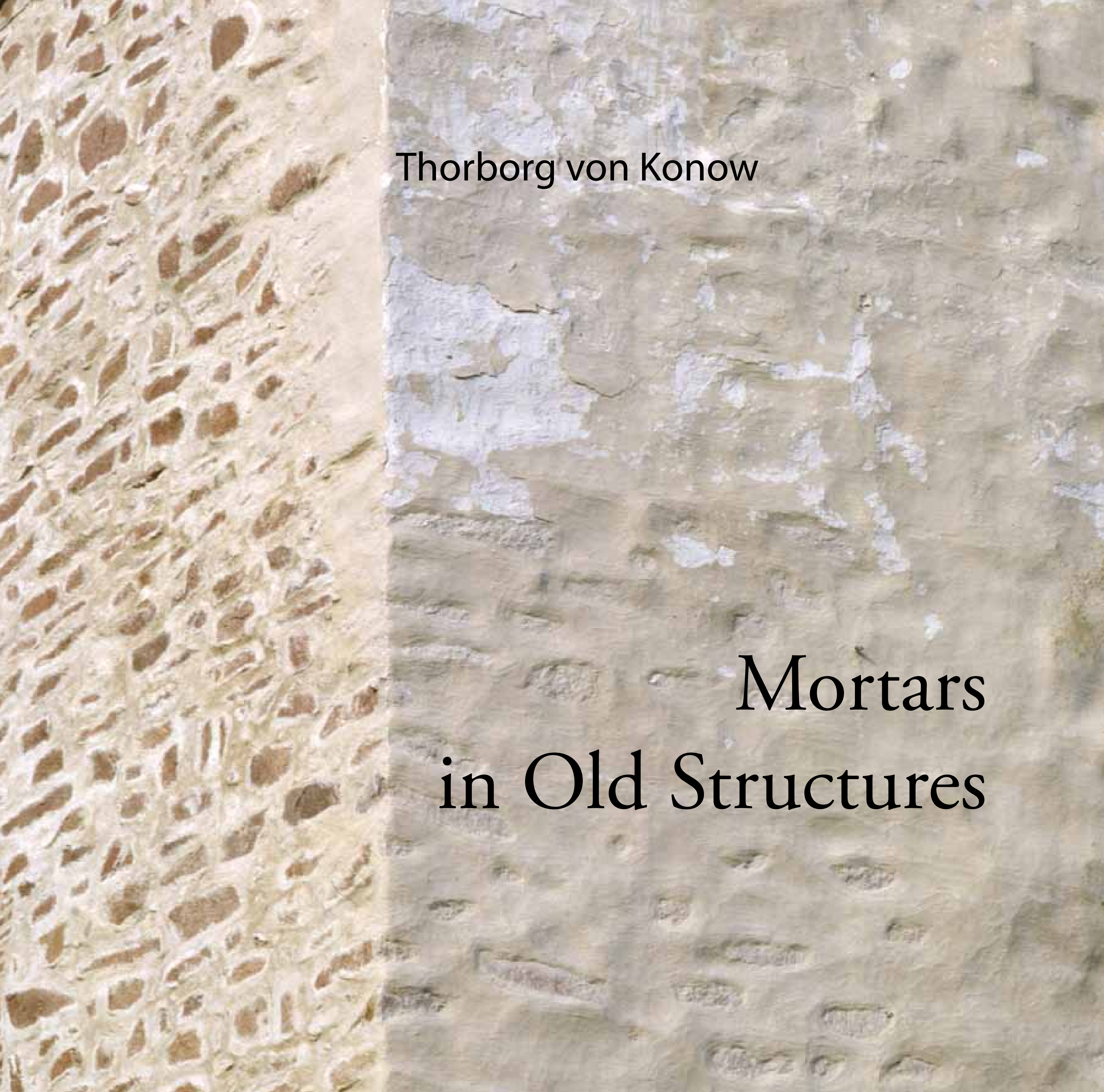
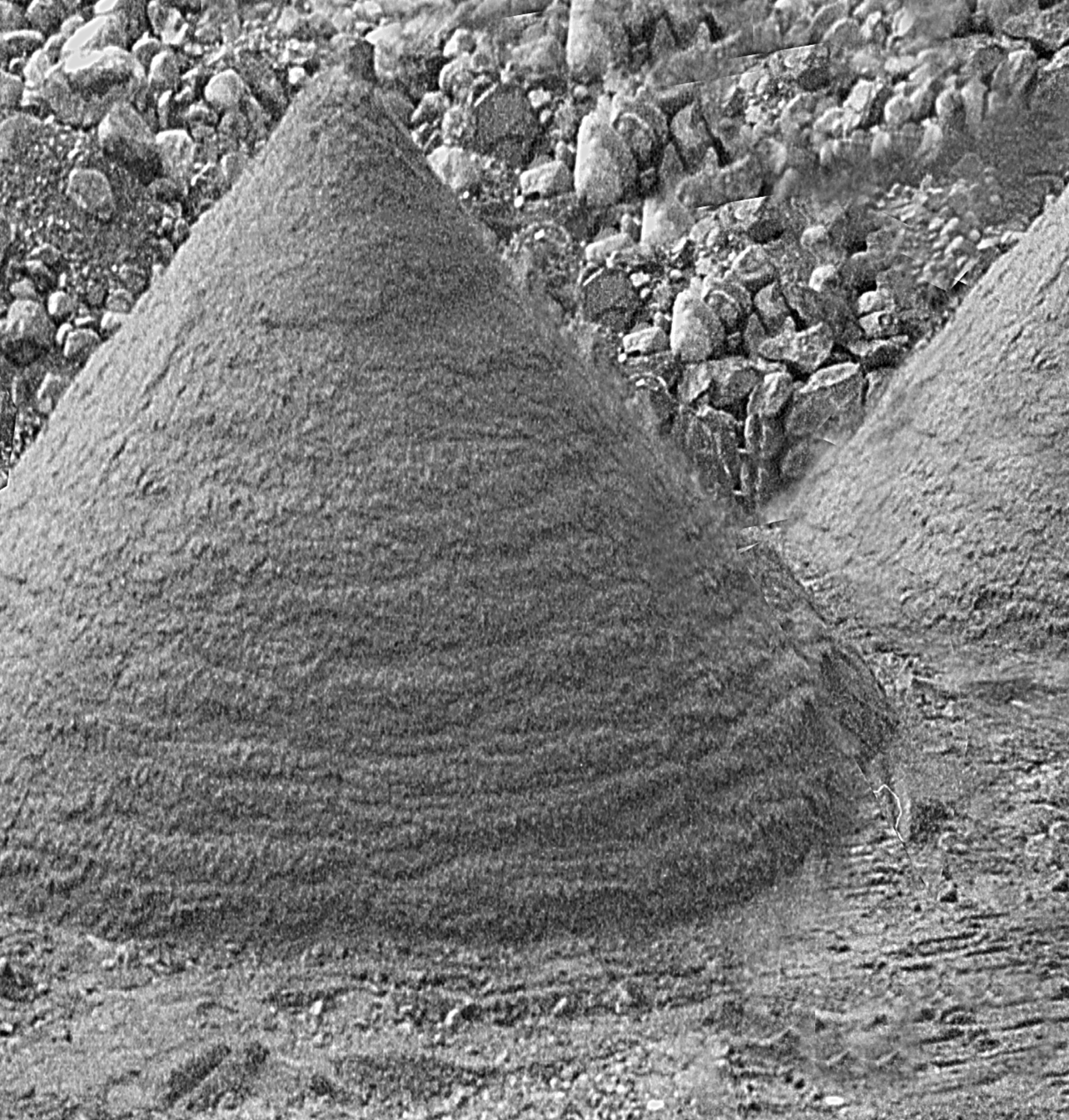


Thorborg von Konow

Mortars in Old Structures



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Thorborg von Konow

Mortars in Old Structures

SUOMENLINNAN HOITOKUNTA
THE GOVERNING BODY OF SUOMENLINNA

Contents

To Leonardo

The English version is dedicated to the memory of our friend and colleague Thorborg, and to her life´s work.

Preface

The primary objective of repair and construction work that is respectful of traditional methods is to use original materials in the restoration of a building. One of the most challenging of these is mortar. Lime mortar is a natural material the quality of which varies locally, as do traditional methods of preparing it. A further factor in the final result is the weather at the work site.

At present, work site expertise is becoming increasingly divided. The skills that a single master workman once brought to the task should now be possessed by block managers, consulting firms, contractors and subcontractors, material salespersons, and the building material industry.

It is becoming ever more difficult to be in overall control of the big picture when it comes to the problems of restoration work. Nonetheless, if by scientific means we can unearth the secrets of the old masters, the possibilities of success increase enormously.

The right mortar in the right place. The current trend is for old materials to be studied and working methods documented. In this book the history of building, practical experiences and scientific research are skilfully woven together by researcher Thorborg von Konow. Her expertise in the history, study and testing of mortars used at different times in the history of Suomenlinna, and her participation in international projects and numerous publications have all contributed to the successful restoration of Suomenlinna for over a decade.

Heikki Lahdenmäki

Architect SAFA

Restoration Director

The Governing Body of Suomenlinna

To the reader

What happens to a lime mortar when it is mixed in its tub, spread as plaster on a wall or used as masonry on a brick? What happens to it when it dries, hardens, and gets wet? And how do binders and aggregates influence its properties?

There was a time when the master mason knew the answers to these questions from the experience and professional skills developed over a lifetime. Theoretical explanations about the functions of mortars never crossed his mind. He seldom if ever wrote down his mortar recipes, because he was not a penman and his professional tricks were a trade secret. Yet the results of his work are still with us — damaged over time through inadequate maintenance and the severity of climate.

In trying to answer the question of how one could develop correctly functioning restoration mortars for repairing old buildings, I have delved into the innermost world of lime mortar and its chemical and physical events. Following intense conversations with masons and plasterers about mixing methods and the working properties of lime mortars, I have come away amazed by how different mortars look in practice compared to the theoretical reviews of scientists.

I have combined the theoretical processes of mortar and the visible events of stiffening, drying and hardening. The result is a set of practical tools for researchers and planners and a handbook for plasterers and masons. This book is also intended for the managers of old buildings, to help them understand the importance of continual and regular maintenance.

The information on the composition of old mortars is primarily from microscopic examinations. The microworld of mortars is deeply fascinating, and one that I hope to share with the reader. I have used microscopic pictures both in the interpretation of the chemical processes of lime mortar and to demonstrate the highly versatile forms of old mortars.

The repair and restoration of masonries and plasters at Suomenlinna have given me the opportunity to put the results of laboratory tests into practice. Many mortar recipes and working instructions have been experimented with and put to use. Subsequently the experiences gained have been applied to other historical stone structures in Finland — castles, medieval churches and smaller valuable objects.

So as not to leave the reader empty handed, I offer a number of keys to selecting restoration mortars. However, solving the secrets remains the mandate of those responsible for the repair plan, because every object has its own building history and mortar, as well as its own problems that cannot be solved from general instructions.

I wish to say a big "thank you" to architect Erkki Mäkiö for his countless viewpoints and suggestions regarding the contents of this book. Architects Tuija Lind, Merja Nieminen, Vuokko Lehmuspuisto and Heikki Lahdenmäki have presented valuable comments and encouraged me throughout the writing phase. Conservator Tiina Sonninen has shared her own views about the conservation problems of historical mortars. Master mason Tommi Vilkanen added his practical experience of the processing properties of lime mortars and working methods. Together with the planners and masters of the Governing Body of Suomenlinna it has been highly educational in developing new restoration mortars for the masonry constructions. Only the future will show whether the new mortars are anywhere near as good as the old ones.

Malla Rautaparta helped with the linguistic form of the draft and researcher Elina Heikkilä completed the language revision of the Finnish version.

A big thanks to all in the words of the song ”Mera bruk i byttan, boys" – more mortar in the tub, boys!

Thorborg von Konow Helsinki 22.9.2006

Introduction

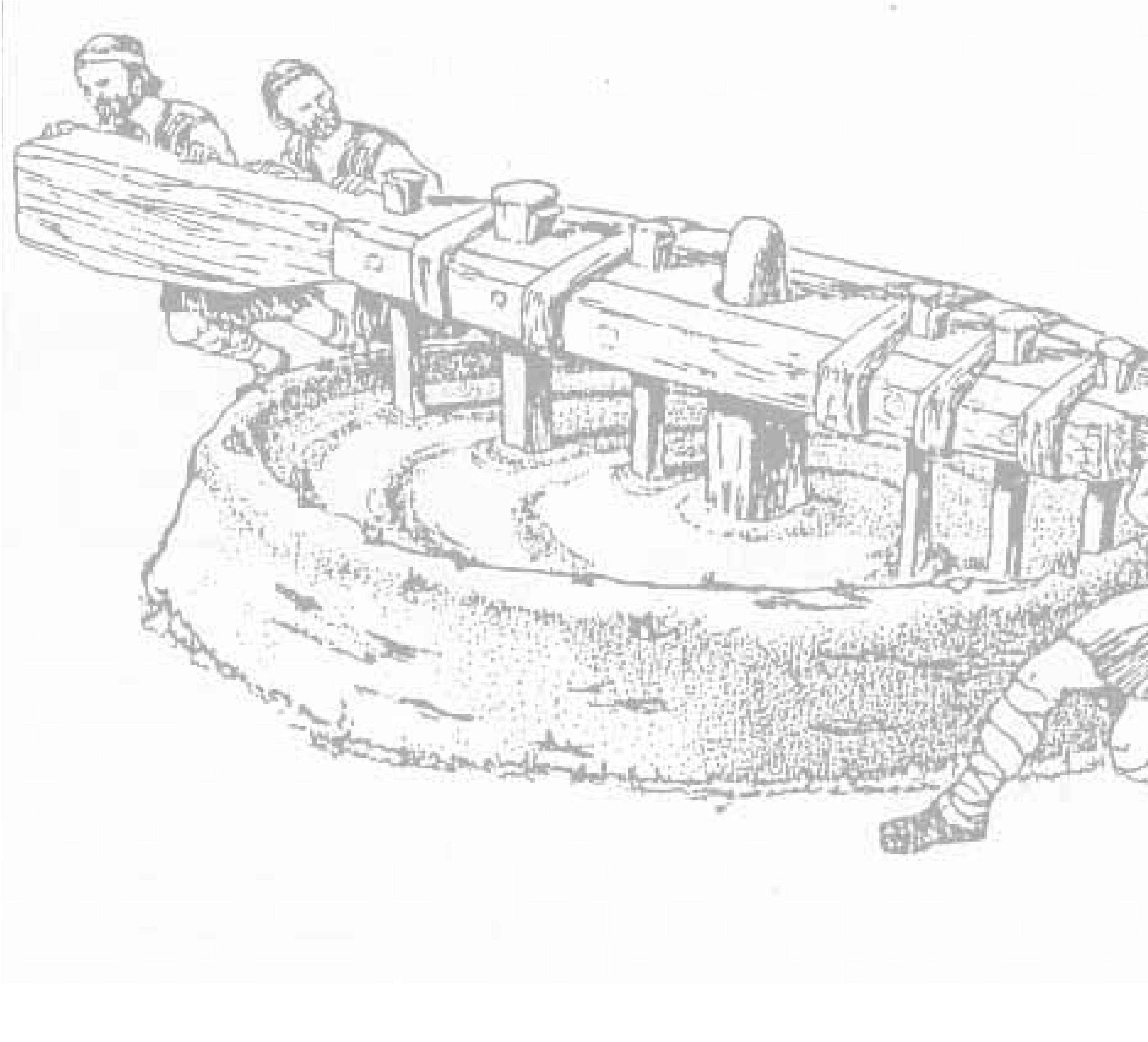
Restoration through the eyes of a material researcher

The maintenance, repair and restoration of buildings have always been a self-evident part of their history — what has been built lasts for a time, deteriorates, and needs repairing. Questions involved in restoration have been discussed actively since the 19th century. Even the concept itself has been disputed. It seems that disagreements occur in every aspect of restoration, from its philosophy to repair materials to working methods.

Writings and presentations in restoration philosophy are like poetry to a material researcher, engraved on building stones reflecting all the colours of the rainbow. The researcher can with his or her own eyes identify the telltale marks left by the wind, rain and frost in weakened mortar joints and weathered masonry stones. Algae, mould and white salt deposits on the surfaces of stones reveal major stresses caused by humidity. Weathering and degradation cannot be stopped, only slowed down.

The researcher always encounters the same problem: how to find a balance between two partly opposite ideologies: whether the authenticity of the building or part of the building to be restored should be retained or new durable repair material found, which would function alongside the material to be conserved without harming it.

However, sometimes historical and weathered mortar has to be replaced by new mortar – but by what kind?



1 Old mortars – what are they made of?

1.1 Lime binder for mortar from limestone

Mortars are used for masonry, plaster, slurring, pointing, fastening tiles, and as putty. They are prepared by mixing binder, sand and water. The most common binder in old mortars is lime, whereas in new mortars it is a combination of lime and cement.

Limestone and burning methods

Old mortars differ from new ones mainly in their binder composition. The most common binder is lime, and this is produced by burning limestone, followed by slaking. According to the literature, compact limestone has been used in the preparation of masonry mortars and rough plaster mortars, whereas porous stone has been used in fine plaster mortar and lime wash.

Limestone in Finland is mainly old and crystalline. Northeast of the Oulu–Kuopio–Savonlinna line it generally occurs as dolomite carbonatite and southwest of the line as calcite carbonatite, although there are some exceptions. In Sipoo Kalkkiranta in Eastern Uusimaa, limestone was already being mined the 17th century. Large amounts of it were used in lime mortars for Suomenlinna's masonries and buildings.

Historical documents confirm that the burning of lime was practised as far back as the 14th century during the building of Turku Cathedral. Lime was usually fired in pit kilns, or in conventional pits used for burning charcoal and dug deep into the hillside. In the 18th and 19th centuries brick firing kilns also came into use for burning lime. The last 30 years have seen an awakening of interest internationally in the old ways of firing lime, and several reports have been published on small-scale lime burning projects. In Finland small amounts of lime are fired in an old-time lime kiln in Kullaa Leineperi. In 1978 and 1985, lime was fired using an ancient method in Alajärvi Vimpeli (Helsingin Sanomat 1985). About 40 cubic metres of burned lime was obtained, requiring the consumption of 210 cubic metres of firewood. However, old ways of firing building lime have not expanded to industrial production in Finland.

Regardless of the burning method, the lime-burning event itself was generally speaking the same in all old-time kilns. Limestone was crushed prior to burning, and the kiln was fired mostly with wood. The limestone was loaded differently depending on the type of kiln, but was always loosely stacked to allow even circulation of hot air and exit of combustion gases. Nonetheless, material close to the kiln wall was frequently under-fired.

When limestone is fired, the sedimentary mineral is converted into burnt lime (calcium oxide). Pure calcite stone starts to decompose at 890°C, but the external appearance remains the same although the stone is becoming more porous as carbon dioxide separates out. In order to produce burnt lime, the temperature has to be at least 900°C and the burning time two to three days. The temperature of the kiln must be raised slowly and brought back down slowly after firing.

When lime is produced industrially, burning takes

There are several forms of sedimentary limestone:

– Pure calcite [$CaCO_3$]

– Dolomite [$CaMg(CO_3)_2$], which includes more than 5% magnesium oxide

– Impure limestone, which includes varying amounts of clay minerals.

Impure limestone belongs to the hydraulic limes, which are described in Chapter 1.2. Lime binder can and has been produced from organic limes like seashells and coral.

place in a rotary kiln in which the limestone is rotated and passed from one end of the kiln to the other. This ensures even burning of the limestone batch. In Finland, industrially burnt lime is used, for example, in the paper and metallurgy industries and in agriculture. Only a fraction of it is used as building lime.

Slaking of lime

Light, burnt limestone from which carbon dioxide has separated is a very parched stone that spontaneously binds humidity from the air to its pores. Pure calcite limes slake quickly, dolomite lime and hydraulic limes less so. Slaking is a heat-producing, or exothermic, reaction. Slaked lime swells and decomposes into fines as it slakes.

One old lime-slaking method has been to let the burnt stone slake by itself under the influence of air humidity and rain. After slaking, this kind of lime is powdery or resembles moist grits. It has been more common to pour burnt stones into a water container, whereupon the water begins to boil. Depending on the amount of water and lime the temperature of the mass to be slaked can rise by several hundred degrees.

Numerous lime-slaking methods have been described in the literature, some of which have been hotly debated since ancient times. In the 2nd century, architect Marcus Vitruvius Pollio wrote about making lime in Rome. During the Renaissance of the 1450s, architect Leon Battista Alberti also wrote about lime, followed in the 18th century by Belidor (1735) and Cronstedt (1731). However, no one can say for sure which slaking method has been the right one.

