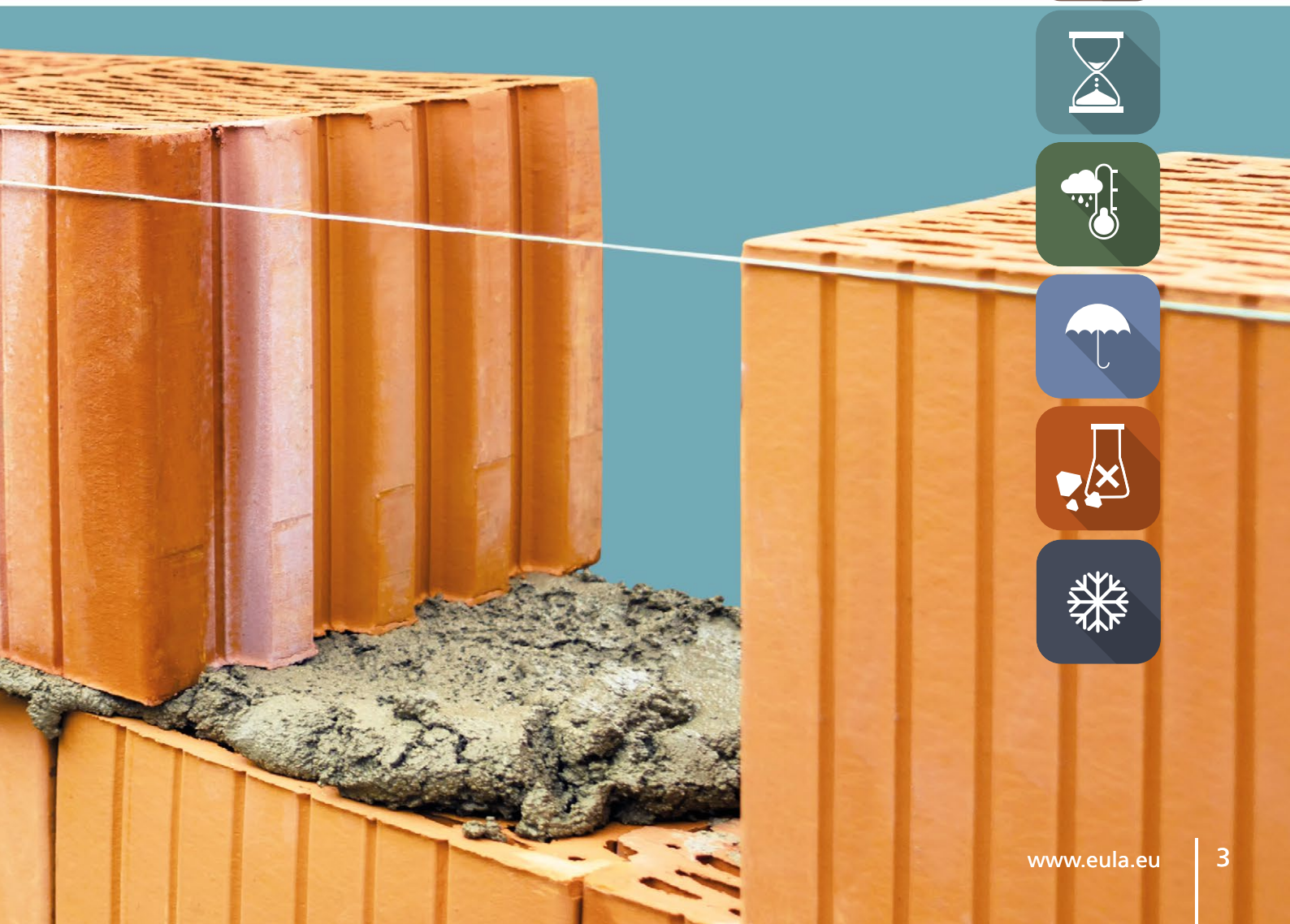
1. Introduction

The combined use of lime (hydrated lime/building lime $Ca(OH)_2$) with cement in mortars has been commonplace for over 100 years. The use of cement in mortars was developed to accelerate the development of strength, whilst in addition to the binding properties, the main purpose of lime use has been to keep the desired "workability" of the mortar in the fresh state, thus providing an easier material for the bricklayer or stonemason to work with. Much of this "workability" is attributed to two modifications to the mortar when lime is added:
• water retention,
• air entrainment.

Although the water retention properties of lime additions have the potential to modify the hardened mortar properties, namely the connectivity of the pore structure, they predominately impact upon the fresh state properties, where as air entrainment modifications are in general carried over into the hardened mortar, and have been shown to have an impact upon durability, specifically with frost resistance.

Many authors have identified the benefits of lime by experimental assessment of lime-cement mortars for specific mortar or masonry properties such as durability, however few have specifically undertaken research into the role lime itself plays. Much of the works published focus on the different performance when compared to Ordinary Portland Cement (OPC), Masonry Cement and Blended Cements, with and without air entrainment. The papers therefore generally fail to identify the causation of the benefit, namely, what role the lime has played in this modification of performance, or if the actual properties (particle size distribution, chemical composition, etc) of the lime influence the end results. This guide draws together the collective "knowledge" from both academia and industry in one informative guide.

$Ca(OH)_2 \cdot MgO \cdot Mg(OH)_2 \qquad Ca(OH)_2 \qquad CaO \cdot MgO$

Figure 1. Hydrated lime (source: Lhoist).

1.1 What is hydrated lime?

According to EN 459-1, hydrated lime is mainly composed of calcium dihydroxide $Ca(OH)_2$. It is obtained by hydrating quicklime (essentially calcium oxide CaO) using specific equipments called hydrators. Quicklime is manufactured by burning limestone of very high purity (made of calcium carbonate $CaCO_3$) at temperatures around 900°C in dedicated kilns [1]. The same cycle can be performed on dolomite made of $CaCO_3 \cdot MgCO_3$, in order to obtain dolime or dolomitic lime (CaO·MgO) and then hydrated dolime or hydrated dolomitic lime ($Ca(OH)_2 \cdot Mg(OH)_2$ or $Ca(OH)_2 \cdot MgO \cdot Mg(OH)_2$) if it is only partially hydrated.

Hydrated lime and quicklime, including dolimes, for construction and civil engineering applications are specified within the European standard EN 459-1 [2]. The principal qualities of the various grades of hydrated products are summarized in Table 1. The grades for hydrated calcium lime are labelled:

$$\textbf{CL XX S}$$

where **CL** stands for calcium lime and the number **XX** identifies the purity in terms of mass content of CaO + MgO. The letter **S**, standing for "slaked", identifies hydrated products in powder form, whilst D stands for dolomitic lime. This allows for differentiating with quicklimes (Q) and hydrated lime in the form of putties (S PL). Hydrated lime purity can be assessed by EN 459-2 [3]. The method consists basically in an acid-base titration. Hydrated lime generally comes in the form of a dry white powder with an absolute density close to 2.2 Mg/m^3. Because of a high level of particle porosity (of order 50%), however its apparent density typically ranges from 0.35 to 0.8 Mg/m^3 as measured by EN 459-2.

[1]   Chemistry and Technology of Lime and Limestone, 2nd ed., Boynton, R. S., New York (New York, USA): Wiley-Interscience, 1980.

[2]   European Committee for Standardization, EN 459-1: Building Lime. Part. 1: Definitions, Specifications and Conformity Criteria.

[3]   European Committee for Standardization, EN 459-2: Building Lime. Part. 2: Test Methods.

$$CaCO_3 \qquad CaCO_3 \cdot MgCO_3 \qquad Ca(OH)_2 \cdot Mg(OH)_2$$

Table 1. The various grades of hydrated lime according to EN 459-1:2010. ❶ Available lime content is inferred from the difference of the Total CaO + MgO weight % based on the minimum MgO content for DL limes in Table 9 of EN 459-1:2010.

Grade	Particle size [% residue by mass]		CaO + MgO [wt %]	Available lime [wt %]
	0.09 mm	0.2 mm		
CL 90 S			≥ 90	≥ 80
CL 80 S			≥ 80	≥ 65
CL 70 S			≥ 70	≥ 55
DL 90-30	≤ 7	≤ 2	≥ 90	≥ 60 ❶
DL 90-5			≥ 90	≥ 85 ❶
DL 85-30			≥ 85	≥ 55 ❶
DL 80-5			≥ 80	≥ 75 ❶

2. Benefits of use in fresh mortar

The term "fresh mortar" refers to the initial "wet" state when water is added to the mixture of cement, lime and sand. This is a transient stage of the use of the mortar, however the properties of "fresh" mortar are as important as their "hardened" state properties, not least as at this stage the ease of use and "workability" are important to the mason (brick/block layers) in order to achieve the daily rate of construction.

Modern construction practice throughout Europe has seen the move from "site mixed" mortar, where the sand, cement and lime are all added, along with the water on site, as and when the mason requires it, to pre-mixed or batched mortars which are "factory made" and delivered ready to use to site. These **factory made mortars** tend to come in 2 types:

- **Retarded ready to use**, mortars delivered in containers (normally 0.25 - 0.5m^3) in a wet state and ready to use, with no mixing required on site. The mortars contain "retarding admixtures" which delay the setting process of the mortar until it is laid on the brick/block work, and has a "open working life" of typically between 48 and 72 hrs, depending upon the specification.

- **Silo or dry mixed mortars**, are pre-mixed delivered to site which have all the active components pre mixed in a dry state (sand, cement, lime and admixtures) and then delivered to site, normally in a silo or bags. On site the silo is connected to a power and water supply. When mortar is needed, the silo discharges the dry mortar mix into a screw feed, where it is mixed with the correct amount of water and discharged into containers for distribution across the construction site. When delivered in bags, the mason will homogenise the mortar in a mixing device adding the prescribed amount of water.

Most batching plants, producing mortars, have the ability to add hydrated lime to the mix, if requested, and depending upon the mortar specification, lime additions can reduce the amount of chemical admixtures required to provide the workability and air entrainment properties.

For the mason, there are a number of advantages gained by using hydrated lime additions in the **mortar mix**, which generically are referred to as "workability". These include properties such as:

- easy to mix
- easy to use
- water retention
- air content
- cost

As previously described, the tendency is that mortars are delivered to the building site pre-mixed or ready to use, where the performance is the responsibility of the supplier. Site mixing is more labour intensive, typically undertaken by the most junior and least experienced of the site workforce, and thus requires the appropriate supervision. The use of lime will make the mortar mix more robust and less prone to quality variations. Throughout Europe site mixing is preferred for small projects and for renovation work. The majority of commercial developments use either "ready to use" or silo mix mortars.

The functionalities dealt with in the articles are the functionalities in relation to the interest "easy to use". In relation to the other interests no articles have been available.

2.1 Workability

Workability is a descriptive term used to describe the way a mortar feel on the trowel and thus encompasses a number of properties related to the mixing and application of the mortar to the masonry units, bricks, blocks and stone, and the ease of application, and thus the rate of construction. Mortars containing only sand and cement can be difficult to work with, and to the mason, feel either too stiff or too wet. In order to get a better workability, additives that provide "plasticity" to the mortar are often added, however admixtures could have a negative impact upon durability. Traditionally this was by adding hydrated lime, though now chemical admixtures, called "plasticizers", are widely used with or without hydrated lime. However, badly controlled use of these admixtures can have a negative impact upon mortar durability and adhesion.

Workability is the sum of the application properties of a mortar which give its suitability. The special physical and chemical properties of hydrated lime make it a very good plasticizer for mortar. Lime used as a mortar plasticizer requires the following four significant features [4]:

• it is made up of very small hydrated lime crystals,
• the hydrated lime crystals should have the correct shape (plate-like),
• there should be a sufficient film of liquid surrounding the hydrated lime crystal,
• the lubricating liquid should have a low surface tension.