The term wet slaked lime is used when considerably more water has been used for slaking than is theoretically needed for transforming calcium oxide (CaO) to calcium hydroxide ($Ca(OH)_2$).

Pit lime is produced when slaked lime is stored for several years in a borrow pit which is usually coated with boards. Pit lime has received a lot of attention, and its good strength and fine crystallinity are praised with a degree of nostalgia. In primitive kilns, however, there were great differences in the burning grade of limestone; therefore a mixture of under-burnt, hard-burnt, and sintered stones were added to the pit. Large, hard-burnt and impure stones require substantially longer slaking times than soft-burnt ones; which was probably one reason for the long slaking time of pit lime. These prolonged periods allowed the hard-burnt limestone blocks to slake at least partially and the unslaked stone and other impurities to deposit on the bottom of the pit.

Karin Kraus (1989) has put forward several reasons why pit slaking has broken through in discussions pertaining to restoration. While studying the Latin writings of Vitruvius she noted a number of incorrect interpretations in the translations. In the original texts, Vitruvius noted that pit lime must be used in fine stuccowork – on the surface of internal plasters and lime painting. Lime used for masonry mortar and coarser plastering has not been pit slaked, but has been slaked on the building site and used about a month after slaking.

In Scotland, lime currently used in restoration mortars is slaked soon after burning and stored for at least three months. The consistency of this lime is cheese-like (Historic Scotland 1995).

If the amount of slaking water used is only a little more than the theoretical amount, the burnt lime slakes as dry powder. Lime is slaked this way industrially and the product is called building lime, or lime

Burning of lime

	900°C		
$CaCO_3$	$\rightarrow CO_2$	+	CaO
Limestone	Carbon dioxide		Burnt lime
Calcium carbonate	*Gas exits*		*Calcium oxide*

Slaking of lime

$$CaO + H_2O \rightarrow Ca(OH)_2$$

Burnt lime + Water → Slaked lime

100 kg *32 kg *)* *132 kg*

**) Theoretical amount of water*

Lime carbonation (hardening)

$$Ca(OH)_2 + CO_2 + (\text{humidity}) \rightarrow CaCO_3$$

Slaked lime + Carbon dioxide → Carbonated lime

hydrate. The amount and temperature of the slaking water influence the size of the resulting hydrate particles, but there is no clearly defined slaking method for building lime.

In ancient literature a special method is described in which lime is slaked together with sand or under a sand cover. The method has been tried in laboratory conditions in Germany and Finland VTT (Technical Research Centre of Finland), and in Sweden in a test plastering of the façade of Läckö castle in 2003–05. The Swedish name for this slaking method is 'stukasläckning'. The sand used during slaking functions as the aggregate of the mortar. The mortar can be used immediately after slaking, and is called 'hot lime mortar' in the UK. However, usually the mortar is taken into use a couple of weeks after slaking to avoid unslaked lime lumps. Microstructurally this kind of lime mortar resembles old lime mortar, which includes lime lumps and non-homogeneous, coarse binder.

Lime lumps are included in almost every old lime mortar. Because the limestone in the kiln was not all fired at the same speed, some of the stones remained as harder lumps compared to other slaked stones. Under the microscope these are distinguished by their darker fields, which can be several millimetres in diameter.

Carbonation of lime

Carbonation, i.e. hardening of lime, is a very slow process lasting for years, and deep inside the masonry the lime does not carbonate at all.

During carbonation the carbon dioxide (CO_2) in the air reacts with the lime binder, i.e. calcium hydroxide $Ca(OH)_2$ of the mortar. The reaction also needs humidity for the gas to dissolve into; therefore the relative humidity of the air should be over 60%. Lime hardened this way is called air-hardening lime. The mineralogical composition of wholly hardened i.e. carbonated lime is that of calcium carbonate ($CaCO_3$), from which the lime has been burned.

1.2 Hydraulic lime

Hydraulically acting substances

Limestone that includes clay mineral impurities is known as hydraulic limestone, because when burned and slaked it hardens (hydrates) with water. In Finland there is very little if any hydraulic limestone. However, hydraulic components or elements that react hydraulically with lime have been found in addition to air-hardening lime in lime mortar samples from many historical buildings.

During burning, clay may have been mixed into the limestone if e.g. the last stone layer in the kiln was covered with clay. (Kilns are covered to equalize the burning temperature.) Wood ash and cinder remaining at the bottom of the kiln were mixed with the lime when the kiln was emptied. Hydraulic lime and pozzolans were also ordered from abroad for demanding building works.

Hydraulically acting substances like cinder and wood ash that are more or less accidentally included in mortar are not fine-grained. Biggish granules react very slowly in mortar, reducing their reactivity with the lime.

Crushed or finely ground brick has also been added to mortar to give it hydraulicity and colour. In old Finnish mortars crushed brick is rare, but was used plentifully in some lime mortars when Finland was under Russian rule. This kind of mortar is found e.g. in the pointing and plaster mortars of the buildings of Suomenlinna.

When the function of crushed brick mortar was studied at Suomenlinna for the pointing of brick masonry of the Tenalji von Fersen building, it was found to

Air-hardening limes

Lime putties

Wet lime, wet slaked
Pit lime, wet slaked and stored in the pit for several years

Lime powder

Building lime, dry slaked (e.g. SL 90T)

have another effect also. The brick binds significant amounts of humidity, which the mortar can utilize during slow hardening. This reduces the formation of shrinkage cracks.

Burning and slaking of hydraulic lime

In his extensive studies of building materials, French engineer Louis Vicat (1786–1861) determined how lime sets under water. He called lime hardened this way hydraulic lime. Vicat tried different types of clay and observed that they developed pozzolanic properties when fired. In 1812, he was able to prepare synthetic hydraulic lime by burning a mixture of limestone (chalk) and clay.

When impure limestone is fired, the temperature has to be over 900°C but below 1200°C. The necessary temperature is a little higher than when burning pure limestone, but considerably lower than when burning cement. During firing of hydraulic lime the calcite in the stone reacts with the minerals in the clay. Part of the stone burns into calcium oxide, like air-hardening lime. Hydraulic limes are slaked by dry-slaking. When the hydraulic part is very low, they can also be wet-slaked. The result of slaking is a product including calcium hydroxide as in air-hardening lime, and calcium silicate hydrates as in cement.

1.3 Standardization of lime

There is a big variation in lime types, yet previously no product specification was needed. Old standards have long classified lime mortars in the same group: weak mortars. However, with new interest arising in hydraulic lime, its manufacturers now want clear standards for different qualities of lime products.

Air-hardening lime can be pure calcium hydroxide or it may include small amounts of hydraulic components (8% by weight max). Lime that includes more than 10% by weight and hardens under water is called hydraulic lime. The amount and quality of hydraulic components give different properties. Mildly hydraulic lime (also called water lime) includes 8-12% by weight hydraulic ingredients, whereas strongly hydraulic lime includes 18-36%. Natural cement includes 45-55% by weight hydraulic components and Portland cement about 90%.

Hydraulic natural lime (natural hydraulic lime NHL) has no ingredients other than burned hydraulic lime. Hydraulic lime (HL) has been prepared by mixing air-hardening lime with suitable hydraulic substances, the most common of which is cement. This differentiates HL from NHL.

Experience of the function of hydraulic limes as restoration mortars is still relatively limited in Finland. To date their use has been primarily in the repair of natural stone masonries at Suomenlinna.

Substances with hydraulic reactivity

Pozzolana is a volcanic ash that has been used in water-resistant mortars in antique bridges and water constructions; it was known as far back as the Minoan period in 1400–1200 BC (Malinowski 1994). Volcanic ash from Santorini was used on Crete and at Mycenae. In Germany, the corresponding ash is called *Trass.* Pozzolanas include plenty of silicate (silicon dioxide SiO_2). Only amorphous, or glassy, silicate reacts with lime. Crystalline silicon dioxide such as quartz does not react at all with lime at normal temperatures. As long as the lime binder of mortar has not been carbonated but is in the form of a hydroxide, it reacts with the amorphous silicon mineral and forms similar silicate compounds as in the hydration of hydraulic lime or cement. Also *wood ash* and *cinder* react according to the same principles. In a mortar it is very difficult to identify the minerals that have reacted with lime; they cannot be separated by chemical analysis from the clinker minerals in cement, but under thin-section microscopy they can be recognized from a reaction edge around the lime lump.

Old lime mortar with hydraulic components. A reaction border has formed around the mineral in the middle. The section shows lots of binder and only one aggregate granule. Photomicrograph x20, parallel nicol (//-nicol).

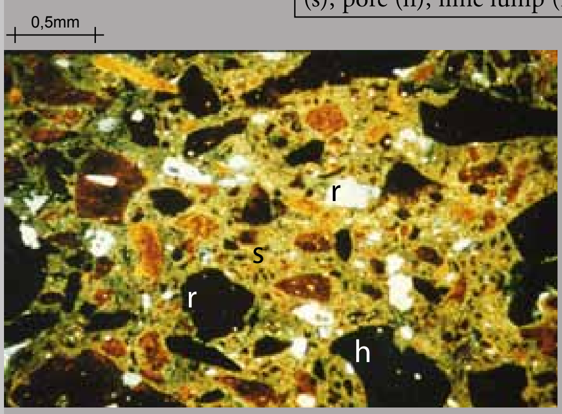
Hydraulicity of brick

When bricks are fired above 500°C but below 700°C, amorphous (glassy) silicate compounds are formed which can show hydraulic properties with lime. When fired above 700°C the reactivity with lime is lost (Krenkler 1980).

Nowadays bricks are fired at 1000–1100°C. If the firing temperature is higher still, silicate compounds begin to sinter. Sintered brick is partly glassy and its silicate oxides react similarly to pozzolanas or low-fired brick. However, the prerequisite to the reaction is that the brick is finely crushed.

In earlier times, brick firing was not as carefully controlled as it is today. Both weak and hard bricks ended up in the same firing batch. It is therefore possible that among old bricks there were some that reacted hydraulically with lime.

Abbreviations: aggregate (r), binder (s), pore (h), lime lump (Kp)



Mortar from Building C74, Suomenlinna, prepared during the period of Russian rule. The mortar includes plenty of crushed brick, coloured red and black. Photomicrograph x4, cross nicol (X-nicol).

Terminology for binder types in Finland

K lime
Kh hydraulic lime
S cement
M masonry cement

The amount of binder(s) is 100 parts by weight and the amount of aggregate is given relative to that. For example, KKh 70/30/650 is hydraulic lime mortar with 70 parts by weight of lime, 30 parts by weight of hydraulic lime, and 650 parts by weight of aggregate.

In the new EN-standards (SFS-EN 459-1 2002) all limes are coded.

CL calcium lime
DL dolomitic lime
HL lime mixture including hydraulically reactive minerals
NHL natural hydrated lime
NHL-Z natural hydrated lime with pozzolanic additives
Q burnt lime (quicklime)
S slaked lime

The designations are given numbers specifying the strength of the hardened lime. For example, NHL 2 indicates that the compressive strength of the lime at 28 days is 2–7 MPa; NHL 5 indicates a compressive strength of 5–15 MPa; in between is the designation NHL 3.5.
Air lime also has its own number codes: CL are numbered 90, 80 or 70 depending on their chemical composition (CaO + MgO). For example, CL 90 lime has at least 90% of calcium oxide and less than 5% of magnesium oxide. Correspondingly, DL 85 lime has at least 85% of calcium oxide and maximum 30% of magnesium oxide. This classification is not very useful for actual users of building lime, because the most important indicator of the lime's functionality, its calcium hydroxide (Ca(OH)2) concentration, is absent from the standards. The concentrations of free lime have been classified instead.

Mortar types (binders)

One binder	*Blend of two binders*	*Components react with lime*
Lime mortar (air-hardening lime)		Lime mortar with brick powder
Hydraulic lime mortar (hydraulic lime)	Lime mortar with hydraulic lime	Lime-pozzolan mortar
Cement mortar (cement)	Lime-cement mortar	Lime-trass mortar

Classification of limes according to their hydraulic ingredients and compression strength

Lime binder	Hydraulic ingredients (% by weight)	Compression strength MPa 28-day classification according to EN-standard	
Air-hardening lime	0–8	No qualifications	
Mildly hydraulic	8–12	Class 2	2–7
Hydraulic	12–18	Class 3,5	3,5–10
Strongly hydraulic	18–35	Class 5	5–15
Natural cement	45–55	No information	
Portland cement CEM IIA	80–94	Classification of concrete Class 32.5	35–52

Clinker minerals in old and modern cement

Modern cement includes about 60% alite and about 10–15% belite. For comparison, English concrete from the 1890s includes 9% alite and 60% belite; in old concrete the relation of these calcium silicates is therefore the reverse to that of modern concrete (Mallinson and Davies 1987). Considerably larger amounts of belite than alite have been detected in old concrete samples from Suomenlinna. The mineral compositions of cement mortars have not been analysed. Modern cement is ground very finely to a granular size of 0.002–0.1 mm (average 0.020 mm).

The hydration of alite (C_3S) is fast and begins immediately in the presence of water, with the release of heat and a large amount of calcium hydroxide. Belite (C_2S), the main mineral in old cement, reacts substantially more slowly and less exothermically; therefore its reactivity is weaker. Furthermore, the amount of calcium hydroxide formed in old cement is only one third of that released in new cement.

1.4 Old cement – "natural cement"

Old cement differs from modern cement in many ways. Cement has a relatively short history if one starts from the patenting of Portland cement in 1824. Although cement-like binders had been made before that, the raw materials and their relationships differed from those of Portland cement and firing was done at much lower temperatures. The grinding of burnt cement (i.e. clinker) was both labour-intensive and costly; thus the formation of hard clinkers during firing was avoided as much as possible. The importance of clinker formation for the development of strength in concrete was not understood, nor was the importance of grinding the clinker.

When firing occurs near the burning temperature of hydraulic lime, similar minerals to those of hydraulic lime are formed. In both old cement and hydraulic lime, the main mineral is belite (C_2S). At higher temperatures alite (C_3S) is formed. If the raw materials include aluminium and iron compounds in addition to lime, aluminate and ferrite are both formed during firing. If the burning temperature is over 1000°C, no free lime remains in the cement.

Because of insufficient grinding, the clinker sizes of old concretes and cement mortars are much larger than in modern cement. Very large clinker granules, up to 0.5–0.9 mm in diameter, have been found in old cement mortars under microscopic examination. The average size of a clinker granule of Portland cement is 0.02 mm. The large clinker granules have hydrated only at the surface, although they are 150 years old. Old and new cements differ also in their hydration speed due to their different mineral compositions. Large clinker granules reduce the reactivity even further, and not all large granules react with water at all.

It would seem that old cement and lime function better together in the hardening phase than do modern cement and lime.

Governing Body of Suomenlinna

Example from Suomenlinna. Mortar containing Jura lime has been used to repair the masonries of Kustaanmiekka fortifications. Its composition is close to that of natural cement. In Russia the production of cement started in 1856 and in Finland only in 1914 (Nykänen 1957). The first cement-bearing plasters in Suomenlinna were made in 1889, during the period of Russian rule.

Reactions of hydraulic lime and cement with water – hydration

Reaction of the main mineral of burnt **hydraulic lime** with water

Dicalcium silicate + Water → Calcium silicate hydrate + Calcium hydroxide

C_2S (belite) *CSH*

$$2(\,2\,CaO\,SiO_2\,) + 5\,H_20 \rightarrow 3\,CaO\,2SiO_2 \bullet 4\,H_20 + Ca(OH)_2$$

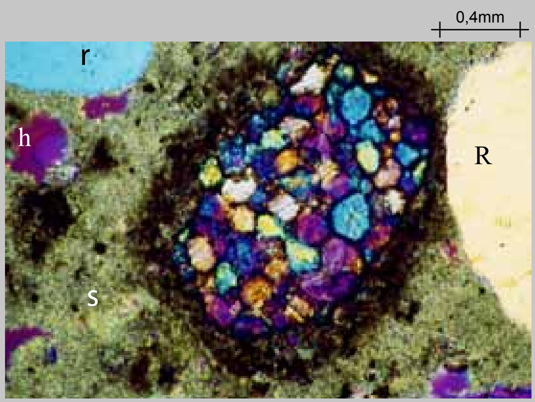
Reaction of the main mineral of **cement** with water

Tricalcium silicate + Water → Calcium silicate hydrate + Calcium hydroxide

C_3S (alite) *CSH*

$$2(\,3\,CaO\,SiO_2\,) + 7\,H_20 \rightarrow 3\,CaO\,2SiO_2 \bullet 4\,H_20 + 3\,Ca(OH)_2$$

The most common cement is Portland cement. In 1824 British cement manufacturer J. Aspdin synthesized hydraulic lime by firing a raw-material mixture of lime and clay at sintering temperature. He called the burnt, crushed mixture Portland stone, referring to a natural material found on the Isle of Portland in Dorset that had the same shade of grey. Nineteen years later, his son William Aspdin was able to fire a mixture with a similar composition to that of modern Portland cement (Mallinson and Davies 1987).



Large clinker granule (belite), diameter 0.6 mm, in old cement. Only a couple of aggregate gnanules (R) and one pore (h) are visible. Bastioni Polhem, Suomenlinna. Photomicrograph x20, X-nicol, gypsum plate.

1.5 Aggregate in mortar

Sandpit in Vihti

Sand, i.e. aggregate, forms the biggest part of a mortar and can have a variety of grain sizes. The designation "aggregate," which means to bring together, is very descriptive. Sand grains form the framework of the mortar, and the binder glues them together. The size of the sand grains determines the supportive strength of the framework. By screening the sand (e.g. through sieves of 4–0.07 mm) and weighing the grains that remain in the sieves, the granularity of the aggregate can be calculated and its grain size curve (grain distribution) deduced.

The importance of the aggregate in mortar was discussed fairly widely in the 18th century. Ziegler and Boltman were of the opinion that a mortar can include quite a lot of sand without its strength being weakened (Gilly 1818). This is somewhat confusing because the amount of aggregate in old mortars is usually much smaller than in new ones. Vitruvius and later Alberti presented a simple testing method for determining the sand needed: "Mortar sand must be explored by hand. The sand is not sharp enough unless one can feel every grain separately. If a lot of dust remains in the hand, the fine fraction of the sand is too great. The granularity of the sand in the plaster mortar has to be finer than that in masonry mortar." Large amounts of lime, which filled the empty spaces between sand grains, were often added to mortars. Therefore good, old mortars are compact and durable. (However, not all old mortars are compact.) In a mortar with lots of binder, the effect of the aggregate distribution of sand is marginal.

Lately little attention has been paid to mortar aggregates in foreign literature, and any mention is superficial. The amount of sand in mortar is generally given in parts by volume. Grain size distribution curves are seldom shown; only the maximum grain size of the aggregate is given. Only a few studies have looked at grain size distributions of historical mortar aggregates. One explanation could be that the proportion of aggregate in old lime mortars is small, in which case its significance for the function of the mortar is insignificant.

When the amount of aggregate is larger, both the aggregate and especially its grain distribution have a significant influence on the properties of the mortar. The effects of aggregate are discussed in greater detail in chapter 5.

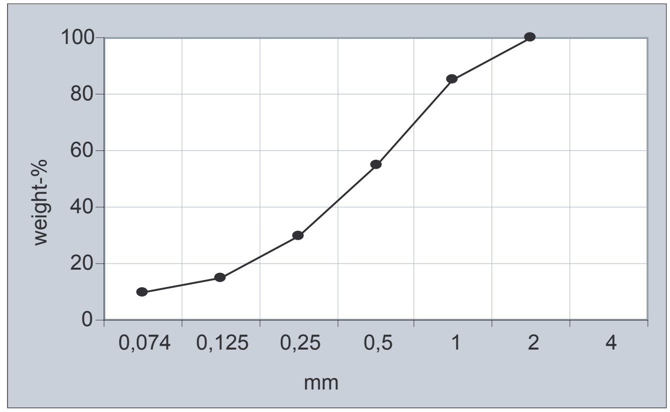
1.6 Hardening of mortar

When mortar has been spread on a wall or between masonry stones, the water in the mortar is immediately absorbed and part of it evaporates, causing the mortar to stiffen. During this phase a network of pores forms in the mortar consisting of round air pores or large void pores linked by cracks.

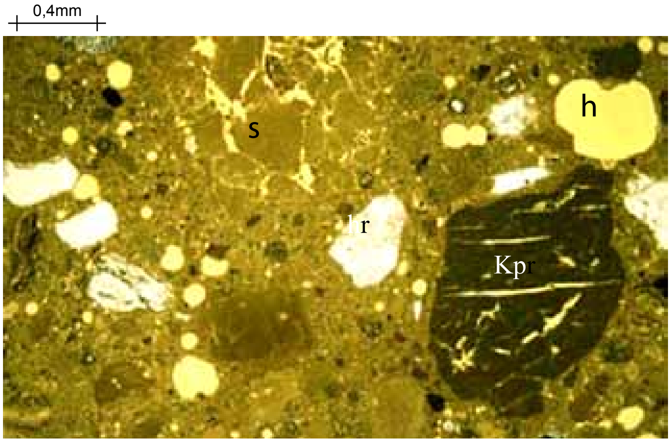
Lime hardens by crystallizing slowly with carbon dioxide gas (CO_2) into calcium carbonate. The reaction begins only when additional water has separated from the mortar and the pores have begun to dry. Carbonation always begins at the surface of the mortar, to which the CO_2 gas has free access. Deeper in, this reaction lasts for years. In order for the carbon dioxide in the air to be absorbed into the mortar and react with the lime, there must be humidity in the mortar but not free water, which blocks the pores. Carbonated lime binder has plenty of very small pores, or micropores, about 0.3–0.5 µm in diameter, in which humidity can move around freely.

Cement and hydraulic lime begin to react immediately with water or humidity, and this is where hydration calcium silicate and other silicate compounds are formed. The hardened cement binder is relatively compact because of its gel-like hydrate network, and water cannot move as freely through it as in lime binder.

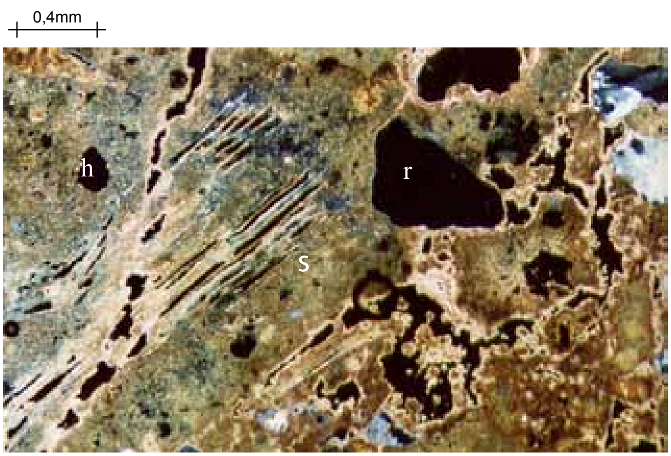
Hardening of lime mortar is a continuous process. In very humid conditions small amounts of carbonated binder may re-dissolve and recrystallize gradually and repeatedly. This phenomenon is called recrystallization. New crystals attach to the surface of the pores and cracks and can even fill the cracks and the smallest pores. Recrystallization increases the density and strength of mortar and this is believed to be one reason for the substantial strength and durability of old mortars.



Granule distribution of sieved aggregate. The Y-axis shows the passing percentage of aggregate; the x-axis shows the sieve size of granules with a given penetration value.



Compact pore network of an old lime-rich mortar.
The pores and cracks appear yellow, the aggregate is whitish and the carbonated lime binder is brown. The large brown granule on the right is a lime lump, which is typical of old lime mortars.
Photomicrograph, magnification x4, //-nicol



Filled cracks of recrystallized binder in an old lime mortar of Ulvila church.
Photomicrograph, magnification x4, X-nicol

Bibliography, Chapter 1

Alberti, L. B. 1912, Zehn Bücher über die Baukunst. Translation M. Theuer. H. Heller & Co, Wien und Leipzig.

Belidor, de B F, 1982 [1739], [La Science des Ingenieurs dans la conduite des travaux de fortification et d´architecture civile], part I. p. 7–22. Translation A. Nieminen. Museiverket, Helsinki.

CEN standard EN 459-1 2001. Building Lime. Definitions, specifica-tions and conformity criteria.

Gilly, D. 1818, Handbuch der Land-Bau-Kunst. Erster Teil von den Baumaterialien. Braunschweig.

Helsingin Sanomat (1985) Poltetaan Vimpelissä vanhanaikainen kalkkiuuni. 9.11.1985.

Historic Scotland 1995, Preparation and Use of Lime Mortars. Technical Advice Note 1. Edinburgh.

Johansson, S. 2004, Hydrauliskt kalkbruk. Miljövetenskap, Göteborgs universitet.

von Konow, T. 1997, Restaurering och reparation med puts- och mur-bruk. Doctoral thesis, Institutionen för oorganisk kemi. Åbo Akademi.

Krenkler, K. 1980, Chemie des Bauwesens. Band 1, Anorganische Chemie. Springer-Verlag.

Kraus, K. – Wisaser, S. – Knöfel, D. 1989, Über das Löschen von Kalk vor der Mitte des 18. Jahrhunderts – Literaturauswertung und Laborversuche. Arbeitsblätter für Restauratoren. Heft 1, Gruppe 6, Stein.

Malinowski, R. 1994, Dichtungsmörtel und Betone in der Antike. – Beiträge des neunten internationalen Symposiums zur Geschichte der Wasserwirtschaft und des Wasserbaus im Mediterranen Raum. Pompeii, October 1994, p. 191–199. Edited by Nathalie de Haan & Gemma C. M. Jansen. Leiden Stichting BABESCH 1996.

Mallinson, L. & Davies, I. 1987, A Historical Examination of Con-crete. Commission of the European Communities. Nuclear Sciense and Technology. Report EUR 10937 EN.

Nykänen, A. 1951, Betonin historiallinen kehitys. VTT, Helsinki.

Vicat, L., J. 1837, A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural. Translation J. T. Smith. J. London.

Firing of lime in Vimpeli, 1985

Limestone blocks before firing.

Long logs of wood are pushed into the combustion chamber.

Flames in the kiln.

Dick Sulin

Combustion gases rising from between the cover stones of the kiln.

Slaking of lime to pit lime

Slaking of lime in Gotland. Burnt stones are poured into cooling water. Next to the cooling vessel, the lime pits are ready to receive the slaked lime.

2 Research methods for the old mortars

Arno de la Chapelle

2.1 Studies at the worksite

It is always interesting to clarify from what and how an old structure has been made, and to ponder how it can have survived for centuries in very different conditions. When a mortar from an old building is studied, samples are taken in order to develop new repair mortars or for planning the painting of a façade, or to gain information about the composition of the original mortar and its microstructure. Mortars are also analysed for historical documentation. Analysis reveals e.g. the composition of different plaster mortar layers and previous painting treatments of old plaster. Damage to mortar can also be ascertained.

Examination of the age of mortar samples begins on site by studying the structure of the brick masonry, its surface treatments, construction of the wall and the reason for orifices. This helps clarify where possible during which period a given a masonry was laid or a wall plastered. The surface of a plaster can be examined under oblique light, which clearly reveals old repairs and roughness.

2.2 Sampling

Before collecting mortar samples from a historical building, one needs a good preliminary plan and exact documentation of the sampling sites and their immediate surroundings. It is also wise to clarify beforehand what information one expects from analysis of the mortar and for what purpose it will be used. Asking the right questions helps the analysis laboratory select the appropriate methods, because each examination demands its own analytical approach. Different methods also require different-sized test specimens. A suitable size for a test specimen of a historical mortar is about 30 x 30 x 30 mm^3.

The sample is carefully removed by chiselling with a diamond wheel or small drill. Some mortars in masonry joints are very tight and must be removed with patience and special care. At this point a preliminary examination can be made of the state of the plaster, masonry or pointing and the reasons for damage assessed. The condition is indicated on photographs of the sampling site as well as damaged areas and types of damage. The mortar samples are examined as such and are classified according to hardness and shade. Closer examination is done in the laboratory.

To be taken into account in the preliminary plan:

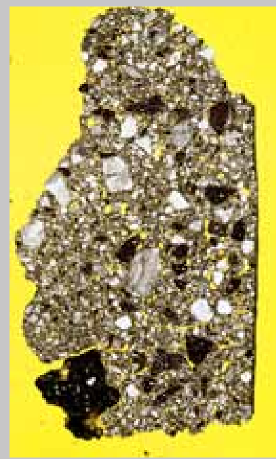
- What kind of information is expected from the analysis?
- What is the purpose of the analysis?
- How many samples are worth taking from the object and from where?
- What should the sample size be for each analysis?
- Are ladders or scaffolding needed for accessing the samples?
- Have all the necessary tools and sampling bags been acquired?
- How will the samples be sent for testing? Remember they are fragile and must be carefully packed.

Specimens from an old plaster with several layers of paint.

When interpreting the examination results it should be remembered that they reveal only the current state of the mortar, not what it was like during the plaster stage when the masonry was laid. Over the years the composition, strength and porosity will have inevitably changed.

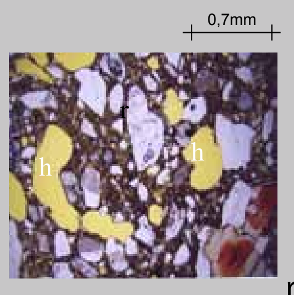
2.3 Microscopic examination

A polarizing microscope provides the best information on a mortar, using transmitted light that passes through the sample. The examination reveals different layers of the plaster and all the paint layers left on the mortar. Microscopic analysis enables the binder types and aggregates of the mortar to be differentiated and aggregate minerals, various fibres, crushed brick and pozzolanic substances to be identified.

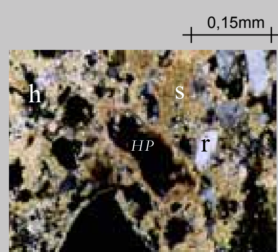


Robert Perander

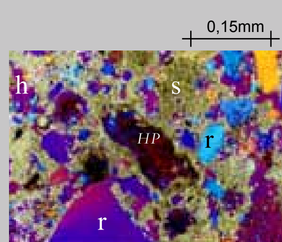
Thin section in natural size. 35 x 50 mm.



Photomicrograph of a mortar, unpolarized light. The pores are yellow, the sand grains whitish and the binder is brown. Magnification x4, //-nicol



Photomicrograph of a mortar, polarized light. The pores are black and the binder is brown. A hydraulic particle (HP) is visible in the middle. Magnification x20, X-nicol.



Polarized light with gypsum compensation plate; a hydraulic particle (HP) is visible in the middle. Magnification x20, X-nicol, gypsum plate.

Pores and cracks resolve well, and the compactness of the binder is clearly visible. Microscopic analysis also reveals to what depth the mortar has carbonated and how far the cement clinkers have hydrated.

For microscopic analysis a special thin-section sample is prepared as follows: A piece of mortar is dried, impregnated with pigmented resin, stuck to a glass plate and polished with special equipment to a thickness of about 0.025 mm. A mortar sample polished to the right strength is covered with a glass slip ready for microscopic analysis. Thin sections can be prepared from a sample as small as 20 x 20 mm^2. When the thin section is examined under unpolarized light (//-nicol), the microstructure of the mortar becomes visible. The pores, voids and cracks appear yellow due to the resin impregnated in the sample. The aggregate is usually whitish, black or opaque. Under polarized light (X-nicol), the quality of the binder and the mineral composition of the aggregate can be examined. A gypsum compensation plate mounted in the light path of the microscope changes the colour to red. This is an excellent way to separate cement clinkers and other hydraulic materials from the binder. Different sized objectives give a general view of the pore network and binder structure deep into the mortar.

2.4 Analysis of binder composition

Chemical analysis provides information on the amount of binder, types of binder and amount of sand in the mortar. Analysis is performed essentially as follows:

A piece of mortar is finely crushed then dissolved in acid. The lime binder dissolves quickly with a fizzing reaction. Hydraulic substances, like cement, dissolve more slowly. The amounts of calcium, magnesium, silicon and sulphur oxides are analysed from this solution. The oxide values allow the components of cement and lime in the binder to be calculated based on a given formula. The remaining undissolved residue is the aggregate (sand) of the mortar. The washed residue can be screened through a set of sieves to obtain information about its various sizes; this will give the aggregate's size distribution curve.

Several uncertainty factors are involved in chemical analysis (Lindqvist 2006). If there is limestone, dolomite stone or their finer-grained filler among the sand, they dissolve in acid like the binder, either completely or partially. The analysis results are then distorted, because the dissolved limestone is counted as binder. In the calculation formula determining the amount of hydraulic binder, the average amount of sulphur trioxide in Portland cement is used as a reference value. If the mortar includes unknown hydraulic material of unknown composition, the formula does not give a reliable result. By dissolving in acid, different hydraulic materials cannot be separated from each other and other methods are required.

However, chemical analysis can give a relatively good picture of the relation of binder and aggregate and of the amount of hydraulic substances. The best analysis result is obtained if mortar is first examined as a thin section and a rough estimation made of its composition. This tells which components can affect the analysis and what kind of binder is included in the mortar; this is then taken into account in the calculations.

X-ray diffraction reveals what additives (e.g. gypsum or clay) have been used in the mortar. Aggregate minerals can also be determined this way. The "fingerprints" of a lime mortar are obtained by heating the sample to different temperatures: at 100°C the humidity of the sample disappears; at 600°C the water bound to the hydraulic binder exits, and at 900°C the calcium carbonate decomposes.

Water-soluble salts in mortar are determined by crushing the mortar sample and soaking the crushed material in water for a day. Salt components and the total salt amount in the sample can be analysed from the filtered water extract.

2.5 Water absorption tests

Plaster and pointing mortars on outside walls get wet from rainwater and become dry again in relation to changes in air humidity. This phenomenon can also be studied in the laboratory. Both sides of the specimen are smoothened. The specimen, which must be large enough, is dried and weighed and the smooth area measured.

A capillary water absorption test will reveal how much and how fast the mortar absorbs water from the surface. A piece of mortar is weighed both dry and after soaking, and the water absorption ability of the mortar calculated from the difference. The drying rate is measured with a corresponding method that allows one side of the object to dry freely while the other side is prevented from drying by sealing it watertight. Drying of the object is monitored by weighing at certain time intervals. The water vapour transmission rate can also be measured with special equipment. (von Konow 1997)

Capillary water absorption test

Test objects

Historical mortars are often problematic because large samples can seldom be detached from an old wall. The best samples are obtained with a rotary diamond-bit drill, which bores out a cross-sectional sample from a plaster or mortar joint. With new repair mortars, specimens can be prepared in a mould. The specimens are allowed to harden for at least a month before testing. Suitable hardening conditions are air humidity over 70% and temperature around 20°C.

The test method:

A moisture-absorbing cloth (e.g. Wettex) is placed at the bottom of a small basin and enough water is added to saturate the cloth and just cover it. The smooth surface of a dry and weighed mortar sample (e.g. outer surface of a piece of plaster) is placed on the cloth, whereupon it absorbs water immediately. The sample is removed after one minute, weighed and returned to the basin. The piece is weighed again after 5, 10, 30 and 60 minutes. The capillarity is obtained by calculating how much water has absorbed through the surface of the sample during 0–5 minutes and 10–30 minutes.

Calculation:

Capillarity value 0–5 min [kg/m² √h]

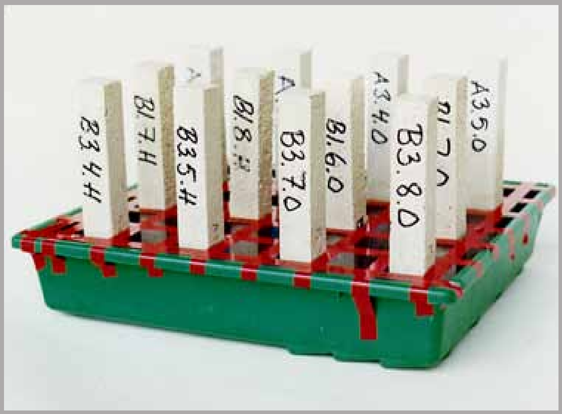
$$[(\text{weight}_{5\ \text{min}} - \text{dry weight}) / \text{area})] \times 10 / \sqrt{(5/60)}$$

Capillarity value 10–30 min [kg/m² √h]

$$[(\text{weight}_{30\ \text{min}} - \text{weight}_{10\ \text{min}}) / \text{area}] \times 10 / [\sqrt{(30/60)} - \sqrt{(10/60)}]$$

Water absorption ability in % by weight (2 days under water)

$$\frac{\text{weight}_{\text{wet}}}{\text{weight}_{\text{dry}}} \times 100\ \%$$



2.6 Strength tests on old mortars

Nowadays, different strength values are given for the resistance of building materials, but it is not necessarily worth measuring the strengths of mortars from old buildings. The strength of weathered mortar is apparently weak, thus it need not be measured, and the strength of undamaged plaster or pointing mortar on the other hand has been sufficient to withstand weathering for centuries.

The adhesion of plaster to its base can be determined by a simple method: dragging the edge of a hammer along the surface of the plaster. A hollow sound indicates lack of adhesion, i.e. there is a pocket between the plaster and the base.

If this simple method is not enough to evaluate the adhesion, the adhesion strength can be measured with tensile testing equipment developed for this purpose. The measurement also gives information about whether the breakage is at the junction interface of the base and plaster or in the mortar itself. Adhesion measurements might be necessary when the functionality of a new repair mortar is estimated in a test model field. The measurement can only be done once the mortar has hardened and carbonated. Lime mortars require a hardening time of at least 3 months. It should be remembered that the strength values of wet mortar are always lower than those of dry mortar.

The strength of a mortar sample can be roughly evaluated by rubbing it in one's hand, and the strength of a plaster surface simply by scraping the surface.

Analysis procedures, calculations and interpretations of results are described in detail in international and EU standards.

C14 dating

A historical building can be dated from old and original lime mortars. The carbon dioxide in air includes quantities of C14 isotopes that have varied down the centuries. When a fresh lime mortar carbonates, it also binds the C14 isotopes present in the carbon dioxide. The amount of isotope bound to the mortar is analysed in a carbon-isotope laboratory. Comparing the amount of C14 in the sample against a calibration curve gives the hardening date of the mortar. At the same time it tells when the masonry was laid or the building plastered with the mortar under study. Carbon isotope determination is only suitable for pure lime mortars. If the aggregate of the mortar includes limestone, lime filler or organic lime, which cannot be removed during preparation of the sample, the age of the mortar cannot be determined with this method. (Heinemeier 1997)

Frost resistance is perhaps the most important property of mortars used outside. It is needless to determine the frost resistance of old mortars in the laboratory, as these will have undergone numerous freeze-thaw cycles in natural conditions. The frost resistance of new repair mortars can be determined at about 3 months (K mortars) and at about 1 month (KKh and KS mortars). The determination of frost resistance is relatively slow and expensive, but is worth doing in special cases.

Visual examination of a mortar sample from a building
(Lindqvist et.al. 1994)

Age	Type	Colour	Hard-ness	Granule size	Pores	Lime lumps	Other	Estimated binder
16th century	Plaster	Yellow-ish	1	< 1.5 mm	Few, some largeri	Many	Breaks off easily	Probably lime mortar
1750s	Joint	Red	2	< 3 mm	Many	Some	Crushed brick	Lime mortar and crushed brick
1920s	Plaster	Grey	3	< 2 mm	Few	None	Probably cement	Lime cement mortar

Examining a mortar sample from a building visually or with a magnifying glass or a loupe gives preliminary information about e.g. the hardness, porosity and binder of the mortar.