For the mason the workability is the most important functionality of a mortar. Many articles demonstrate that the use of lime putty (mixed calcined lime with water) in mortars leads to a good workability of the mortar [5]. The same is the case if the mixing time is extended (15-20 minutes) when using dry hydrated lime in the mortar. As the definition states, the workability is the sum of application properties. Different test methods have been used to determine the workability with different results.

In the European masonry mortar standard EN 459-2, only one method is specified for testing the workability of mortars (flow table method). A good workability of mortars is normally established by using pre-wetted hydrated lime (lime putty or long mixing time for dry hydrated lime) and/or admixtures. For the optimum properties it has been reported that an extended mixing time is needed before dry hydrated lime is fully wetted and establishes a good workability [6].

It should also be noted that the sand grading (particle size and shape) and the total amount of sand also plays an important role, as well as the type of binders (cement) with a high specific surface area. With well graduated sand the amount of voids among the sand grains is smaller compared to sand where a great part of the grains have equal size. Where sands are poorly graded, the resulting mortar "feels" gritty to the mason and can result in being over watered before being laid.

[4] Lime, an irreplaceable mortar constituent. Tsimas, S., Raikos, K. ZKG International Vol (6), 1995.

[5] Microscope and lime. Walker, D., Proceedings of the 4th International Conference on Cement Microscopy, 1982.

[6] Investigation of the rheology and microstructure of hydrated lime and sand for mortars. Abell, A., Nichols, M. Masonry; Opportunities for the 21st Century, 2003.
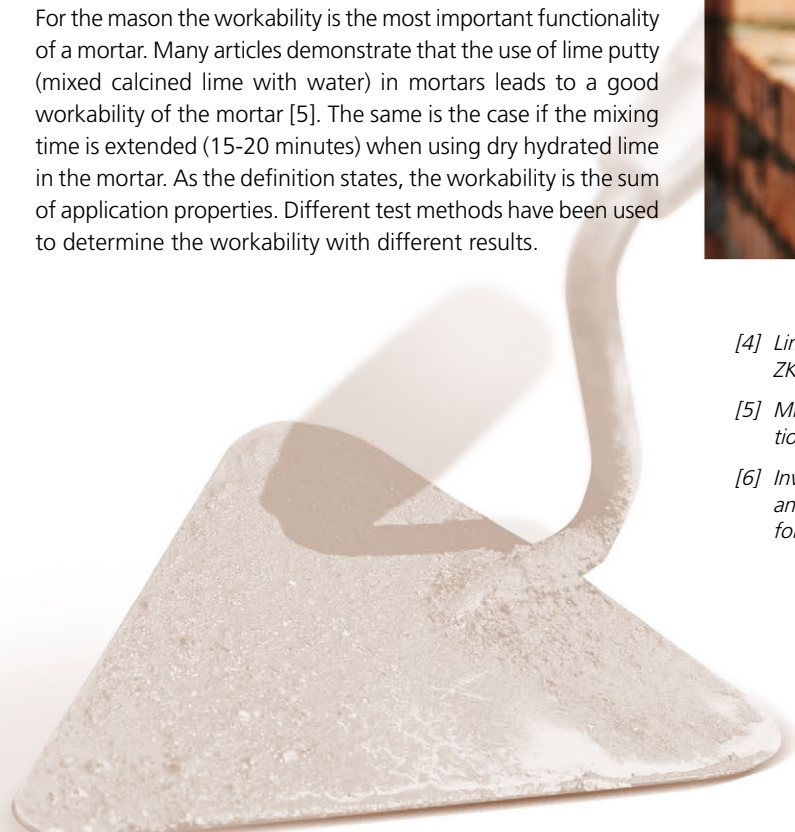
2.2 Water retention

Water plays a vital role in the development of both the "fresh state" mortar and the hardened mortar properties. In the "fresh state" water acts as a lubricant, allowing the mixing and laying characteristics to be developed to provide a good workable mortar for the mason to use.

The possible loss of water, either through evaporation, through the hydration reaction with the cement binder phases, or through bleeding, can result in a reduction in the "workability" of the mortar shortly after the mixing process. Water retention within the mortar is therefore vital, if the mortar is to retain the properties of good workability for extended periods whilst on the mason's mortar board, and when initially laid.

In addition, and when laying bricks, blocks or stone with high suction rates, it is possible that the water in the mortar mix can be rapidly drawn out on the mortar and into the masonry units. This results in premature drying out and stiffening of the mortar reducing the potential for adjusting the units or for "tooling" the mortar joints. Early loss of water from the mortar can also result in a "false set", which is when there is a stiffening before optimum hydration of the mortar has taken place. This often results in poor strength development and can ultimately result in weaker mortars with poor durability and resistance to rain penetration in service.

Work has shown that hydrated lime provides a more robust mortar with good water retention properties, and thus mitigates some of the issues resulting from the early loss of water from the mortar after laying [7]. The work concludes that it is the high surface area of the hydrated lime that aids the retention of the water, and a relationship between surface area and water retention properties was established. Similar conclusions are drawn from work which shows that hydrated lime particles are typically 1:500th of the size of cement particles. Lime particles of this size have the ability to coat the sand grains, allowing enhanced workability and water retention properties to be fully developed [8]. Work undertaken on mortar for general masonry applications has shown that building with cement – lime mortars mixed 1:2:9 (cement:lime:sand)

CEMENT　　LIME　　　　　　　　SAND

1:2:9

provides adequate wall strength for nearly all uses of masonry construction [9]. Moreover, results of the work show that the high lime content in the mortar contributes to other important characteristics such as improved workability and water retention leading to the development of a good bond between the masonry units and mortar and thereby the establishment of watertight joints. The work concludes that the cement in the mortar is mainly used to provide high early strength so that the construction work can proceed rapidly.