Bibliography, Chapter 2

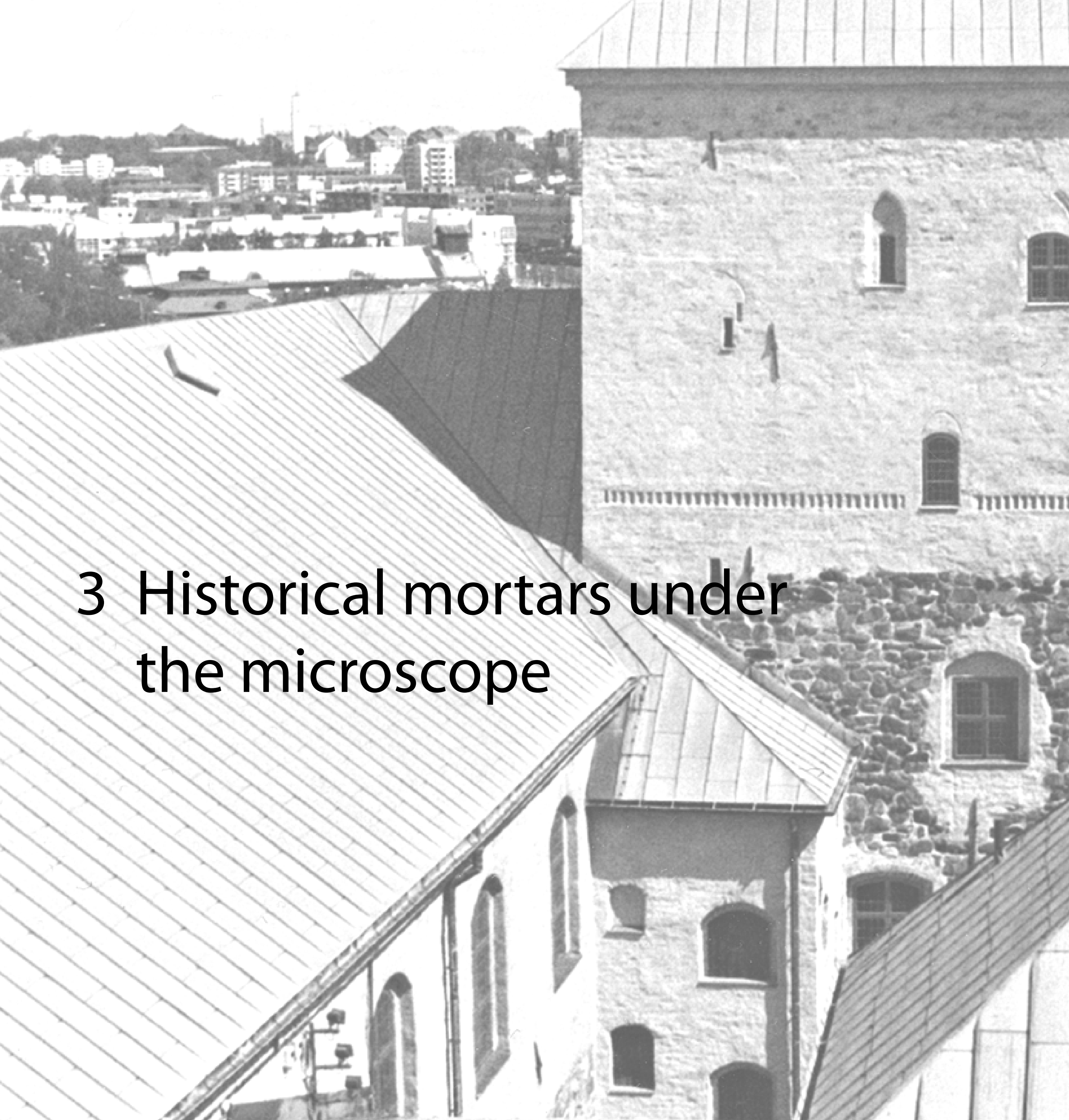
Heinemeier, J. et.al. 1997, AMS 14C dating of lime mortar. – NIMB Beam Interactions with Materials & Atoms. XIII. Archaeology Applications. Nuclear Instruments and Methods in Physics Research B 123, p. 487–495.

Lindqvist J.-E. et al. 1994, Gamla kalkputs – analys och utvärdering. Riksantikvarieämbetet. ISBN 91-7209-140-1.

Lindqvist J.-E. et al. 2006, Analysis of Mortars with Additives. NT Technical Report TR 594. Approved 2006-03.

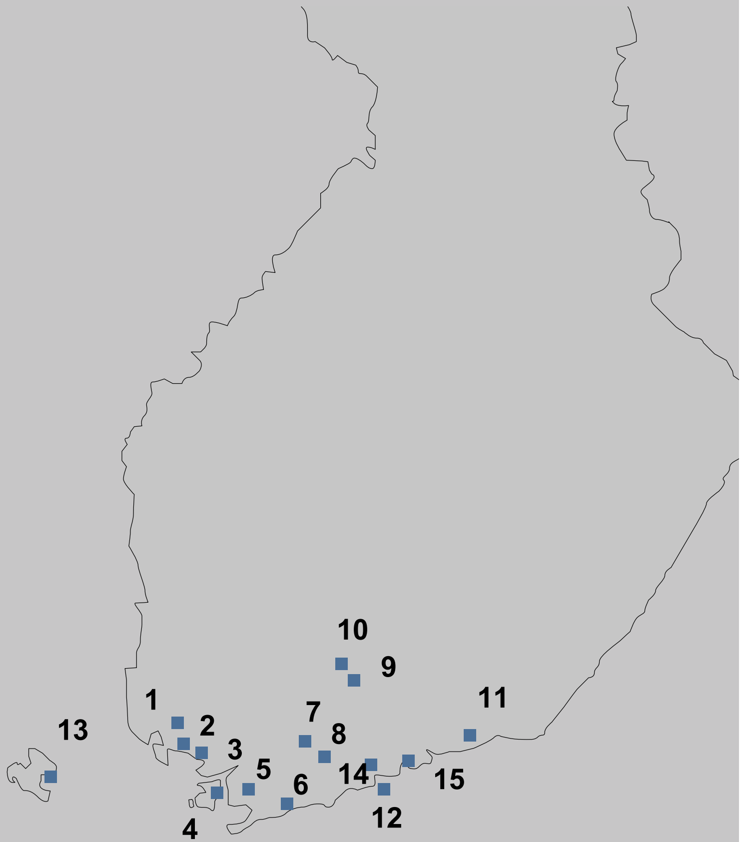
von Konow T. 1997, Restaurering och reparation med puts- och murbruk. Doctoral thesis, Åbo Akademi.

3 Historical mortars under the microscope



3.1 Mortars of historical buildings in Finland

Mortars of historical buildings were studied extensively at VTT for the first time during the 1980s in connection with a mortar study of historical stone buildings in Finland (Perander et al. 1985). This was the first study of such an extensive nature in the Nordic Countries. Additionally to the mortar studies, an in-depth archival study was done to glean information about original mortars or other mortars used in repairs, including their lime, aggregate and additive contents. From the archive material it became evident that mortar and its preparation method or components had not been considered worth recording. Unfortunately this is also true of later reports on restoration works.



1. Louhisaari Manor
2. Turku Castle
3. Karuna Manor
4. Kemiö Church
5. Tenhola Church
6. Raasepori Castle
7. Lohja Church
8. Suitia Manor
9. Häme Castle
10. Hattula Church
11. Svartholm Fortress
12. Suomenlinna
13. Kastelholm Castle
14. Espoo Old Church
15. Porvoo Cathedral

The 15 objects of the study were medieval castles, churchies and several manors in southern Finland. The northernmost object was the church of Hattula. The masonry of many of these buildings had been repaired during the 20th century with mortars that included cement. About 60 original plaster and masonry mortar samples were collected dating from the 13th–18th centuries. Wide grey granite pointing was considered as plaster mortar. Sometimes very little was left of the original mortars and it was difficult to take large enough pieces for examination. Only about half of the test specimens were sufficient for use in e.g. chemical, mineralogical and microscopic analysis of mortar composition. Among the samples there were only a couple of mortars from the 18th century and the other samples were from the 13th–16th centuries. Since then, other historical mortars have been analysed in Finland in connection with various restoration projects.

It is impossible to paint a uniform picture of old mortars in Finland, either in terms of their geographical location or the age of the buildings they are found in. In the VTT examination there were big variations in the compositions of the mortars. The most interesting observation was that there were not many "completely pure lime mortars" among the samples. Almost all of the lime mortars included some hydraulic material, being 3–30% of the amount of the binder and on average about 20% by weight.

Old mortars are clearly fatter and have more binder than modern mortars. In the latter the volume of sand is twice to threefold that of the binder. In mortars dating from 1350 to the 15th century, the relation of binder to aggregate is fairly constant, with ratios varying from 1:1 to 1:2 parts per volume; the sand has a similar mineralogical composition to modern mortar sand, and the aggregate is mainly rounded hillside sand. The granularity of the aggregate varies from sample to sample. The density of the examined mortars was 1600–1700 kg/m^3, but among them were some very porous mortars with a density below 1320 kg/m^3.


Governing Body of Suomenlinna

In Suomenlinna, extensive studies on old mortars as well as a wide range of reparations with specially developed mortars have been carried out..


Arno de la Chapelle

Häme Castle

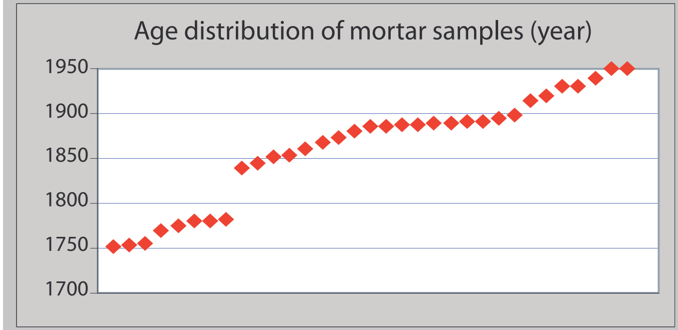
Information from archives on the use of lime in Häme Castle

According to ancient account books from Häme Castle, throughout its building period lime was delivered to the castle both as quarry-burnt and unburnt stone. Lime quarries were active at various times in Ridasjärvi in Hausjärvi, Pälkäne, Valkeakoski and Vihtijärvi. Lime was transported to the building site by waterway and the deliveries were paid for in February-March. This could refer to the lime being brought in time for the next building season, i.e. for one year. No references to slaking methods are found.

3.2 Old mortars of Suomenlinna

The buildings and masonries of Suomenlinna provide lots of examples of mortars from the periods under Swedish and Russian rule. In the internal parts of the defence masonries between the stones, the remaining mortar is mainly original. Part of the masonry and pointing mortar of the brick masonries is old mortar. Original plaster mortar can still be found on surfaces of some plasters that have been well protected or were hidden during renovation work. These original mortars are usually quite compact and firm. Under Swedish rule lime mortars were used that often included blast furnace cinder impurities. The cinder either came into the mortar with the sand or was knowingly added. Some of the mortars from the time of Russian rule show the addition of crushed brick, sometimes even more than aggregate. Some of the plaster mortars from this period are quite rich in cement.

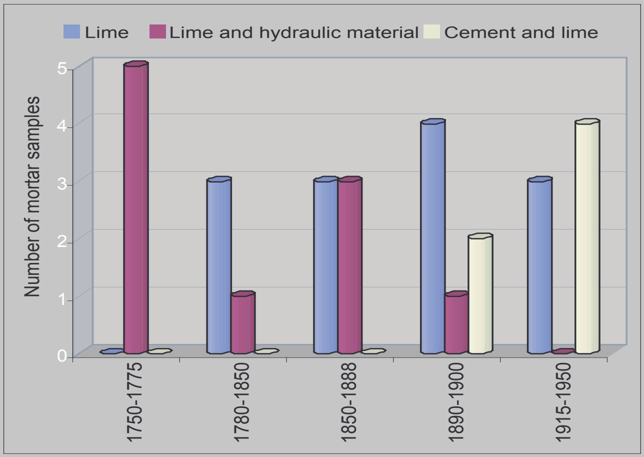
Mortars used in buildings and masonries of Suomenlinna differ from each other quite a lot depending on the period. The reasons include different ranges of use, diverse working methods, and the varying professional skills of the masons. This is clearly evident from the analysis results of the mortar samples. Not even mortars from the same period resemble each other very much.



Age of mortar samples from Suomenlinna buildings. Most of the studied mortar samples are from the 1890s. Mortars from the 1780s to 1840s have not been examined.

3.3 Time distribution of the mortar samples and types of mortar

In all, 33 samples have been collected from 12 buildings in Suomenlinna, eight of from the Tenalji von Fersen building. The oldest mortar samples are from 1758 from the old pharmacy (D11) and the newest from the 20th century plasters of Myllysali in Tenalji von Fersen. Eight mortars from the 18th century have been examined, 17 from the 19th century and seven from 1900 to the 1950s. These mortar samples have not been sampled systematically from any given period, but were collected during restoration of the buildings. It has been necessary to evaluate the age of samples at times, because it is almost impossible to know for certain when a mortar reparation was carried out. Mortar samples are taken mainly from façade plasters, pilasters and mouldings, and from plasters on the inside walls.



Age distribution of binders and binder mixtures in old mortars of Suomenlinna.
During the building phase of Suomenlinna from 1750 to 1775, the mortars included binder made from a mixture of lime and hydraulic components. From 1780 onwards, the binder was lime only and there were fewer hydraulic components. Cement was used in mortars for the first time in 1890. Hydraulic components other than cement were not found in mortar samples after 1915.

3.4 Binders in the old mortars of Suomenlinna

The composition of old mortars is more diverse than shown by the accompanying, simplified diagrams. A binder may be pure lime i.e. air-hardening lime, old cement or different hydraulic materials. In the samples from Suomenlinna part of the hydraulic material is cinder granules (cinder from metal casting).

Map of Suomenlinna showing structures from which samples have been collected for more detailed analysis..

Of 33 samples, 13 are “pure lime mortar” without hydraulic materials. Of eight samples from the 18th century, only three are lime mortars. Of 17 samples from 1840 to 1890, eight are lime mortars, and of eight samples from the 20th century, two are lime mortars. Among the lime binders the strangest one is in a masonry mortar from building H2 (Lonna). The lime is very porous and grit-like.

Altogether 10 mortar samples include cement. Old cement differs from modern Portland cement, which is described in greater detail in Chapter 1.4. Five samples that include cement date from 1880 to 1900, and four date from 1920 to 1950. The newest are repair mortars.

The most interesting mortars are those that include as binder some other hydraulic material such as blast furnace cinder, hydraulic lime, brick powder or some other, unknown material. The oldest mortars from the 18th century include cinder granules among the lime. Around some granules there is a reaction ridge formed by the hydraulic reaction of lime and cinder; this was observed in six out of eight mortars from the 18th century (from B12, B17, C54 and D11). Four mortars from the 19th century belong to this group, although they include crushed brick and unidentified hydraulic granules. Only one includes cinder. The mortar with the most hydraulic components originates from the stairwell of the old pharmacy (D11).

3.5 Porosity of mortars

Thin-section studies have been performed to clarify mortar porosity, sizes and types of pores, amount of cracks and compactness of binders. The microporosity of mortars falls into four groups as shown in the following table, based on subjective visual observation.

The microporosity of mortars from the 20th century was the weakest: six of seven mortars had degree 1. Of the 18 samples from the 19th century half were good or very good and only three were weak. The microporosity of the oldest mortars was mainly satisfactory, a couple had good or very good microporosity and only one had weak microporosity.

Mortar samples from Suomenlinna	Outer samples	Inner samples
Plaster	16	9
Masonry	3	1
Pointing	1	
Slurry	1	1
Ornamental	1	
Total	22	11

There is an interesting variation in quantities of binder. Cement mortar from the 19th century includes the most binder and mortars in the inner surfaces the least.

Volumetric ratio of aggregate and binder (average of mortar samples)

All inner mortars	2.4:1
All outer mortars	1.9:1
Outer mortars from the 18th century	2.1:1
Outer mortars from the 19th century	1.6:1
Cement mortars from the 19th century	1.3:1

Porosity of old mortars from Suomenlinna and their binders from the 1730s to the 1950s.

Mortar samples from the outer walls are indicated in green.

Building No	Mortar preparation	Porosity 1	Porosity 2	Porosity 3	Porosity 4	Binder classification K	Kh	S
B17	1950	■				x		
B17	1940	■						x
B17	1940		■					x
B17	1930	■						x
C1	1930	■				x		
D11	1920	■						x
H2	1915	■				x		
B15	1898		■			x		
B17	1890			■		x		
C1	1890		■			x		
C1	1890		■			x		
C1	1890		■				x	
C1	1890			■				x
C52	1890				■			x
B17	1889			■				x
B39	1888			■				x
B39	1888		■					x
B39	1888	■				x		
D9	1885	■				x		
E11	1885			■		x		
C54	1880			■				x
C74	1868			■			x	
D11	1852				■		x	
D11	1852		■				x	
D9	1845	■				x		
B17	1782		■			x		
C54	1780	■					x	
C54	1780		■			x		
B17	1775		■				x	
B12	1770			■			x	
D11	1752		■				x	
D11	1752				■		x	
D11	1752		■				x	

4. Excellent

The mortar is homogeneous throughout. The pores are small (under 0.3 mm in diameter) and round and not connected to each other. There are no shrinkage cracks in the mortar. The adhesion of the binder to the sand grains is good and the binder is compact.

3. Good

Relatively compact mortar. The pores are not connected through the cracks and some of the pores are round and small. There are few if any cracks. The adhesion of the binder to the sand grains is good and the binder is compact.

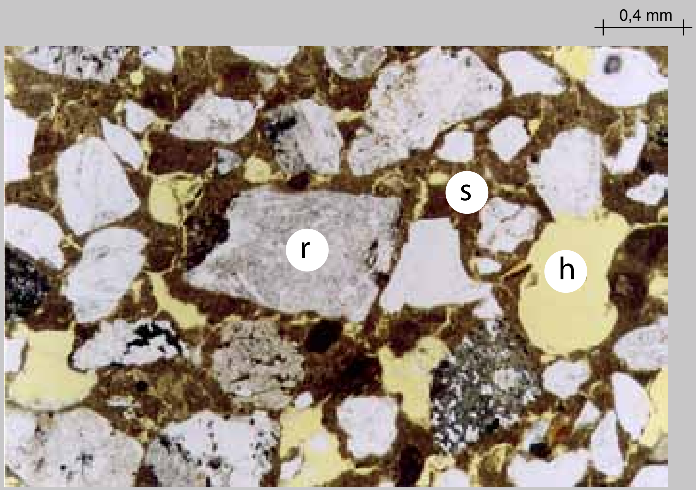
2. Satisfactory

There are void-like pores and cracks in the mortar, but the pore network is not fully open. This kind of mortar is often inhomogeneous, in places compact.

1. Poor

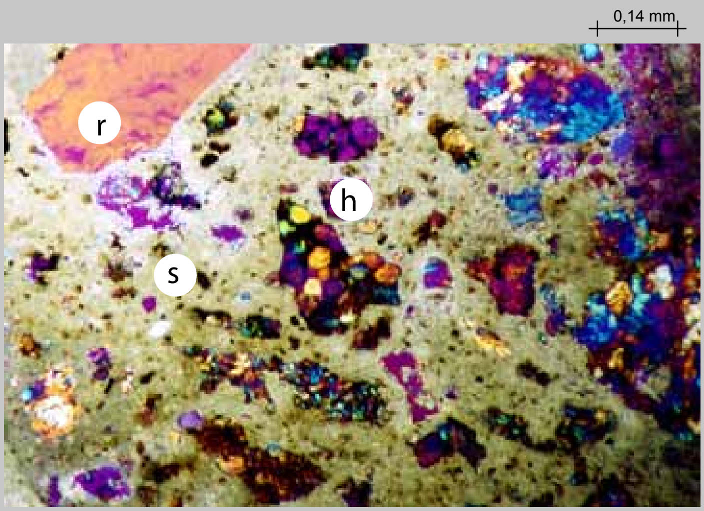
The pores form a pore network, with all the pores connected through the cracks. Round, small pores are not found in the mortar. In this kind of mortar there are often more pores than binder.

Jetty barracks (C1), built by the Russians as military barracks in 1890. The plaster covered with red lime paint is mostly original lime plaster.



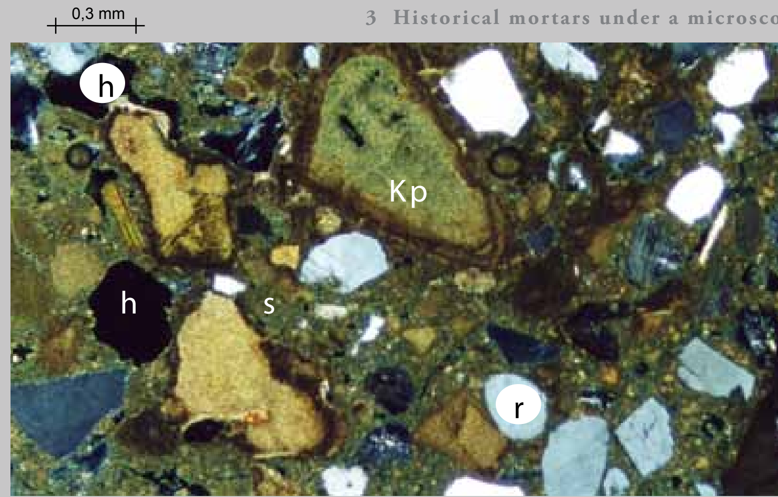
Original lime plaster mortar provides an overall picture of the composition and microstructure of 19th century mortar. Old lime mortar is relatively compact. Its binder aggregate ratio is about 1:1.5 and there are round, mainly void-like pores in the pore structure (see previous table, 2:satisfactory). There are plenty of lime lumps and some reacted hydraulic granules. In this thin-section photomicrograph the aggregate is grey, the lime binder brown and the pores yellow.
Magnification x4, //-nicol.

Original dentils under a window flashing of the Jetty Barracks (C1). They are moulded from a very cement-rich mortar, with aggregate making up only one third of the binder.



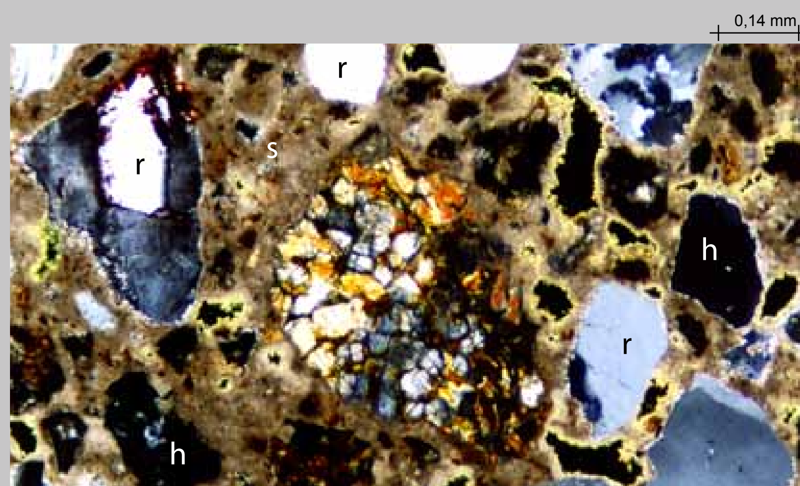
In this thin-section photomicrograph, cement clinkers appear as colourful clusters. Only three aggregate granules are visible. The carbonated binder is light brown. Magnification x10, X-nicol, gypsum plate.

The old pharmacy (D11) on Pikku Mustasaari, built in 1752–56, is the oldest stone building on Suomenlinna. When its façade plaster was repaired, small areas of original lime plaster were found in the lowest plaster layer. All of the old mortar samples from this building contain hydraulic material in addition to lime.



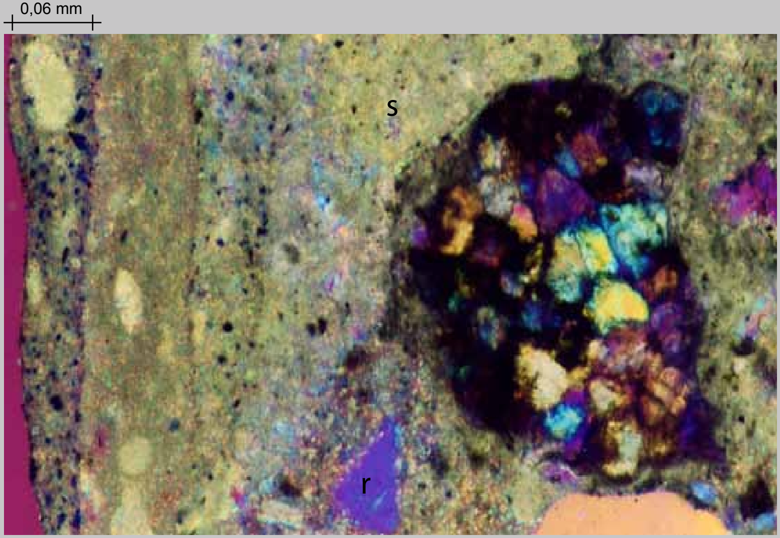
This original lime mortar from the old outer wall is surprisingly compact and homogeneous. There are only a few small, round pores (h) and no cracks (4: excellent microstructure). In the upper middle is a lime lump (Kp) with a reactive ridge. The pores are small and round and appear black. The aggregate (r) is bluish grey or white and the lime binder (s) is greenish. Magnification x4, X-nicol.

Stairwell A of the Bielke Bastion (C52) was built in 1847 as a latrine tower and converted to a stairwell in the 1890s. The slurry of the façade is cement mortar, apparently from the 1890s or 1913.



The large granules of cement clinker in this mortar show that the slurry is old, probably original, and has lasted well. The binder aggregate ratio is 1:1. In the middle is a beautiful unhydrated cement clinker granule, 0.5 mm in diameter. The aggregate (r) is grey, the pores are black and the binder is brown. Magnification x10, X-nicol.

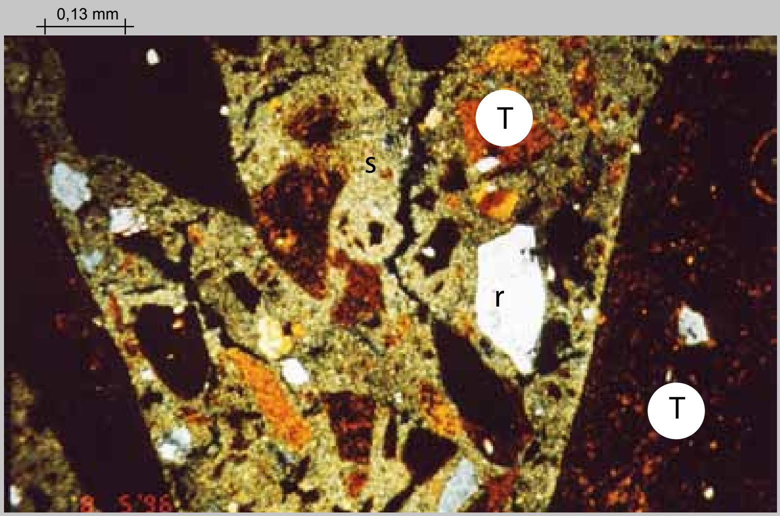
The Blue House (B39) in the Great Courtyard in Suomenlinna was built in 1881–1882. The building was originally painted blue, first with lime paint including carbon black, and later with a dark blue synthetic ultramarine pigment.



Photomicrograph of lime paint surfaces. The small blue spots are pigment particles. The plaster is a mortar that includes cement, with a cement clinker granule visible on the right. Magnification x20, X-nicol, gypsum plate.

Arno de la Chapelle

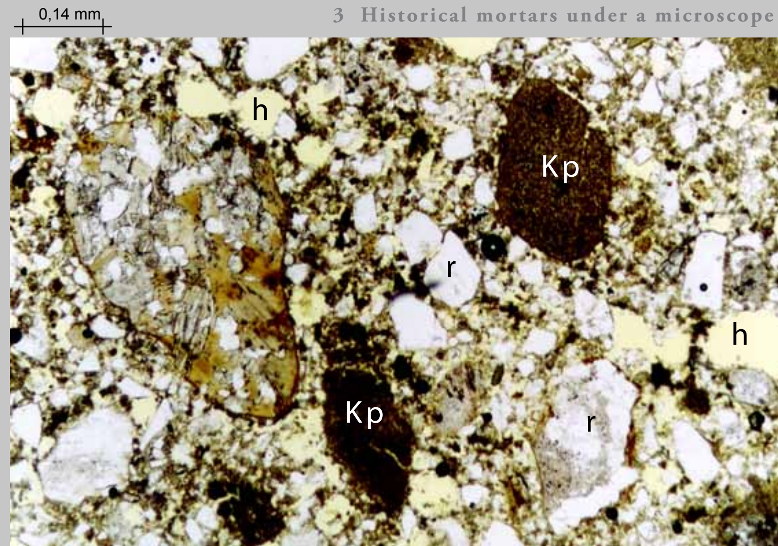
The Inventory Chamber (C74), built in 1868, today houses the Suomenlinna Centre.



Mortar sample from the masonry of an inner wall. The mortar is special, because more than 90% of the aggregate is crushed brick (T). The finest component of the crushed brick has reacted with lime. There are many small shrinkage cracks, which developed when the fresh mortar dried in the brick masonry. Magnification x10, X-nicol.

Reetta Amper

Building H2 is situated on the small island of Lonna, to the north of Iso Mustasaari. The building was completed in 1915 and used as an assembly and storage building for mines. The joint mortar is completely missing.



This masonry mortar sample differs from all the other lime mortar samples. The mortar is very porous and the binder lime is oddly grit-like. It is difficult to imagine how and from what kind of lime this mortar was mixed. The pores are light yellow, the aggregate is whitish and lime lumps appear as large, brown granules. The binder is distributed very unevenly between the aggregate granules. Photomicrograph, magnification x4, //-nicol.

Jussi Kärnä

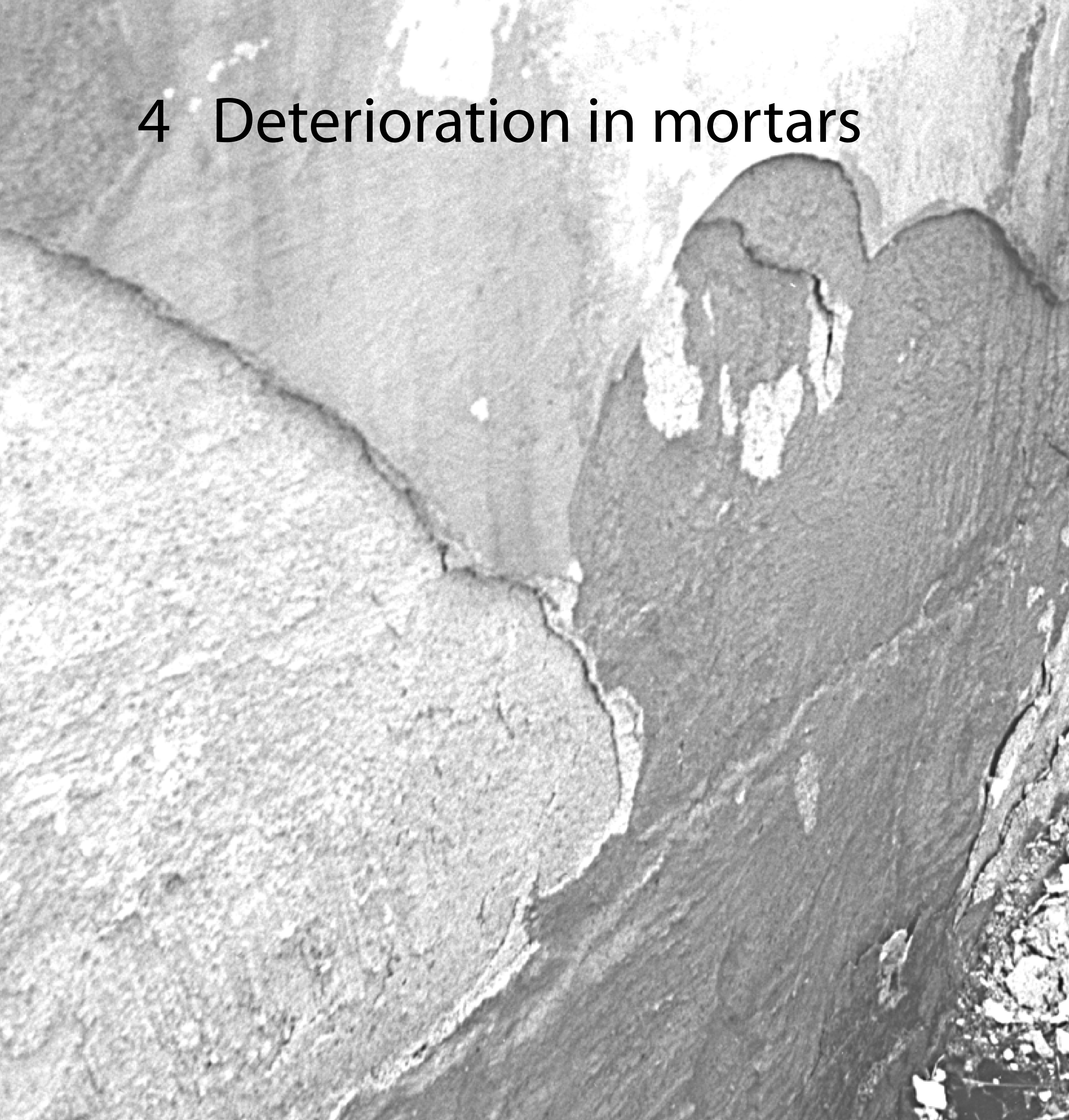
Building H2. Close-up of the masonry

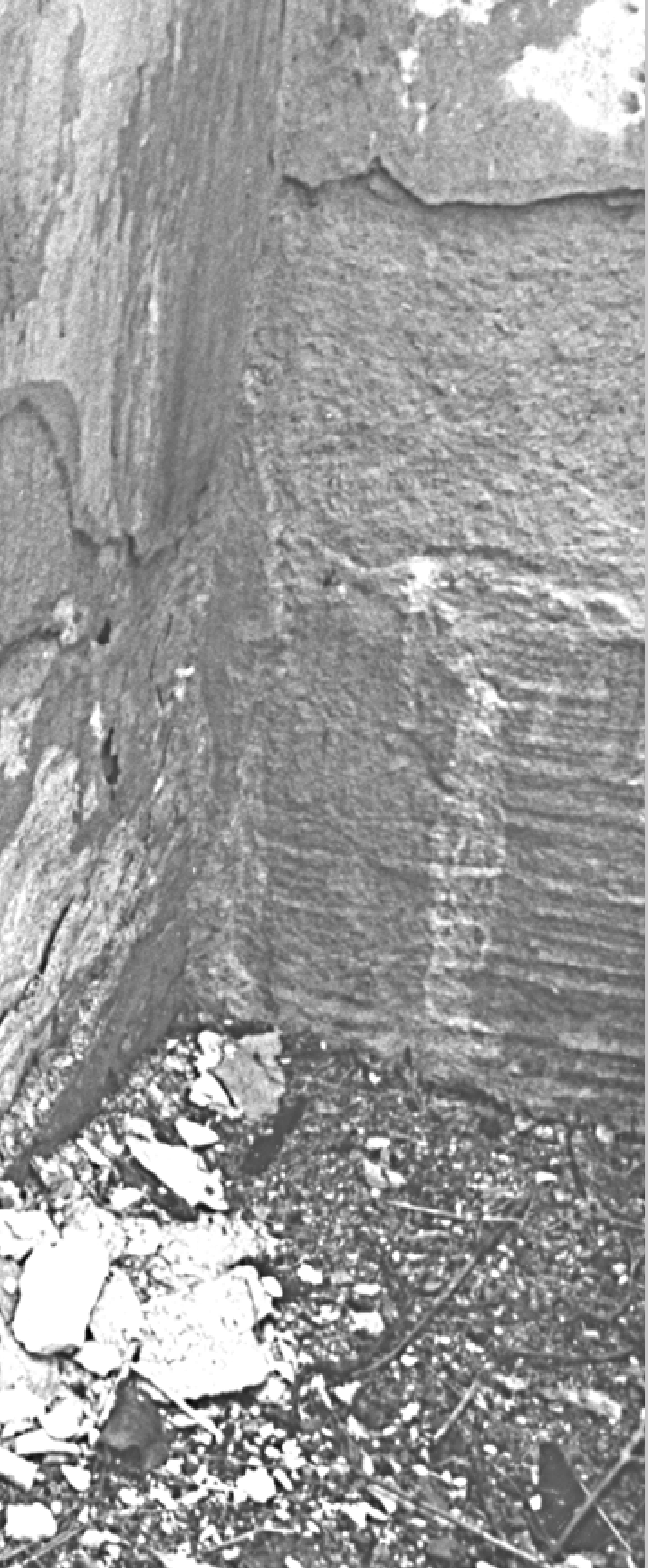
Bibliography, Chapter 3:

Perander (von Konow) T. et al., 1985, Historiallisten kivirakenteiden laastit. VTT tutkimuksia 341, Espoo.

Suomenlinnan rakennusten historia. 1997 Museoviraston rakennushistorian osasto, Suomenlinnan hoitokunta.

4 Deterioration in mortars





4.1 Cause of deterioration and reason for damage

"When examining the deterioration of a plastered façade it is important to distinguish between the cause of deterioration and the reason damage occurred. This is important, because the cause of deterioration is nature (rain, wind, solar radiation, temperature changes etc.) and the reason damage occurs is man — the planners, builders and users of the house. Natural laws are almost entirely beyond the control of man, and must be obeyed when raising a structure.

If we build against nature, it will retaliate. A mistake by man, not nature, is the reason damage occurs. Of course not all damage is human error — some of it results from normal wear and tear, and some cannot be resolved in a more sustainable way through present knowledge.

Additionally, we should bear in mind the characteristics of architecture through different era and the various susceptibilities to damages relating to them."

Erkki Mäkiö. Rapatun julkisivun kuntoarvio. Suoritusohje. (Condition assessment of plastered façades. Practical guide.) Page 2. Rakennustietosäätiö, 1990.

4.2 Mortars also deteriorated in the past

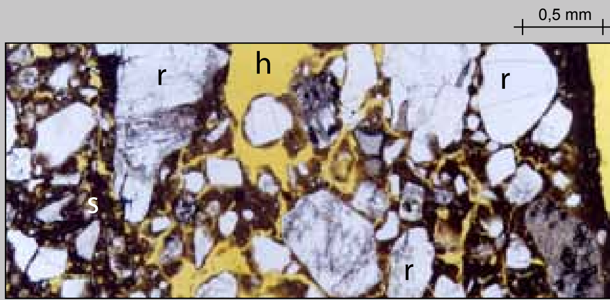
There is a common impression that old lime mortars were considerably better and much stronger than those created nowadays. This is true of old mortars that are still functional as masonry mortar or as small plaster fragments in a building over a hundred years old. Plaster mortars of façades in particular are subject to major stresses and needed constant repair even then. The discovery of many kinds of additives demonstrates earlier attempts to improve the strength of mortars. Ancient literature mentions many kinds of additives including wine, beer, bull's blood, eggs, honey, milk products and animal hair. The effects of these additives on mortar properties have been at least partially clarified.

4.3 Water, freezing and hardening of mortar

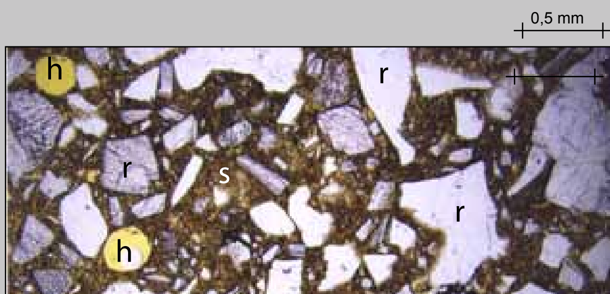
We try to protect the façades and outer masonries of a building from rain through various construction solutions like rain mouldings, eaves sheeting and flashings. Harder mortars are often used for the plasters of foundations than for the rest of the wall, in order to protect the plaster from moisture rising from the ground. Sheet metal or some other hard material is used to protect the wall from mechanical knocks. If these types of protection do not work and rainwater soaks into the wall, damage results. Similar damage develops when lime plasters are painted with polymeric paints (e.g. latex paint). Rainwater always finds its way through cracks in the coating, but evaporates back out from the wet plaster considerably more slowly, meaning that the wall never gets to dry. The reasons for such problems are failures in maintenance, planning errors, or mere ignorance. However, it is usually possible to correct these mistakes.

In the Nordic countries, most damage to buildings is caused by water and frost. Freezing water expands in the pores of the mortar, causing brittleness and decomposition. Decomposition takes place if the mortar has not attained sufficient strength through carbonation or hydration. If a lime mortar is made in late summer or autumn, it has no time to carbonate more deeply than the surface before the onset of winter frost. Another factor affecting the frost resistance of mortar is its pore structure. Large pores connected to each other through cracks are called voids. A pore network composed of voids can fill with water. Small, round pores (about 0.1–0.3 mm in diameter) not connected to each other through cracks form protective pores which do not fill with water, allowing the pressure of freezing water to discharge into these without damaging the mortar. Protective pores are especially important to the frost resistance of concrete and very cement-rich mortar. However, merely a disadvantageous pore structure is not enough to generate frost damage unless there is a lot of water in the pores at the time of freezing.

Luckily most of the moisture from the mortar is absorbed by massive brick masonry. More troublesome are natural stone masonries with a water absorption ability that is virtually non-existent. Lime mortar adheres well to natural stone, but does not necessarily withstand frost when thickly layered. The usage of pure lime mortar as a filler in natural stone masonry should be considered with care, because deep between masonry stones the carbonation of lime either takes a long time or does not happen at all, in which case the mortar stays soft.



Poor pore structure: large voids and cracks (yellow). This kind of mortar becomes damaged when water freezes in the pores. The sample is from a damaged plaster. Photomicrograph, magnification x4, //-nicol.



Good pore structure: small, round air pores. This sample is from a good plaster. Photomicrograph, magnification x4, //-nicol.

Arno de la Chapelle

Crystallized salt on the surface of brick masonry. Cellar vault in the Tenaille von Fersen building of Suomenlinna.

4.4 White salt deposits

Old brick masonries often contain water-soluble salts, which decompose not only weakly fired bricks but also weak mortars. Salt destroys bricks and mortars when it repeatedly dissolves and crystallizes with changes in air humidity and temperature. Every salt has its own equilibrium moisture limit (relative humidity RH), in which it changes its form. Salt crystallizes when the humidity of air falls under this relative moisture limit, and dissolves again when the air humidity rises above it. For example, the equilibrium moisture of table salt (NaCl) is 75% of the relative humidity. Soda (Na_2CO_2) is more complex, because it binds different amounts of crystal water. Its equilibrium moistures are 66% RH when it binds one, 73% RH when it binds seven, and 90% RH when it binds 10 crystal waters, respectively. Both types of salts are quite common in old masonry structures. The RH values for atmospheric air and for the internal air of cold structures are in the range of the equilibrium moistures of these salts. That is why it is difficult to eliminate the adverse effects of salts in structures with major variations in humidity.