[7] Assessing workability of mortar by means of rheological parameters and desorptivity. Hendrickx, R., Van Balen, K., Van Gemert. Proceedings of the 14th International Brick & Block masonry Conference, 2008.

[8] Lime's role in mortar. Speweik, J. Masonry Construction (35278), 1996.

[9] Strength considerations in mortar and masonry. Boynton, S.R., Gutschick, K.A. Masonry Mortar Technical Notes (2), 1984.

2.3 Air content

The air content of a mortar is a property developed during the mixing stage when the mortar is fresh, and thus is related to the mortars workability. However, the main benefit of the retained air content in a hardened mortar, relates to the enhanced protection from frost damage the voids provide.

The air content allows the release of the confining pressure that develops as moisture converts to ice and expands. These entrapped air voids act as mini pressure release valves, thus imparting some additional frost resistance, above and beyond that offered by the strength of the mortar itself.

Investigations of the effect of air content on the **durability of cement-lime mortars** have been undertaken [10]. The objective was to obtain data that might indicate the air content levels that are beneficial in cement-lime mortars by reference to physical properties such as shrinkage of mortar bars, dry density, absorption, compressive strength, and resistance to freeze-thaw cycling of mortar cubes. The works main conclusions are that increasing air content has a minor effect on shrinkage and absorption properties, reduces water requirements and compressive strength, and improves freeze-thaw resistance.

Although a reduction in compressive strength may be viewed as a negative result of hydrated lime addition to a mortar, the resulting performance does provide some accommodation from minor movement of the masonry, thus reducing the associated cracking, as typically seen with high strength (cement rich) mortars which although strong are more "brittle".

It is also reported that too much air entrainment can lead to significant loss in flexural strength [11]. Mortar with over 20% air entrainment significantly reduces the flexural strength of the masonry, up to 50% reduction from 10% air entrainment. When mortars are cement rich, the impact appears to be greater and the loss in strength more profound. Hydrated lime additions therefore can be used to moderate the flexural strength losses and maintain a "protective" level of air entrainment for **frost resistance** in mortars.

[10] Effects of air content on durability of cement-lime mortars. Davidson, J. Durability of building materials (1), 1982.

[11] Luftindholdets indflydelse pa vedhaeftningsstryrken. Kjaer, E. Danish Technological Institute (Internal Report) 1991.

20% air entrainment in the masonry mortar reduces the flexural strength of the masonry up to 50% compared to a mortar with 10% air entrainment.

3. Benefits of use
in relation to hardened mortar

Mortar by nature of its desired function acts as the binder that holds masonry units together to form a functional structural (load bearing) or non-structural (none load bearing) masonry. Such masonry provides a number of functions, from acting as the load bearing component of a building, through to providing weather-tightness and resistance to wind loadings, moisture ingress through wind driven rain and insulation of the building, both from the cold or heat.

The mortar therefore has to be able to accommodate a number of different functions simultaneously. Though limited, the academic work that has been undertaken (and referenced in this report) regarding the benefits of hydrated lime and its use in cement mortars on this aspect, is on the whole.

There is significantly more "in-service" anecdotal evidence that the performance characteristics of mortars containing hydrated lime are enhanced, than for cement only mortars, hence to common use of such lime-cement mortars in construction throughout Europe today.

The performance of mortars in the **hardened state** can be divided into 2 main functional areas, mechanical behaviour and durability.

The performance of mortars in the hardened state can be divided into 2 main functional areas, **mechanical behaviour** and **durability.**

3.1 Mechanical behaviour of hydrated lime – cement mortars

The structural performance of masonry structures in Europe is governed by the European Standards guidance document **Eurocode 6 (EC6)** [12] which relates to the design of masonry structures. Within the context of EC6 there are a number of material properties that are taken into account when designing structural masonry, including the properties of the mortar.

The mechanical or structural properties of mortars are measured in relation to the compressive strength and the flexural strength of the masonry, therefore combining both the properties of the masonry units (bricks/blocks/stone) and the mortar.

Whilst compressive strength can assess the strength of either the masonry (masonry units and mortar) or the mortar on its own, flexural strength is always measured on the masonry, rather than on mortar alone. One of the main factors influencing the flexural strength of masonry, in addition to the "laying/coursing pattern" (bonding pattern) is the actual bond formed between the mortar and the masonry unit, which in turn is influenced by the fresh mortar properties, including water retention, and the suction rate of the masonry units themselves.

In terms of compressive strength, the addition of hydrated lime to cement based mortars shows that lime-rich mortars are able to withstand a higher degree of deformation before failure [13]. The observations made, indicate that the lime additions allow for some accommodation of movement either under compressive loads or shear loading, and unlike the brittle failure of cement rich mortars, those with high lime content (where volume of lime is twice that of cement, e.g. 1:2:9 mortar) some elastic-plastic deformation is observed prior to brittle failure with increased lime content [14].

Work investigating the links between masonry unit and mortar characteristics and the overall performance of the masonry itself has shown that rather than strong high cement content mortars resulting in strong masonry, the converse was found [15]. The results indicate that high cement content can result in high shrinkage of the mortar and poor development of bond strength, particularly when high suction bricks are used. The results indicate therefore that good water retention properties are as important, if not of greater importance as the absolute compressive strength of the mortar, as previously described.

It should also be stressed that if there is little or no suction from the masonry unit on the fresh mortar at the time of laying, this can also lead to low strength mortars and weak bonding. The suction process draws cement and lime from the mortar into the surface of the masonry unit. This allows the formation of a physical bond at the interface of the 2 materials. When there is little or no suction, the excess water in the mortar is only lost by evaporation, after the hydration of the cement phases has taken place. This excess retained water results in increased capillary pore structure and micro-cracks, thus weakening the mortar, as well as inhibiting the formation of bonds between the masonry units and the mortar bed itself. Excess retained water also increases the risk of lime bleeding [16] that results in aesthetic issues with the brick or blockwork.