Salt accumulates in structures from many sources. Salts in soil are produced e.g. by decomposed parts of plants, urine and dissolved anti-icing salts. Coastal structures are also exposed to sea air, which includes salt-water drops. Also, a significant source of salt is cement. Additionally to alkali salts, calcium hydroxide is formed as long as the cement is hydrating. This absorbs into the brick, where it is partly converted into sodium carbonate, or soda, one of the causes of brick decomposition. Mortars including cement should therefore be avoided in repairs of old brick buildings.

In early spring, new brick masonry surfaces that have turned white are a frequent source of wonder. The salt originates mainly from the cement of the masonry mortar or concrete, and will normally vanish within a few years. If there are bigger humidity leaks within the masonry structure, the salt problems may remain until the humidity problems are solved. (von Konow 2002).

An effect of long-term moisture: moss has grown on the pillar surfaces.

4.5 Repair mortar that is too compact

Cement forms a compact binder paste with water, a gel-like mass that hardens quickly and through which humidity and water pass weakly. This differs from well-hardened lime, which has an open pore structure. Hardened cement mortar is not only compact but inflexible and brittle as well.

Compact repair mortar may damage an old lime mortar, for example when these masonries have been repaired with an overly compact and hard cement mortar. Rainwater does not absorb into the repair mortar, but rather into the lime mortar adjacent to or behind it which has a far greater absorption ability. The space into which water may spread is smaller than before the mortar repair, and greater amounts of water are therefore absorbed into the old lime mortar than the mortar would stand without being damaged. Drying of the masonry also slows when the old mortar has been replaced by a more compact one. Decomposition problems are transferred to the weakest link, the original mortar, which gradually crumbles away.

Cement mortar can also cause tension, for example in old lime plaster, because the moisture expansion

Insufficient maintenance and erroneous mortar solutions cause problems of their own.

Kaj Holmberg

This plastering showed damage already during the first winter. The reasons are still being examined, but may include a very wet autumn or possibly too soft a surface mortar.

A leaky drainpipe has damaged this outer plaster on Turku castle.

Well-built flashings ensure the stability of plaster. The plaster in this picture has been too wet and has come loose as a result of freezing.

of cement mortar is considerably greater than that of lime mortar.

In the 1970s, Parmu mortar was used for repairing masonries. This has only lime as fine aggregate and the binder is wholly cement. Masonry areas pumped with this mortar were called “big stones”. They were believed to form artificial stones inside the masonry in places where the old mortar had decomposed. The aim was to generate a new “bond” between the natural stones. Today it is still unclear whether this mode of repair is good. Many old fortresses, like Raasepori Castle, Olavinlinna and the defensive walls of Suomenlinna, have been repaired with Parmu mortar.

Mortars that include cement have high tensile strength and strong adhesion to their base. This makes their removal difficult, for example when reverting an old repaired structure to its original form. It is especially difficult in old churches to remove this type of repair mortar from the surfaces of plaster painted with lime without damaging the original lime paintings.

4.6 Maintenance of buildings and prevention of damage

Maintenance of historical culturally important buildings and structures is as important as successful repair with good materials. Maintenance inspections should be carried out at roughly five-year intervals. The appearance of damage on the surface of a plaster or crumbling of a masonry joint indicates a problem that needs addressing. Behind the problem may lie damaged drainpipes or eaves, which increase local absorption of rainwater into the wall structure. The problem can also be due to anti-icing salt having penetrated the foundation along with melting snow, or extrinsic materials used for repair whose thermal expansion or moisture conductivity clearly differs from that of the original materials. Differences in thermal expansion may lead to tension and cracking of the structure. A surface that is impermeable to moisture may also cause moisture problems and mould on other surfaces, especially the inner surfaces, of an old building.

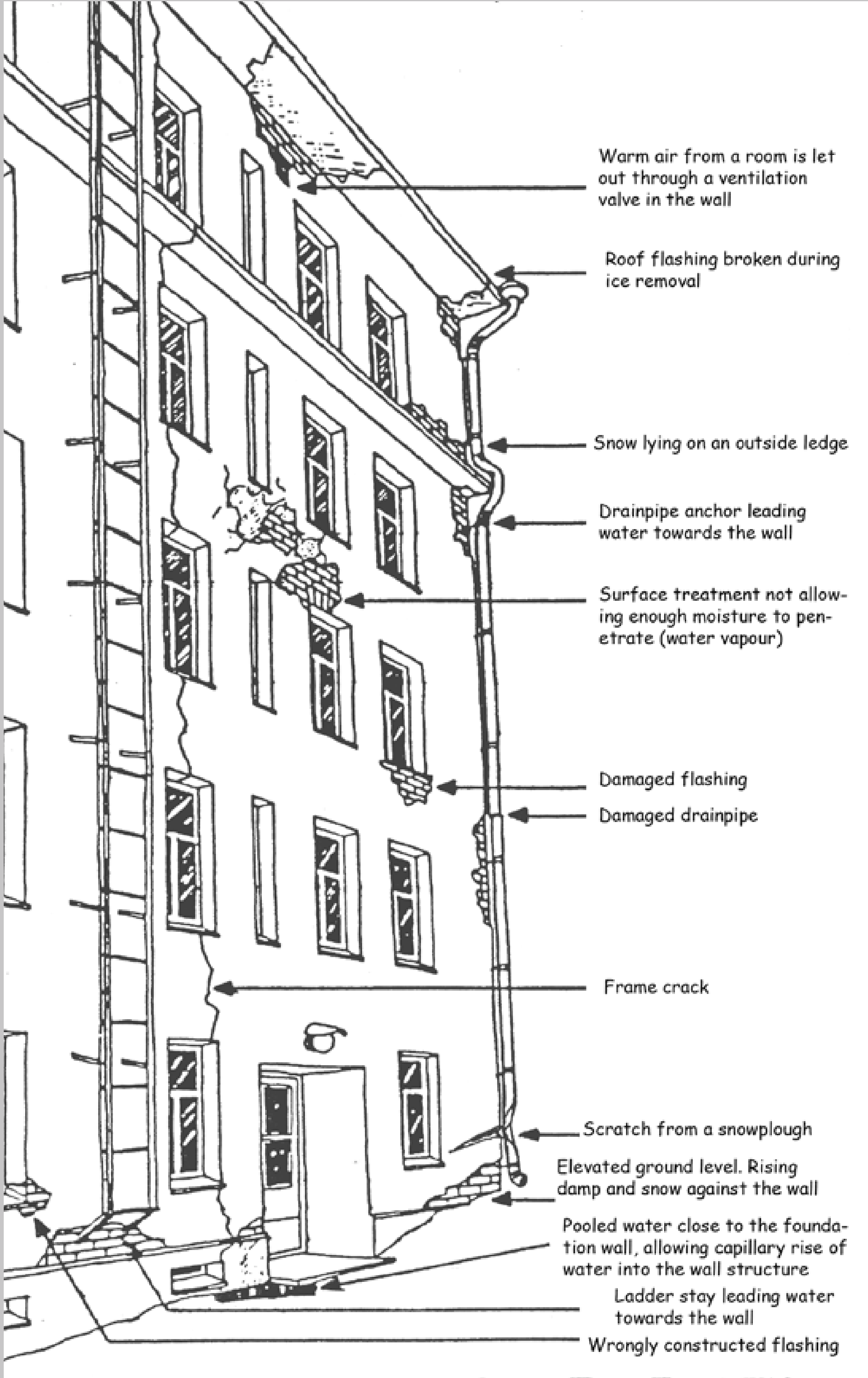
These and many other causes of damage must be recognized during a maintenance inspection, any mistakes corrected, and damaged drain-pipes repaired. A plaster laid when it was too fresh can be damaged locally by the influence of rain and frost. It is worth repairing damaged areas before the trouble spreads. Well-planned and managed maintenance extends the age of a building considerably.

The following illustration, annotated by Erkki Mäkiö, shows the types of damage that can result from inadequate maintenance of façade plaster.

Bibliography, chapter 4:

Mäkiö E., 1990. Rapatun julkisivun kuntoarvio. Suoritusohje. Rakennustietosäätiö.

von Konow, T. (ed.) 2002. The Study of Salt Deterioration Mechanisms. Decay of Brick Walls influenced by interior Climate Changes. European Heritage laboratories – Raphaël 1999. Suomenlinnan hoitokunta ISBN 951-9437-29-0.



Mäkiö E., 1990. Rapatun julkisivun kuntoarvio. Suoritusohje. Rakennustietosäätiö.

5 Making new lime mortars durable

5.1 Problems with lime mortar before the 1990s

In Finland, interest in using old methods to prepare lime for mortar has been somewhat limited. Occasional charcoal firings have been carried out but the properties of the resulting limes have not been examined any further. Nor has there been much interest in developing lime mortars. Industrially produced lime mortar has been, and still is, wet mortar to which cement is added at the worksite. Lime mortar has seldom been used as such in façades. Negative experiences with the weather resistance of lime mortars due to poor composition or working methods have led to attempts at "improving" the mortars with cement. Since the 1960s, mostly lime cement mortars and Parmu mortar have been used for masonry.

However, interest in old true lime mortar has reemerged, appearing first in the Nordic Countries and Great Britain before spreading to other parts of Europe. For example, lime for restoration mortar produced in Scotland has proven to be an excellent lime binder and there is already many years' experience with its use.

Lime fired in an obsolete kiln and slaked in a lime pit or with sand is a fascinating substance. However, preparing lime occasionally according to traditional methods makes its homogeneity uncertain from one firing to the next. The quality of the lime also changes depending on the limestone, firing method or slaking method. By contrast, both a mortar aggregate and its granularity are controllable and changeable.

5.2 Importance of aggregate in mortars

What was known earlier…

The importance of the granularity of aggregate in mortars was studied in the middle of the 20th century. Nycander (1941) saw the importance of filler in the preparation of compact concrete and emphasized that mortars must be porous enough to allow air and humidity to pass through them. He recommended that the amount of filler in compact concrete should be about one third that of sand. In Germany, Piepenburg (1954) studied the granularities of mortar aggregates from Sweden, England, Germany and the USA. At that time the granularity of aggregates in German mortars differed from elsewhere because of its larger proportion of filler and its greater coarseness. Piepenburg considered the fineness of sand important in its role as a filler of empty spaces between bigger granules. Högberg (1963) studied the influence of filler in lime mortars and found that it reduces the amount of mixing water needed, and compacts the mortar if the amount of aggregate is big enough. He also found that in fat mortars with a binder amount exceeding 16% (K 100/500), adding filler had no effect.

In the late 1960s, a Nordic mortar committee laid down recommendations for the grading of aggregate for plastering and masonry mortars. A standard was later developed based on these recommendations.

And what is known today

Sand grains form the frame of the mortar and the binder glues them together. The surface morphology, grain size and shape of the aggregate all have an effect on the contact surfaces formed between the aggregate grains and the binder, and on the distribution of the binder between the sand grains. Mixing-water for mortar is needed to moisten the contact surfaces between the sand grains and binder and to fill the pores formed during mixing. Part of the mortar water evaporates from the surface and part of it is absorbed into the base. As the mortar dries and hardens, empty spaces are easily formed between the binder and the sand grains. These can be filled with binder or fine-grained sand (the filler) with a grain size below 0.07 mm.

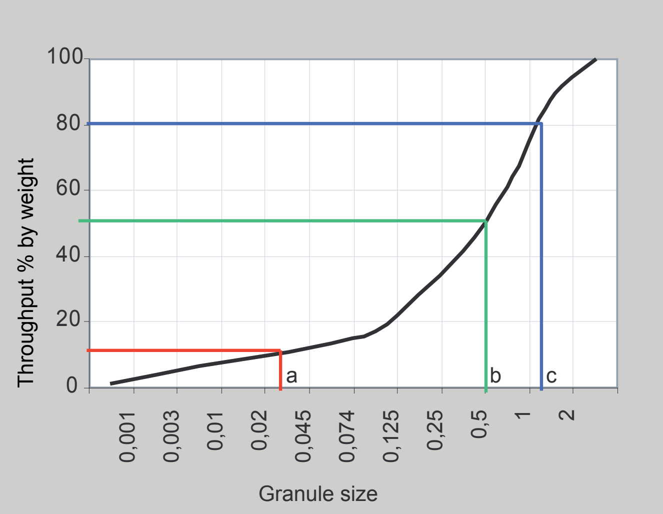
Chapter 4 describes how the porosity of mortars affects their deterioration and especially frost damage. The granularity of the aggregate can be used to modify the pore network of the mortar, for example by reducing unwanted voids. The effects of aggregate distribution on the strength and compactness of concrete have long been exploited in concrete technology, but very little in the design of mortars.

When the maximum and minimum grain sizes of the aggregate are known, its best possible density — the optimum compactness — can be determined with calculation formulae. Such formulae were developed by Andreasen and Furnas in the 1930s (Andreasen

& Andersen 1930) and later modified in line with modern technology.

In my study (von Konow 1997) on the effects of aggregate on lime mortars, the Furnas model was used to proportion 12 aggregate distributions of lime mortars. The aim of the study was to clarify whether the properties — porosity and primarily strength — of lime mortars could be influenced by the mere choice of aggregate and thus improve the poor reputation of lime mortars. Based on the calculations, both good and weak aggregate distributions were obtained. Some of the distributions followed the curve of the aggregate standard; others were well outside it. Some 30 mortar recipes were prepared as a result.

In studies it is difficult to compare the curves with other properties. The aggregate distribution curves must therefore be converted to descriptive numerical values. The aggregate index (AI) has been created for this purpose.



Aggregate index (AI) $$AI = \frac{1}{a} \bullet \frac{(c - b)}{(b - a)}$$

a = grain size at which 10% of the material passed the sieve
b = grain size at which 50% of the material passed the sieve
c = grain size at which 80% of the material passed the sieve

The aggregate index enables the aggregate distributions of test mortars to be calculated with a good enough deviation between values 2.8 and 81 (AI = 2.8 with mortar in which the biggest part of sand is quite coarse, and AI = 81 with mortar that includes filler and some other finer aggregate). The index describes the form of the curve from the smallest grains to the largest, not only the amount of fines.

Sand grades used in my mortar examinations

5.3 Compacting theory in brief

The grain distribution of sand is calculated by an exponential formula that takes into account the maximum and minimum grain size of every chosen sieve opening and mixture. Exponent n is a constant of value 0–1 that describes the curving of the distribution curve from a straight line. As n approaches zero, the distribution curve approaches a straight line; when n is 1, the curving is strongest. If the sand grains are round, their optimal compaction is reached when n is 0.37 (Kronlöf 1994). Because sand grains and binder particles are not round, in practice the value of n is different (0.47 in the studies).

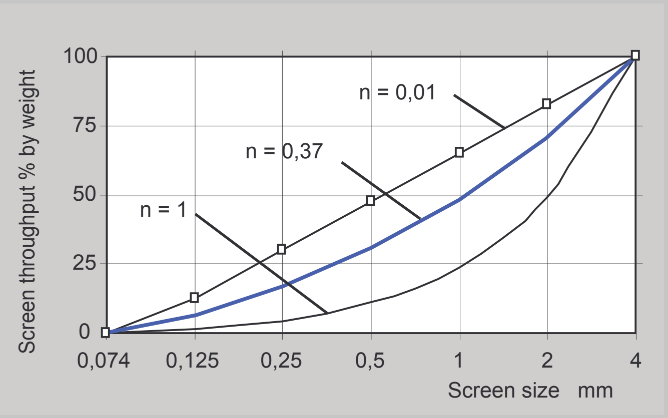
The binder particles also have an influence on compaction. Including the particle distribution of the binder in the calculation formula gives a still more accurate picture of the compaction. When the binder is included in the calculation formula, the curve is called a combined granularity curve.

The aggregate standard curve does not follow the optimal compacting curve. The standard curve ends at grain size 0.075 mm, because the densest sieve for mortar sand is generally of this size. According to the optimal compaction curve, there are a lot of fines less

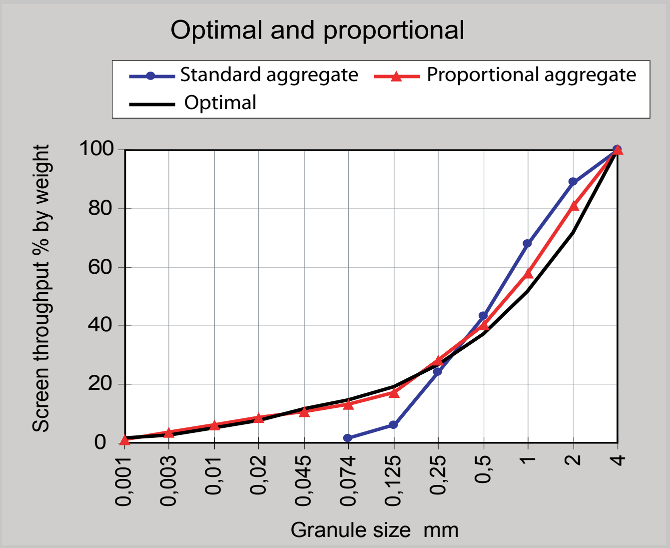
Calculation formula for optimal grain distribution

$$A = \frac{D^n - D_S^n}{D_L^n - D_S^n} \times 100\%$$

A = cumulative % by volume or weight
D = grain size [mm]
D_L = largest grain size [mm]
D_S = smallest grain size [mm]
n = constant describing the shape of the distribution curve



Distribution of grain sizes calculated from the formula for optimal compaction. Three examples of how constant n affects the distribution.



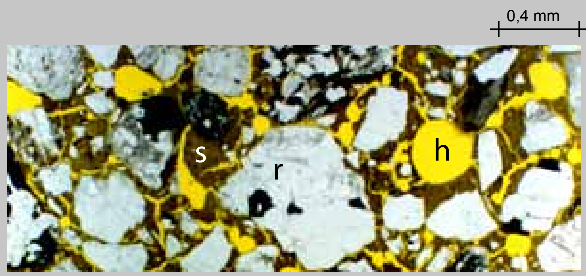
The black curve shows the grain distribution of optimal compaction; the blue curve is the granularity curve of standard sand; the red curve is a well-proportionated granularity curve from the study.

than 0.25 mm in size. In these studies attention has been paid to this finer sand fraction. The finest fractions of all the mortar ingredients had to be screened by laser and the coarser ones with ordinary screens. The grain distribution of the aggregate changed with sands of different coarseness, giving the red granularity curve shown in the figure. Note that this closely follows the optimal curve. All other aggregates in the test mortars were proportioned this way. All the test mortars included the same amount of binder, with only the aggregate ratios changing. Granularity curves were obtained from six sand fractions that differed significantly from each other. Lime and quartz filler were used in most of the mortars.

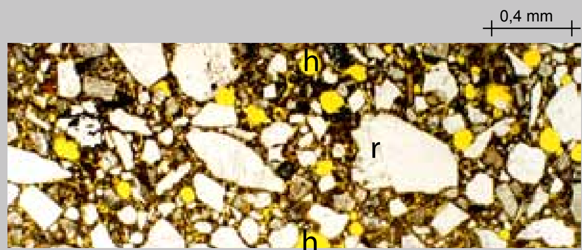
5.4 How do choices of aggregate affect the properties of mortars?

Lime mortars in the study that had the same binder aggregate ratio, i.e. K 100/850, but different aggregate distributions showed very different properties. Low index aggregate distributions had not compacted the mortar at all, showing instead lots of large pores, voids and cracks (upper photomicrograph). The water absorption ability of these mortars was high and the frost resistance very poor. This somewhat disadvantageous aggregate distribution also weakened the strength of the mortar. Conversely, mortar that had a high RI value was densely compacted, its pores were small and round, and there were only a few cracks, which were quite short (lower photomicrograph).

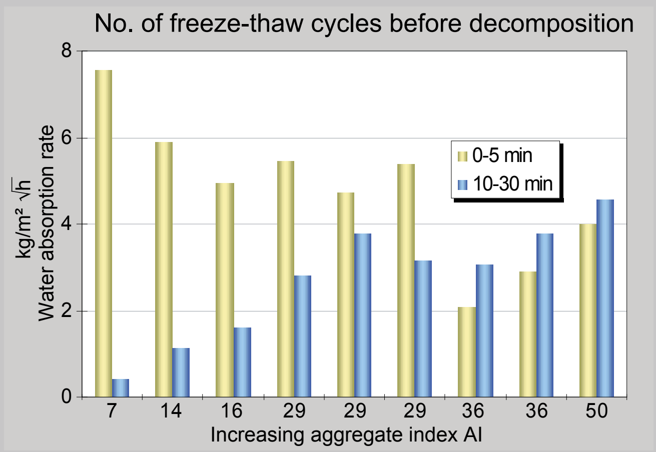
Measurement of the water absorption ability of mortars is a simple way to acquire information about the porosity of the mortar. The bar graph shows the capillarity values of test lime mortars indicating how much water the mortars have absorbed in 0–5 minutes (yellow) and 10–30 minutes (blue). The aggregate index



Photomicrograph of a mortar with a low aggregate index. Large pores and cracks are visible. Magnification x4, //-nicol.



Photomicrograph of a mortar with a high aggregate index. The mortar includes small round pores and its microstructure is compact. Magnification x4, //-nicol.



Effect of the aggregate index of mortars on water absorption rate and frost resistance. The columns represent the water absorption rate during 0–5 and 10–30 minutes. The numbers at the top indicate the frost resistance (No. of freeze-thaw cycles). The aggregate index (AI) increases from left to right.

of the mortars increases from left to right. The figures at the top indicate the number of freeze-thaw cycles the mortar samples underwent before decomposing.

The far left column shows the results for a mortar with a low aggregate index and no fine aggregate. The mortar absorbed water quickly during the first few minutes (tall yellow column) and almost nothing after 10 minutes. This indicates the presence of large open pores that filled rapidly with water. This mortar quickly suffered damage in the presence of frost, succumbing after seven freeze-thaw cycles. Mortars with a high AI value (60), on the right side of the graph, behaved differently. They started by absorbing water slowly and less than the mortars on the left, but after 10 minutes the absorption accelerated (tall blue columns). This indicates lots of small pores that absorbed water slowly but over a longer period of time. The frost resistance of these mortars was quite good, enabling them to undergo 36–50 freeze-thaw cycles without damage.

This kind of water absorption ability test is quick to perform and gives preliminary information about the porosity of the mortar and its pore size within half an hour.

5.5 Advantages of aggregate proportioning

One way to strengthen lime mortars is to choose the correct aggregate ratio. Strengthened and compacted lime mortar is neither harder nor more compact than good old lime mortar that has a random aggregate distribution, but its weather resistance is better. It is difficult to mix different sand grades for mortar on site, and the accuracy of measurement is questionable. This is a principle reason behind the advent of ready-mix sand mixtures available from mortar plants. The aggregate ratios of these mixtures are tailored to each restoration object.

Aggregate proportioning enables mortars to be designed with different properties. This is important in the conservation of old lime mortars where the aim is to preserve them (these are mostly plaster mortars). If a plaster in very poor condition has to be repaired with a new one, the water absorption of the repair mortar should preferably be such that rain-water directed towards the plaster is absorbed by the repair mortar rather than by the original plaster surface. Particularly well-designed repair mortars are a must for painted plasters (frescoes and al secco paintings) in old churches. The repair mortar must both support and fix the old plaster surface without affecting the movement of moisture within the wall surface.

Aggregate proportioning is the best way to influence the properties of lean mortars. In fat mortars the grain size distribution is less important.

The binder-aggregate ratio of old lime mortars varied a lot: volumetric ratio 1:1–1:3 and weight ratio 100/250–100/800.

Today, very fat lime mortar is not produced because
1) It shrinks more than lean mortar when drying
2) Hardening is slow (high amount of carbonating binder)
3) Its workability is difficult to control with modern technology.

Kari Helenius stands beside a pile of crushed, screened sand in Tervakoski. To find a suitable aggregate can be laborious. Often, sands with different grain sizes have to be mixed to give the desired aggregate distribution. Ideally, ready-proportioned factory-made sand mixtures would be available in which the finest aggregate (grain size less than 0.075 mm) has been screened by laser or wind sieve.

Lean lime mortar

Lime 100 parts by weight
Aggregate more the 600 parts by weight

Fat lime mortar

Lime 100 parts by weight
Aggregate less than 500 parts by weight

Bibliography, chapter 5:

Andreasen, A. & Andersen, J. 1930, Über die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten aus losen Körnern. Kolloid-Zeitschrift 50/3, p. 217–228.

Högberg, E. 1963, Sandgradering och bruksproportionering. Puts- och murbrukslaboratoriet. 29. maj 1963. Intern rapport till Nordiska putsmötet.

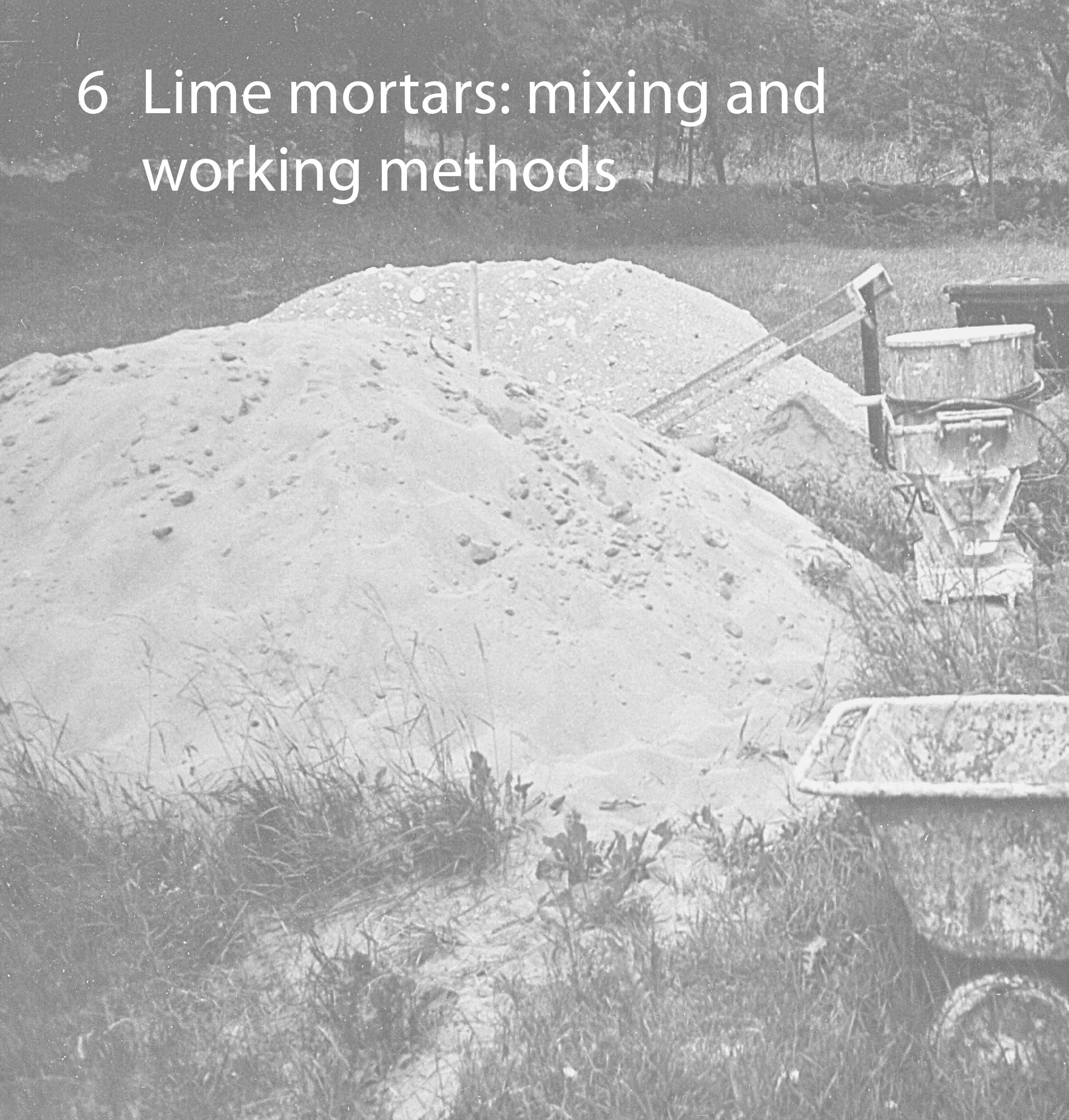
von Konow, T. 1997, Restaurering och reparation med puts- och mur-bruk. Doctoral thesis, Åbo Akademi.

Kronlöf, A. 1994, Effect of very fine aggregate on concrete strength. RILEM, Materials and Structures vol. 27, p. 15–25.

Nycander, S. 1941, Provputsningar i samband med Södersjukhusets uppförande och de resultat, som därvid erhållits i samarbete med Cementföreningen och några av de större murbruksfabrikerna i Stockholm. – Teknisk Tidskrift 22 nov., p. 162–176.

Piepenburg, W. 1954, So macht man guten Putz. Bauverlag Gmbh, Wiesbaden–Berlin.

6 Lime mortars: mixing and working methods



6.1 The mason is critical to the success of mortar repair

Restoration mortars made from good raw materials, detailed working instructions, and good weather conditions are not enough to guarantee a good final result. The actual restoration or repair work is done by a mason or plasterer, and at the end of the day it is his professional skills, motivation and interest in the work that will determine the durability and functionality of the restored object. Below is a look at mixing instructions and working methods for lime mortars, which differ from working methods of lime cement mortars familiar to many skilled workers.

6.2 Lime binder

Burned and slaked lime used as binder in mortar can be good quality pit lime (about 3 years in the pit) or dry lime hydrate (building lime). Wet lime is prepared from lime hydrate by mixing with water, and is left to brew for 2-3 months before use. Factory-mixed lime mortars have also been used, either wet or dry. The granularity of the aggregate must follow the granularity curve corresponding to the purpose of use of the mortar (see chapter 5).

6.3 Mixing

Mistakes can be made already in the mixing phase, the commonest being that too much water is added to the mortar or that the lime putty is too wet.

Restoration mortars for Suomenlinna are mixed, almost without exception, from more ingredients. For the mortar to function as desired it is very important that these ingredients are carefully mixed. Small amounts can be mixed with a drill mixing paddle in the mortar container. Bigger amounts are mixed with a vertical-shaft mixer. A concrete mixer that only drops "mud" while rotating is not suitable for lime mortars. During the mixing phase all the dry ingredients of the mortar, like hydraulic lime, filler and sand, must be moistened well to ensure the presence of a water film around the tiniest granules. In wet lime the extra water moistens the dry ingredients. Mixing the ingredients for too short a time or with an ineffective mixer may cause some of the dry ingredients to cake together or the mortar mass to be inhomogeneous.

6.4 Colour shade

Mortar derives its colour shade mainly from the binder and fine aggregate. Thus the shade of a light-coloured lime mortar can be altered with the choice of sand colour or brick powder. The surface of old mortar joints often has a patina caused by air pollution and/or moss. Adding pigment (e.g. iron oxide pigments like green, yellow or brown, or earth pigments like umber, ochre or burnt umber) makes it possible to match the repaired surface to the old one.

It should be noted that in mortar that has not brewed long enough, the binder will try to rise to the surface

Preparation of wet lime

Slaked lime*) (dry)	40 kg	(1 bag)
Water	58 l	

The ingredients are mixed well and left to stand in a sealed plastic vessel for at least 2 months before use.

The mixture keeps for several months above +5°C.

*) Lime SL 90T

Mixing of mortar

First, the dry ingredients are mixed together. About one quarter of the sand is put aside to be added last. Next, wet lime and enough water are added to make the mortar quite soft and easy to mix. Mixing should be done carefully for 10–15 minutes. Finally, the rest of the sand is added and mixing is continued for about 10 minutes. The mortar stiffens and is then ready for plastering.

Screening of sand and mixing of mortar with a vertical-shaft mixer..

during the working phase. Thus, regardless of the shade of the stone material or pigments, the result may be a light mortar surface.

6.5 Properties of fresh lime mortar

Lime binder has the ability to bind lots of water. It has a good composition, i.e. good water retention capacity, when water does not rise to the surface of the mortar in the tub. In this kind of mortar, all the aggregate granules are coated with lime binder, and lime and filler fill all the voids in between. All the properties of dry lime mortar improve considerably if the mortar is allowed to brew, i.e. stand, mixed in water for a couple of months before use. In Scotland all lime mortars, including those made from lime putty, are allowed to stand wet for at least 3 months before use. Wet lime mortar becomes compact and stiff during a prolonged standing period, but its plasticity can be restored without adding water by mixing before use or knocking up with a mason's hoe in a wide tub.

Since the 1960s we have grown used to lime cement mortars that can be applied by throwing or spraying. Using a soft lime mortar weakens the microstructure as the mortar sets, and large voids and crack develop after drying.

Dry mortars meant for pumping often include an additive, which reduces the need of water but increases slipperiness and workability. Lime mortars function in a different way. Lime itself is very slippery and its workability is good without additives. For example, deep fill mortar used in the repairs of Suomenlinna masonries extrudes well through a pump even when relatively stiff. In other words, mortar additives are not needed for good pumping, but a long mixing time is, coupled with lime as a binder together with hydraulic binder and good granule distribution of the aggregate.

In the 19th century plaster mortar was quite stiff and was shovelled onto the wall rather than slapped on, as is frequently done nowadays.

This mortar has cured long enough and the mason has worked it well before use. A mortar must be stiff enough to cling to an inverted trowel or shovel and slide off when turned sideways.

6.6 Plastering and finishing

Three-layer plastering is a relatively new method that has become more common for façades masoned from lime sand bricks. Mortar adheres clearly more weakly to smooth lime sand brick than to burnt brick, thus the former requires a bedding mortar, which is very rich in cement and creates good adhesion to the filling mortar. On a façade masoned from burnt brick, plaster mortar adheres without the need for a bedding mortar. Old lime plasters were applied in one or two coats without a separate adhesion surface. Both layers were usually of a similar mortar and the aggregate of the surface plastering was usually fine structured.

The base to be plastered or masoned must be clean –always. There should not be any old paint, sand or dirt. If the repair mortar is applied to old paint or to a poorly cleaned surface, its adhesion will be poor.

Working and finishing

Finishing the plaster surface has also proven to be problematic. A lime mortar surface can be worked when it has reached its initial strength, contrary to lime cement mortar, which has to be worked while still wet. Rapid hydration of cement stiffens the mortar; thus to get a mortar to adhere to the next layer and avoid cracks, a stiffened lime cement mortar should no longer be floated. The binder of a lime mortar hardens so slowly through carbonation that its surface can be worked hours (sometimes even days) after application. The time needed for hardening depends on the temperature, wind and composition of the mortar. If the surface is finished too early, the roughest aggregate continues rotating and scratching the surface, forming a binder film on it. Likewise, adhesion of a thin surface mortar to its base can weaken and the porosity of the surface mortar can remain too high.

The right time for floating a lime mortar is estimated on site. It is better to wait too long than not enough. The surface mortar is floated and pressed smooth with a suitable trowel. Thus the surface mortar compacts, small cracks are pressed closed, and the plaster will be durable, with no binder film rising to the surface once the plaster has obtained its initial strength.

6.7 At what time of year can one plaster with lime mortars?

The season during which outside plastering can be done without protection of the façade is short in the Nordic Countries. Fresh, wet plaster applied in late summer or during the autumn withstands frost very poorly. The best season for plastering with lime mortar is spring, as soon as the temperature stays above 7°C. The plaster then has time to harden through carbonation for few months before the onset of frosty weather. If plastering has to be postponed until the end of the summer, it is advisable to protect the façade with tarpaulin so that at least the autumn rain will not make it wet. Fortunately, it is now common practice to protect façades from the elements during plastering.

Without protection bad things can happen, such as windy weather drying the mortar and lowering the surface temperature. Sunshine can raise the temperature of masonry to be plastered or pointed to as high as 40°C, causing the mortar to dry especially fast with inevitable cracking.

6.8 Moistening of mortar surfaces and after-treatment

All fresh lime mortar surfaces need moisture during the hardening phase, but they need not be soaking wet. An absorbing old brick surface should be moistened well before plastering or masoning. In damp weather, natural stone surfaces and hard burnt brick surfaces do not need moistening. If moistening of an absorbing base is neglected, it will absorb water otherwise needed for carbonation and/or hydration of the binder. Conversely, if the surfaces are too wet a film of water will remain in the mortar-base interface, preventing the mortar from adhering.

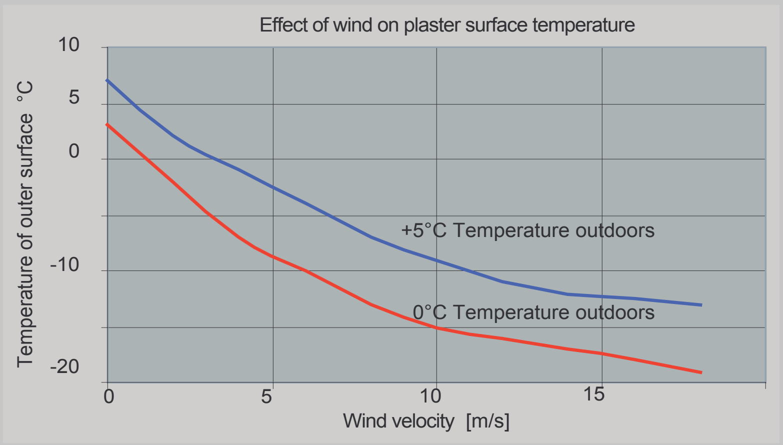
Surface mortar on plasterwork; maximum sand grain size 1.5 mm.

Surface mortar, maximum sand grain size less than 1 mm.

Bedding mortar.

Finishing.

Plastered surfaces



An outer wall plastered in windy weather dries faster and experiences a falling surface temperature. At an outside temperature of +5°C in calm weather, the temperature of the plastered outer surface is about +7°C. At the same outside temperature but with a wind velocity of 10 m/s, the temperature of the outer surface drops to -10°C.

Moistening of a plaster is a precise task. A plaster made from lime mortar has to dry occasionally to allow carbon dioxide from the air (essential for hardening reaction of the mortar) to penetrate its pores. A plaster that is too dry will not absorb carbon dioxide at all. If the mortar dries too fast there is a danger of drying shrinkage and cracking, adhesion to a natural stone surface or plastering base can fail, or the mortar can decompose like puff pastry if the binder does not harden.

Jute cloth is very well suited to the protection of plastered surfaces from overly fast drying indoors, where the atmospheric moisture can be low. The cloth is fixed to the upper part of the wall, letting it hang freely over the fresh plaster. Spraying the cloth with water is sufficient to moisten the mortar surface over the weekend or overnight in warm conditions. Because the upper surfaces of walls dry faster than lower down, jute cloths are wetted more at the top. Plastic tarp is another solution but it must hang far enough from the lime plaster surface to allow circulation of air.

6.9 Painting of lime plaster surfaces

What paint could be more suitable for painting the lime plasters of old façades than lime paint! If it was painted with lime when the building was young, it should be painted with lime now. If it worked then, there is no reason to change the tradition now. Lime paint ages naturally through wear and tear. When necessary it is easy to paint over. The plasters that cause problems are those that were later covered with organic paint; lime paint will not adhere to them. If the old plaster is in good shape, it is worth trying to remove the organic paint with e.g. careful wet sandblasting. This method allows softer limestone powder to be used instead of blasting sand. However, paint removal is not worth doing if the surface of the plaster becomes damaged.

Lime paint can be made from pit lime. Dry lime that has matured in water for at least 3 months can also be used as binder. This kind of lime is slightly yellowish if iron is present. Lime paint is painted on thinly, usually three to four times, but there is no universal rule on the number of coats. Lime paint is diluted with limewater.

Lime paint requires a plaster base well moistened with water. All subsequent paint treatments require a moistened surface.

Earth pigments are the most suitable way of tinting lime paint. The pigments must be both light and alkali-resistant, because lime paint is very alkaline when fresh. The pigments are left to soak in lime water for a few days before use. The maximum amount of pigment that can be used is 7–10% by weight of the amount of lime putty. Tinting is done to the paint used for the last treatment; other paints are diluted from this. The shade of a wall painted with lime can be deepened by spreading bright limewater or limewater tinted with pigment on the surface.

Industrial lime paints are available ready tinted. Industrial lime paint often includes thickening agents or lime filler, which give it better coverage than paint made from lime putty. In England and Scotland, industrial lime paint is called ‘lime paint’ and paint made from lime putty is called ‘lime wash’ in reference to its thin consistency.

6.10 What a good mason takes into account when plastering an old façade

A good mason is proud of his craft. He understands the capricious nature of mortar and how to respond to it. He is satisfied with his own construction and takes good care of it from start to finish.

Mixing

- ✓ The mason keeps the mortar tub, mixing vessel and measuring vessels clean at all times.
- ✓ At the worksite he ensures that all the ingredients of the mortar are protected from wind and rain.
- ✓ He uses accurate measuring vessels for dosage of the mortar ingredients.
- ✓ He mixes the ingredients in the right order, starting with the dry substances and then the wet lime.
- ✓ He determines the right mixing and working time to ensure the right plasticity for each object.