The conclusions drawn for the literature indicate that high-lime mortars have excellent adhesion and bonding properties due to their high degree of workability, stickiness and water retention. Lime-based mortars are able to create continuous bonds with the bricks and completely fill the spaces in brick surfaces. Optical inspections reveal that the adhesion between lime and brick is not always due to purely physical phenomena but also chemical reactions. Most important, the use of high strength cement mortars does not improve the masonry strength because of lack of bond strength and shrinkage of mortars when high absorption bricks are used.

It should also be noted that in addition to bond strength, compressive strength of mortar is important in respect of the structural performance of masonry under normal and extreme circumstances, such as in an earthquake. Guidance is provided regarding the required minimum strength of mortar, (e.g. 5 N/mm^2) in **Eurocode 8 (EC8)** [17] and the national annexes.

[12] EN 1996-1-1: Eurocode 6. Design of masonry structures.

[13] Pore structure and mechanical properties of cement-lime mortars. Arandigoyen, M., Alvarez, J. Cement and Concrete Research (37), 2007.

[14] Blended cement-lime mortars for conservation purposes – Microstructural and strength development. Cizer, O., Van Balen, K., Van Gemert, D. Structural Analysis of Historic Construction, 2008.

[15] Mechanical behaviour of brick masonries derived from unit and mortar characteristics. Binda, L., Fontana, A., Frigerio, G. Proceedings of the 8th International Brick/Block Masonry Conference, 1988.

[16] Bojnings- og trystryrke af mortelprismer fra forma og teglesten. Christiansen, P.D. Danish Technological Institute (internal Report), 2001.

[17] EN 1998-1: Eurocode 8. Design of structures for earthquake resistance.

3.2 Durability of hydrated lime – cement mortars

Within the context of this guide, 4 aspects of durability relating to hardened mortar and the inherent performance of **masonry built with lime-cement mortars** are reviewed:

- Thermal & moisture movement in masonry.
- Resistance to rain penetration.
- Resistance to salt crystallization and chemical attack.
- Frost resistance.

In the UK the Building Research Establishment's "Building Mortar" digest 36218 recommends the use of a "**High Durability Mortar**" in the following conditions:

The principal areas where extra precautions are needed, irrespective of the composition of the masonry units, are below or near external ground level, freestanding boundary walls, earth-retaining walls, parapets and chimneys. An air-entrained **1:1½:4½ cement:lime:sand (C:L:S) mortar is recommended.**

Clearly in the late 1980's and early 1990's the BRE regarded the addition of hydrated lime to a cement:sand mortar as being important to achieve enhanced durability characteristics. Such a position was based on work undertaken when 84 different mortar mixes were subjected to simulated freeze-thaw and wetting/drying cycles to simulate severe exposure in the UK [19].

They conclude that much of the actual in service durability characteristics are dictated by the composition of the mortar and the initial reaction of the placement of mortar onto the masonry unit. Key to the durability aspects of the mortar (frost resistance and resistance to sulfate attack) are the closed and connected pore structure developed as a result of air entrainment (closed and regular sized) and the irregular shaped and sized pore structure resulting from an excess of water in the mix. They also found that the initial rate of suction from the masonry unit has an important role to play in the eventual pore structure of the mortar.

[18] Building Mortar. Digest 362, Building Research Establishment, 1991.

[19] Laboratory scale tests on building mortars for durability and related properties." Harrison, Gaze Masonry International Vol 3 No 1, 1989.

3.2.1 Thermal & moisture movement in masonry

It is widely acknowledged that, in service, movement of masonry can occur as a result of the dimensional stability of the masonry units themselves, or by reversible or irreversible thermal and moisture expansion/shrinkage. Irreversible moisture expansion is of particular relevance to clay masonry of specific types, where the glassy ceramic matrix is known to react with moisture resulting in an expansion of the masonry units. As this is a volumetric expansion, the impact can be seen both vertically and horizontally in the masonry itself.

Accommodation of movement is therefore of importance when considering the potential impact such movement may have upon the mortar as well as the masonry units.

When assessing the deformation stress-strain curve of the mortar, the **Young's Modulus** for compressive strength of cement:lime:sand mortars with varying compositions show similar characteristics, except for those with very high lime content. Work by Arandigoyen [13] reported that:

"*Only the two richest-in-lime mortars do not fit in with this straight line owing to the presence of a noticeable plastic zone before breakage. These plastic zones are characterized by a smaller slope: in these areas, if the load disappeared the material would not recover its initial characteristics, but would suffer a permanent deformation.*

From the results, it can be established that the higher the amount of cement, the lower the plastic zone. In addition, in mortars with over 50% cement, the plastic zone is actually lost, and the mortars go through the elastic zone up until breakage of the material. This plastic zone is not observed during the flexural strength tests, in which all mortars just break after the elastic zone."
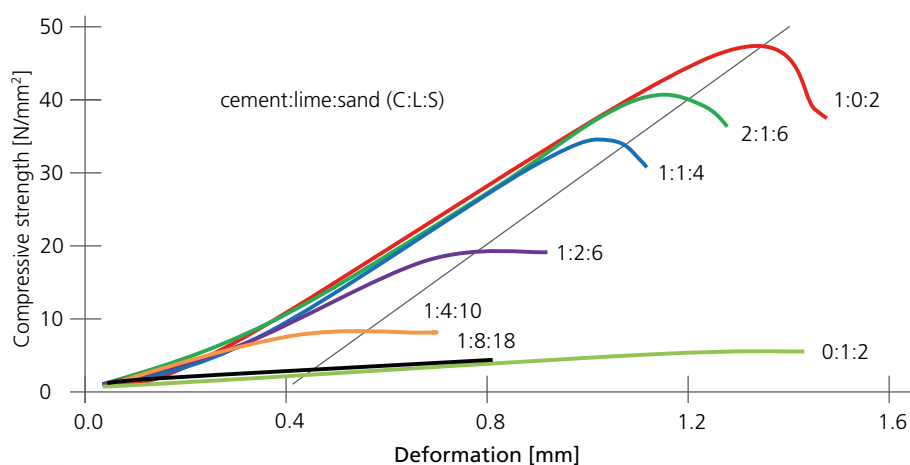
Figure 2. Correlation between compressive strength and deformation (reproduced from Arandigoyen [13]).

These results indicate that the presence of a high lime content in the binder contributes to the ability of the mortar to accommodate plastic deformation as well as elastic deformation before failure. Conversely the higher the cement content the more prone the mortar is to elastic deformation being followed by failure. Work by Van Balen [20] has put into perspective the use of the Youngs modulus and has proposed alternative failure models known as "pore collapse" which explain the difference with a complete plastic material. The main function put forward is that the mortar rich in lime will collapse before the brick will collapse under deformation and tensile stresses.

Work on the thermal expansion characteristics of cement pastes and mortars [21] conclude that by increasing the porosity, the **Thermal Expansion Coefficient (TEC)** is reduced, meaning that the more air voids in a mortar the less it expands as a result of thermal inputs. As lime additions are known to increase the porosity of mortars by the introduction of air voids, lime mortars are therefore likely to expand less than mortars without the same amount of voids (pores), as would air entrainment.

Work on mortars containing high levels of hydrated lime, namely a 1:1:6, a 1:2:9 and a 1:3:12 (cement:lime:sand) all show better accommodation of movement [22], and conclude:

"*Results indicate that lime directly and favourably affects movement in mortars, and deformation without cracking, namely creep, appears to be an important element to consider in selecting mortar mixes.*"

The ability of cement mortars containing lime to accommodate initially elastically, and then through creep, clearly has benefits, not least when considering the reaction to expansive masonry units, either thermally induced or as a result of irreversible moisture expansion.

Elastic strain and recovery plays an important role in protection from damage resulting from thermal expansion and contraction of masonry, thus hydrated lime-cement mortars can provide protection and accommodate temporary applied stress [13].

The ability of the hydrated lime-cement mortar to also accommodate creep, is also beneficial, specifically with the irreversible moisture expansion characteristics of certain clay bricks. This allied with the autogenous healing capacity of these mortars, thus repairing any micro cracks generated at the time of movement, results in the maintenance of the resistance to rain penetration characteristics of the mortar joints and thus the masonry in general.

[20] https://lirias.kuleuven.be/bitstream/123456789/260821/1/ Presentation+microC

[21] Effect of porosity on thermal expansion coefficient of cement pastes and mortars. Zeng, L, Fen-Chong, D., Construction and Building Materials 28, 2012.

[22] Elastic strain, creep and recovery in mortars; Additional analysis. Sickels Taves. Journal of Testing and Evaluation Vol 23, 1995.

3.2.2   Resistance to rain penetration

One of the fundamental functions and thus an important masonry characteristic, is its ability to prevent the ingress of wind driven rain into a building, or more accurately, to minimise the ingress to such a degree that the design of the external masonry envelop is able to accommodate what moisture does penetrate.

Hydrated lime additions impart certain advantageous properties that improve the resistance to rain penetration of the mortar. The **Mortar Industry Association (MIA)** in the UK promotes the use of hydrated lime additions in cement mortars for resistance to rain penetration. In Datasheet 18 [23] they state the following:

"*The inclusion of (hydrated) lime in a mortar promotes more intimate contact between the mortar and the masonry units. For example, the increase in plasticity and cohesion results in a more effective filling of the vertical joints and results in a bond which subsequently resists penetration by wind driven rain better than some non-lime mortars. Furthermore, reduced moisture contents in walls resulting from their greater impermeability increases the thermal insulation of the structure as well as reducing internal damp penetration problems.*"

They go on to state the following in respect of autogenous healing:

"*When lime based mortars crack they tend to do so in the form of a much reduced number of micro cracks. Subsequent movement of rainwater through the surface of the mortar joints dissolves the free lime, which is deposited in the micro cracks as the water evaporates. The lime subsequently reacts with the carbon dioxide in the air and is converted to calcium carbonate, a cementitious reaction. In a short period of time the cracks are healed, a process known as autogenous healing.*"
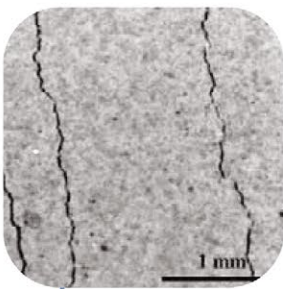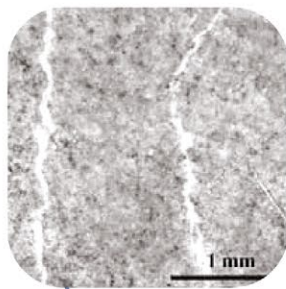

Figure 4. Micro cracks.   Autogenous healing.

Figure 3. Mortar Industry Association. Datasheet 18 [23] (source: www.mortar.org.uk/documents/miadata18.pdf).

Work focussing on the modification to the pore structure and connectivity of the pores in lime mortars with cement additions [24] conclude:

"*From MIP (Mercury Intrusion Porosimetry) results, we concluded that lime-based mortars reduced both their porous volume and their pore size as cement content in the mix increased.*"

By inference this conclusion indicates that by adding lime to cement based mortars the pores increase in size and become better connected. Connectivity of the pore structure therefore allows the movement of both vapour and liquid water, however as already identified, both cement hydration products and lime additions result in an excess of free $Ca(OH)_2$, which can be subsequently transported and deposited as a result of carbonation in this pore structure.

Work on the assessment of the resilience of masonry to wind driven rain penetration has identified that rather than the masonry units or the mortar being the dominant factor, it is the interface between the two that has the greatest influence on performance.

A review of the scientific literature [25] identified that the addition of lime to a cement mortar had a major influence on the reduction in rain penetration, as a result of the deposition of initially calcium hydroxide, which in turn carbonated to calcium carbonate, at the interface. This was attributed to the initial capillary suction of moisture from the mortar into the brick at the time of laying. Although the hydrated cement phase result in the initial strength development, the deposition of these "free lime" products improves the overall performance of the mortar joint "in service". A reduction in rain penentration (through the wall), has the added bonus of reducing the moisture ingress into both the mortar and the masonry units, thus reducing the risk of frost damage.

Work presented by the **National Lime Association** in the **USA** [26] (National Lime Association; Building Lime Group 2000) quantified the benefits in respect of "special lime" (Type S to ASTM C207) additions to cement mortars in terms of rain penetration performance. When compared with masonry cements and blended cements to the ASTM methodology, the following results were recorded:

> "***Time To First Dampness*** – *Walls constructed with cement-lime mortars took 35% to 250% longer to show signs of dampness.*
>
> ***First Visible Water*** – *It took approximately 350% to 575% longer for cement-lime mortars to show signs of visible water.*
>
> ***Percent Dampness –*** *Cement-lime walls showed 5% to 40% less area of dampness than seen with masonry cement mortars.*
>
> ***Leakage Per Panel*** – *The total amount of water leakage collected per wall panel during the test for masonry cement assemblages was 3.5 to 15.3 times the amount collected for cement-lime mortars.*"

This work clearly demonstrates the impact that lime, when added at a level of between ¼ and ½ the cement content, can have upon the "water tightness" of the masonry, specifically on the movement of water at the interface between the mortar and the masonry unit.

Work by Bowler on rain penetration through brick masonry [27, 28] shows that even when different mortar designations (mix designs) were used with both high and low suction rate bricks, it was clear that cement-lime mortars (1:1:5½ and 1:1:6) all performed reasonably well and better on the whole than cement sand mortars.

It was also clear from the results that the initial rate of suction of the masonry unit, when the same mortar was tested, made a significant difference. High suction brick masonry having a lower resistance to rain penetration, and thus the inference made here is that high suction from the masonry units can have a detrimental impact upon the resistance to rain penetration. This could be as a result of greater porosity in the mortar itself due to the capillary draw of moisture out of the mortar initially, and the resulting pore structure, or as a result of removing water from the mortar and thus reducing or limiting the "hydration" process of the mortar.

The work also shows that in addition to the movement of moisture through a masonry structure, there is evidence that the formation of a "lime" rich layer at the interface between mortar and masonry unit can significantly reduce the capillary rise of moisture from the ground.

Studies [29] have shown that in cement based mortars the addition of lime promotes deposition of $Ca(OH)_2$ (Portlandite) at the interface between the mortar and the masonry units (in this case natural stone). This layer significantly reduces the capillary rise of moisture, more so than cement (OPC) mortars and blended cement based mortars, where the migration of $Ca(OH)_2$ from mortar towards the masonry units is less.

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3.2.3 Resistance to salt crystallization and chemical attack

There are 2 potential mechanisms that are worth considering when using lime-cement mortar. Salt crystallization can be regarded as a physical process, resulting from the deposition (growth) of salts within the pore structure of the mortar, in a similar way to the formation of ice crystals during frost attack.

Chemical attack is a different process and results from the aggressive alteration of the structure or composition of the mortar. Sulfate attack is probably the most common form of chemical attack and results from the progressive breakdown of the C_3A (tri-calcium aluminate) content in the cement by water soluble sulfates, resulting in the formation of an expansive calcium--sulfoaluminate-hydrate (Ettringite).

Degradation from the growth of salt crystals (e.g. NaCl) within the pore structure of the mortar ultimately results in "fretting" only when the expansive forces imparted by the salt crystal growth, exceeds the restraining (tensile) forces of the mortar matrix itself. In these situations, as in coastal environments, salt spray can penetrate the masonry, resulting in concentrations of sodium chloride to build up. Studies into the impact of salt crystallization using a 4:1:20 (1:¼:5) mortar exposed to different NaCl levels [30] concluded:

"In the lime–cement mortar NaCl produces dilation during the drying phase of the RH cycle, when the salt crystallizes. The dilation observed in the NaCl contaminated specimens is irreversible and increases with repeated RH cycles until damage occurs. Damage appears as sanding of the outer layer of the specimen where most of the salt has accumulated."

Unfortunately, only one mortar mix was used in this study, therefore not allowing the potential impact on lime content to be evaluated.

Normally it would be expected that the greater the tensile strength, typically as a result of higher cement content mortars, the more resistant the mortar will be to salt crystallization processes. Weaker, cement lean, mortars have lower tensile strengths, and therefore have correspondingly lower resistance to salt crystallization processes. However, this assumes that the

porosity, pore connectivity and pore size distribution are similar. We know that this is not the case. In general the presence of excess $Ca(OH)_2$ in the pore fluids released during the hydration process of mortars, typically the first 28 days, and the change in porosity by 1 year, indicates the deposition and conversion of $Ca(OH)_2$ (liquid) to calcium hydroxide (solid) and calcite (carbonated lime). As this takes place within the pore structure of the mortar, this can reduce the overall porosity, compared to a "lime free" cement based mortar only.

The second form of soluble salt related durability issue with mortars is that of chemical attack. Although many of the chemical attack mechanisms result in the formation of an expansive reaction substance, e.g. ettringite in sulfate attack, the initiation of the process results from a chemical reaction between the soluble component and the mortars binder phases.

In addition to ettringite formation as a result of sulfate attack, thaumasite has also been identified and the potential cause investigated [31]. This work showed that a mortar containing calcium carbonate ($CaCO_3$) either as fine aggregate or as a product of carbonation of $Ca(OH)_2$ can react with magnesium or potassium sulfate solutions, resulting in the formation of thaumasite, and brucite as a result of the breakdown of the calcium-silicate-hydrate as the pH drops below pH10.

Thaumasite is known to develop predominantly in cold wet conditions < 5°C, however the work has confirmed the thought that sulfate attack resulting in ettringite formation typically is a precursor to the thaumasite formation, and that a calcium carbonate phase is required in the mortar before thaumasite will develop.

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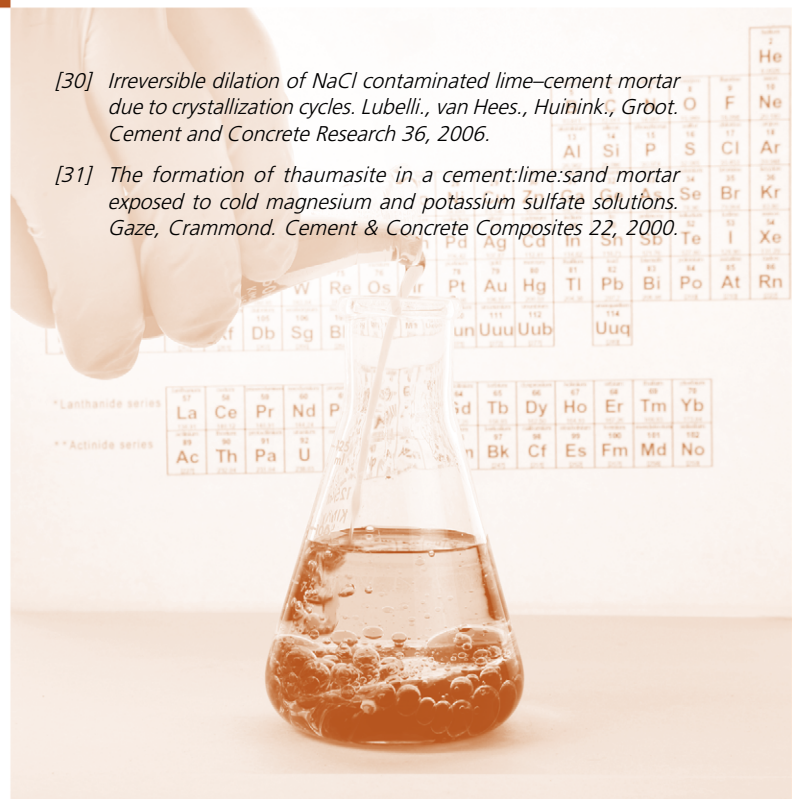
3.2.4 Frost resistance

As with many of the attributes linked with hydrated lime additions to mortars, there is very limited number of studies that have investigated the modification of the mortar's property, and how this benefits frost resistance. Much of the inferred benefits come from some basic attributes, already discussed in this guide, namely:
- pore size,
- pore connectivity,
- reduced rain/water penetration,
- autogenous healing.

The frost resistance of masonry tends to focus on the masonry units performance rather than the performance of the mortar, hence the development of specific frost resistance performance tests for the likes of clay bricks in EN 771-1, although a **harmonized frost resistance test** (TS EN 772-22) is still under development.

No such performance test has been developed for mortar, and freeze-thaw resistance is dealt with within EN 998-2 2010, and clause 5.4.7 still states:

> *"Until a European Standard method of test is available, the freeze/thaw resistance shall be evaluated and declared to the provisions valid in the intended place of use of the mortar."*

Research specifically looking into the properties of the mortar [32], rather than the masonry, generally conclude that lime additions to cement based mortars improve resistance to freeze-thaw action. The work concludes that lime additions

to cement mortars (1:1:6) provided both enhanced resistance to frost damage but also to the combined frost and sulfate attack, especially when the C_3A (tri-calcium aluminate) content of the OPC is < 9%.

In addition the MIA states:

> *"The reduced water penetration achieved with lime-based mortars can minimise the risk of freeze thaw damage."*

Bowler research [24] looked at both early "green stage" fresh mortars and hardened mortars in respect of the role air entrainment has upon this aspect of durability. He states:

> *"...the action of early suction, like the coarse pores imparted by air entraining agents, protects the hardened mortar from damaging frost action."*

Whilst there appears to be a significant amount of anecdotal evidence that lime additions to mortars are beneficial to frost resistance, there is little direct scientific evidence, not least as there is no standard test method developed to assess frost resistance.

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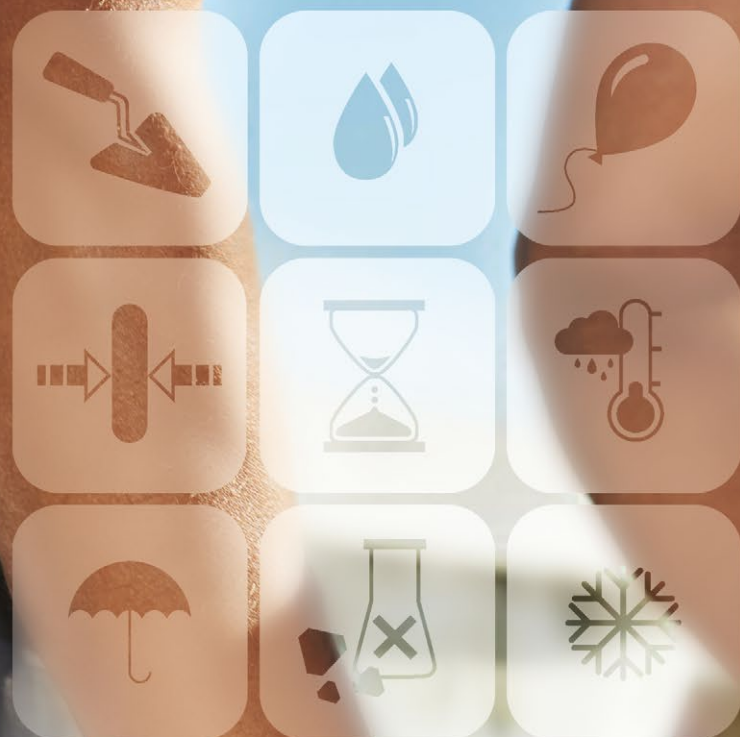
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