Wetting the base

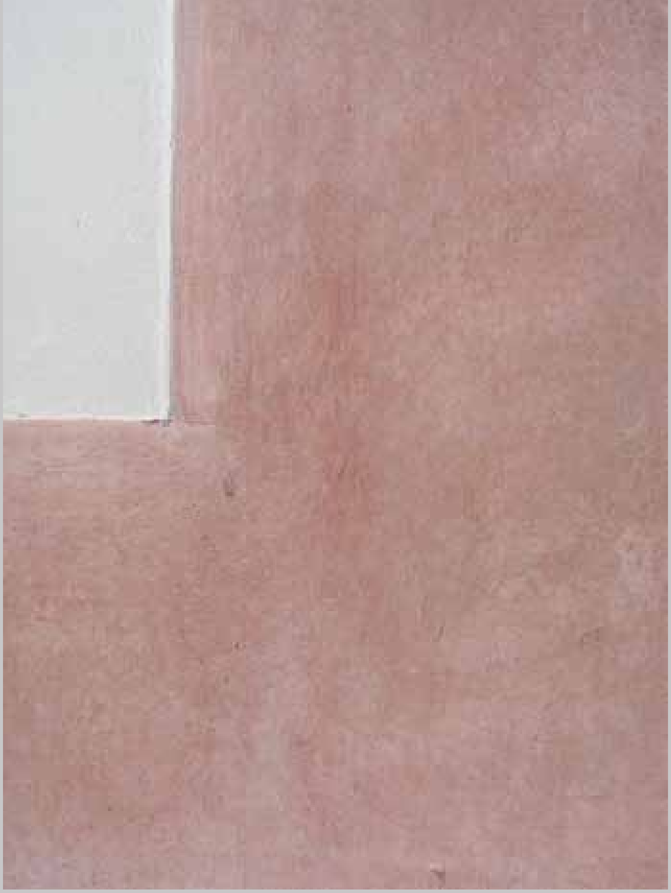
- ✓ A good mason is aware that a poorly absorbing base requires a drier mortar than a strongly absorbing one.
- ✓ He moistens the base sufficiently when needed and observes its absorbing capacity.
- ✓ He understands the effect of weather on drying of the base and plaster layers – windy weather dries things faster than warm weather.

Plastering

- ✓ A good mason knows that lean mortars are more sensitive to the addition of water than fatter ones.
- ✓ He adds water carefully to the mortar. Excess water weakens the adhesion and forms large voids in the hardened plaster, weakening its weather resistance.
- ✓ He uses bedding mortar if the absorbing capacity of the base requires stabilizing, or if there are stones or surfaces of very different qualities in the base.
- ✓ He applies thick plasterwork in more layers to avoid shrinkage cracking.
- ✓ He gives the latest coat of mortar a couple of days to set before adding the next one.
- ✓ He correctly estimates the required texture of the filler mortar from the thickness of the original plasterwork.
- ✓ He lays the filler mortar evenly with the old plasterwork without the need for abrasion.
- ✓ He knows that finishing of the plaster surface is crucial to the success of the project.
- ✓ He waits for the right moment to float the surface plaster, i.e. when the lime mortar has obtained its initial strength and set. This ensures that no binder film will form during the floating phase.
- ✓ He uses a wooden or plastic trowel for floating, allowing him to press the mortar flat and compactly.
- ✓ If shrinkage cracks have formed he closes them by pressing with the trowel.

Moistening

- ✓ The mason uses a water spray for moistening the plaster surfaces, including intermediate layers. He remembers to protect the surface from drying over the weekend.
- ✓ He takes into account that on dry, windy days moistening is necessary, while on rainy, windless days it can be skipped.



Merja Nieminen

Close-up of a plasterwork painted with lime. Thin paint treatments make the surface transparent. Clear or pigmented lime water treatment increases the depth and shade of the paint surface. Plasterwork coated with synthetic paint is uniformly toned and lifeless.

Preparation of lime water

15 litres (20 kg) lime putty is mixed in 100 litres of water.
This is mixed and the lime is left to deposit for one day. The clear solution formed on top is lime water, which is carefully poured from the mixing vessel. The same lime putty can be used to prepare lime water about four times.

Lime paint treatment (suggested proportions)

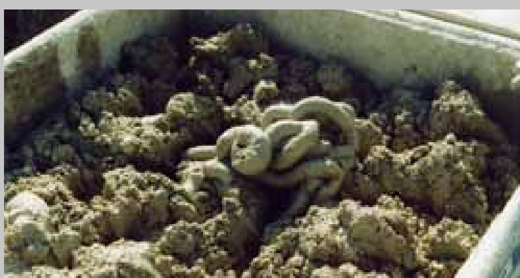
	Base treatment	1st (and 2nd) treatment	Surface treatment
% by volume of lime paint	*15*	*20*	*25–30*
Lime putty (litres)	3	4	5–6
Lime water (litres)	20	20	20

15% tinted paint is obtained by adding 20 litres of lime water to 26 litres (30%) of surface treatment paint.
20% tinted paint is obtained by adding 10 litres of lime water to 26 litres (30%) of surface treatment paint.
Lime putty for use in very light shaded or totally white lime paints should be totally white. (Nordkalk Oy supplies Norwegian white burned lime)

In earlier times iron sulphate (vitriol) was used as pigment in lime paint. The shade of a wet paint with this pigment is initially green, but upon reaction with oxygen in the air it changes to orange due to the formation of iron oxide, which can darken considerably over time. A lime paint surface containing this pigment can cause difficulties when it is repainted.

In Scotland, lime mortar for restoration work is mixed with great care. Stone aggregate and lime putty are mixed in a breaker (pan mixer) with large metallic wheels (roller pan mill). Binder and aggregate are thus mixed efficiently into a homogeneous mass. These mixers have not been used in Finland to date.

Knocking up a mortar that has matured for 3 months before use. (Historic Scotland 1995.)



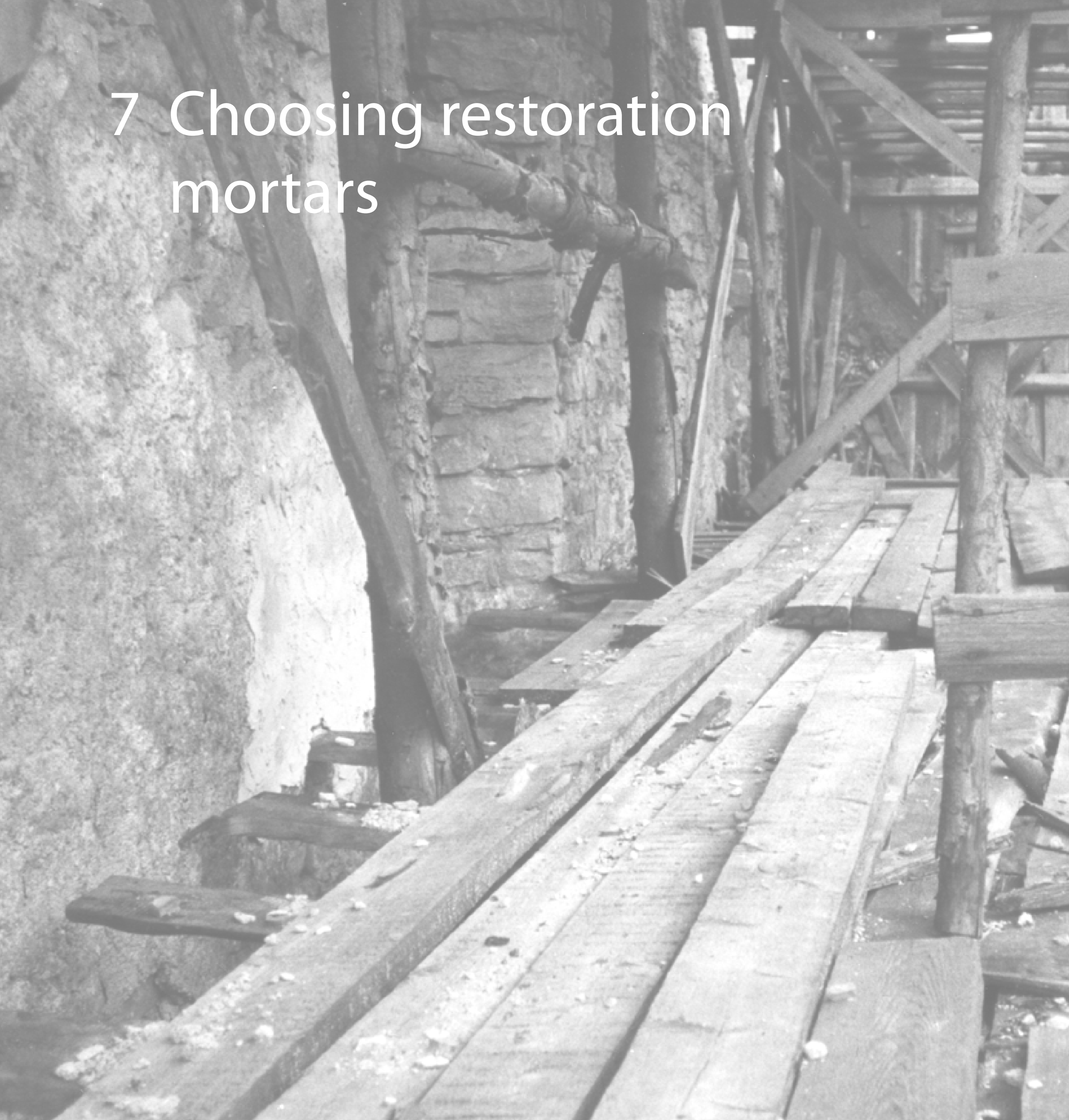
Deep fill mortar (hydraulic lime mortar) for natural stone masonries on Suomenlinna is stiffer than the normally used pumping mortar. The sausage-like mortar on top is straight from the pump.

Washing of masonry from a deep fill mortar is easy because of the hydraulic lime, which hardens more slowly than cement. Stiffer mortar also dirties the masonries less.

Tommi Vilkanen

Jute cloth protects fresh plaster from drying too fast. The upper part is wetted more because the plaster usually dries faster higher up.

7 Choosing restoration mortars



7.1 How can knowledge about old mortars be put to use when choosing a repair mortar?

An old plaster surface is the aspect of a masonry structure that most vividly reveals the hand of the craftsman. Connecting to this craftsmanship can be a profound experience, although the mortar itself is a coarse and mostly replaceable part of the masonry structure. An original mortar in joints or plasterwork that has lasted to the present day must have been an outstanding mortar that was able to withstand the onslaughts of wind, rain and frost for centuries — kudos to the old masters. Old mortars have one significant advantage over modern ones — time. Lime mortars created by the old masters have been allowed to carbonate in peace for decades or even centuries.

A repair mortar must age at the same pace as the old mortars of the masonry, and it must be removable without damage to the surrounding surface. The most natural repair mortar is lime mortar, but what kind?

In principal one should try to copy the composition of an old mortar, but in practice, making a mortar like the original one is not possible. Analysis of the mortar only tells part of the story, and the analysis itself can be a source of error. The ratio of the binder and aggregate can be determined by chemical analysis, as can the hydraulic ingredients, but it is more difficult to recognize whether the latter are cement, hydraulic lime or cinder (chapter 2).

Unless documents are available that relate in detail how the original limestone was burnt and slaked, it is impossible to determine by analysis alone how the lime binder in a mortar was prepared. There is no way of knowing how the mortar was worked, with what tools and for how long. In the case of plasterwork, it is difficult if not impossible to tell what techniques were used to apply the mortar to the wall. It is equally impossible to ascertain the circumstances and conditions that prevailed at the time. The type of preparation, working methods and hardening circumstances all combine to affect the structure, porosity and durability of the mortar. Additionally, the long period of time over which the binder has dissolved, crystallized and transformed makes determination of the composition of the original fresh mortar even harder.

A repair mortar is always made from fresh, raw materials. Is there any sense, therefore, in trying to imitate an old mortar when the task of a repair mortar is simply to repair and support the damaged structure and prevent the damage from spreading? Technically, a repair mortar is best when it is not so hard and compact that it damages the old mortar but not so weak that it succumbs to weather stress.

A fresh lime binder-based restoration mortar is almost always weaker than an old, well-hardened lime mortar. The binder of the old plaster may have undergone some recrystallization (see chapter 1); this

Historical and technical aspects of choosing a mortar

Historical and aesthetical aspects

- Age and historical value of the building to be restored
- Classification of the building (object to be protected)
- Need for repair: preserving the old mortar and patching with new mortar

Old mortar to be replaced

- Age (from which period)
- Appearance: shade, roughness of the surface, colour of the aggregate
- Working method

Technical aspects

- Condition of, and extent of damage to, the building
- Location of the building: severe or mild climatic conditions
- Moisture sources causing damage: can they be eliminated?
- Type and condition of the old mortar
- More accurate analysis: base, other mortar repairs, micro-environment

kind of mortar may have compacted and changed over the years to be as strong as limestone.

In order for the new restoration mortar to attain the same strength as the old one, it will require as many recrystallization processes as the old mortar has undergone. Can we wait that long, or should the repair mortars be made a bit stronger to start with?

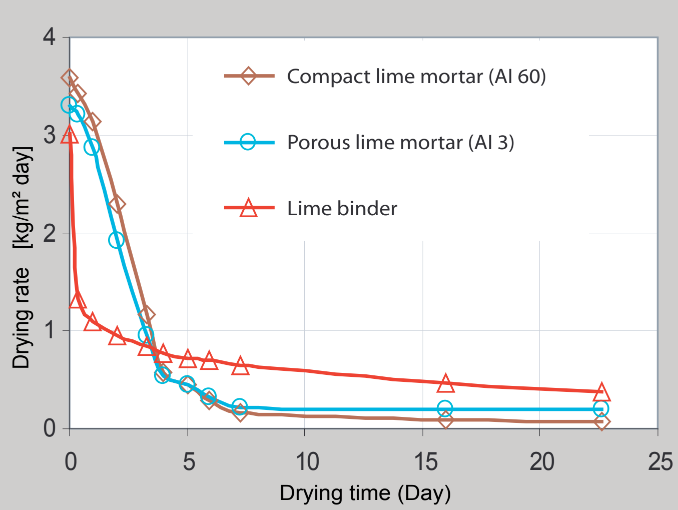
Not all old mortars have undergone recrystallization; weak ones also exist, particularly indoors where they have been protected from moisture.

Too weak a repair mortar can cause damage to old plaster if it needs replacing too soon. In the 1980s and 1990s, lime mortar that was so weak that it suffered damage within a few years was called "sacrificial mortar", which took the hit in order to preserve the old mortar or base. Because every repair also destroys something old, the question arises as to how much benefit there is to a repair mortar whose task it is to decompose.
In special cases where original plasters can be protected by new ones, a sacrificial mortar is a viable solution.

7.2 Restoration mortar: compact or permeable, weak or strong?

One ground rule of restoration is that a repair mortar must not be stronger or more compact than the old mortar next to it. Compact lime mortars are generally expected to dry more slowly than porous ones, and there is concern that they stop the movement of moisture within the masonry. This is important, because outdoor plaster and masonry mortars have to dry fast enough to avert exposure to excessive stress during the winter.

Compactness and drying of lime mortars



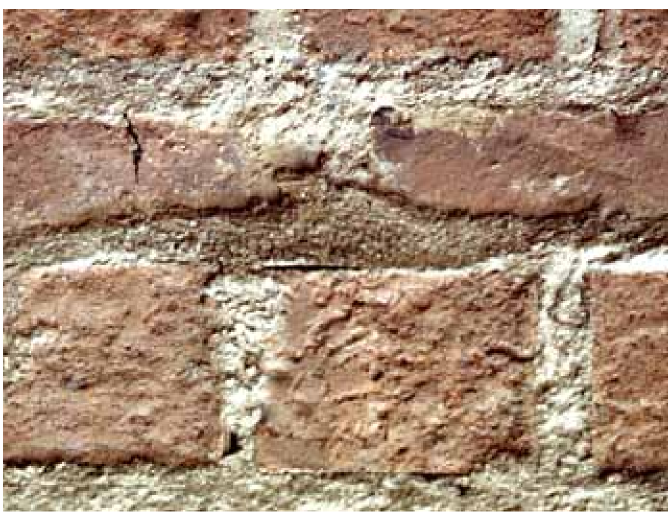
In the figure above there are major differences in the porosity and strength of the lime mortars because of the different aggregates used (aggregate index AI, see chapter 5). However, the test mortars dry equally fast. In 8 hours almost 70% of the moisture has left the mortars, the rest evaporating in about 20 days. Drying of these mortars is slower in the beginning than that of lime (lime binder) (there is only binder in the sample and no aggregate). If the whole drying period is taken into account, mortars dry faster than lime. In other words, the binder in the mortar determines the drying rate independently of the compacting influence of the aggregate.

Lime mortar without organic, synthetic additives does not in any way prevent the masonry structure from drying; there is only a marginal difference in the drying rate. Although the water absorption rate of a mortar depends on its compactness, differences in compactness between lime mortars do not influence the drying rate.

7.3 Restoration mortar and hydraulic substances

Disadvantages of hydraulic substances

Cement in the form of hardened binder has a wholly different microporosity to that of lime, and is considerably more compact. Because of this, addition of cement (more than half of the amount of binder) slows down the drying of a mortar. Also compared to lime, the development of strength of cement is fast and significant, which can lead to problems in old masonries with old lime mortars. Water-soluble salts from the cement and hydroxide formed during the hardening process not only form blooms on the brick surface, but also add to the quantity of salt in the masonries. Water-soluble salts are hydroscopic, i.e. they bind moisture from the air, thus increasing the moisture of the masonry structure. Water-soluble salts can cause major damage to lime paintings and decompose weak bricks.



Parmu mortar used to repair the brick masonry of Häme castle was too hard for the old handmade bricks, resulting in breakage.

Benefits of hydraulic substances

Cement adds strength to structures where the strength of lime mortar is not enough. Hydraulic lime (natural hydraulic lime NHL) does not have the same detrimental features as cement, rather the opposite. It gives lime mortar more strength and durability, but its hardening rate is relatively slow and the final strength only half that of cement (strength depends on the type of hydraulic lime). Hydraulic lime does not include water-soluble salts, and the hydroxide formed is less than one third that produced with cement.

When should one use hydraulic lime or cement?

Adding hydraulic lime or cement to a lime mortar is necessary when repairing natural stone masonries. In brick masonry, which absorbs well, pure lime plaster can keep well in very difficult weather conditions such as on the coast. Conversely, if the base absorbs moisture poorly or not at all, as in the case of natural stone masonry, rain-water and humidity in the sea air stay within the plaster. Mortar with a hydraulic additive

The ashlar façade masonry of Pori town hall (1895) has been repaired with a cement plaster mortar. The composition of the original cement is close to that of natural cement or hydraulic lime. For repairing very old cement plaster, a mortar that includes hydraulic lime as binder is suitable, such as NHL5, or natural cement.

hardens faster than lime mortar and also withstands moisture better. Deep fillings are best done with hydraulic mortar, because the carbon dioxide needed for hardening of the lime has difficultly penetrating deep into the masonry. Hydraulic lime also hardens under the influence of carbon dioxide in air.

However, if for some reason it is considered desirable to use cement instead of hydraulic lime, one should remember that in lime mortar less cement is needed than hydraulic lime. It is also worth remembering that lime cement mortar always hardens faster than mortar in which the binder is composed of lime and hydraulic lime. A maximum of 30% by weight of cement, preferably less, of the amount of binder can be used in plaster mortar. A larger amount of cement changes the nature of the mortar. The influence of cement on the mortar becomes dominant and can cause problems in a weak masonry structure. The use of cement can be justified in plasterwork that is close to the ground.

Cement mortar was already used in plasterwork back in the late 19th and early 20th centuries. The best binder for restoration of these plasterworks is not necessarily Portland cement, because modern cement differs from old cement both in mineral composition and granularity; hydraulic lime or natural cement is a better binder for this type of repair.

7.4 Examples of restoration mortar selection

Universal recommendations cannot be given for choosing suitable repair mortars, because the choice is based specifically on the restoration object itself, its surroundings, and the ambient conditions. One such example is Joensuu manor, where mortars were specially selected for plaster repair of the log walls as illustrated on the following pages. Another example is fixing an old lime plaster with injection mortar in order to conserve it. The selection criteria in two example cases are listed in the table at the end of this chapter. They are based on the location and shape of the object, type of damage, composition of the old mortar, and problems specific to the area under repair. The first example (Object 1) is a plastered house in Suomenlinna. The second (Object 2) is an old lime plaster to be fixed with injection mortar.

Chapter 8 takes a closer look at some of the restoration work on Suomenlinna, where different mortars have been used on various sites in recent years.

7.5 Recommendations for selecting a restoration mortar

Every part of the masonry and every plastered surface of an old building has its unique problems and its own mortar composition. These problems and the damage to the building require study, and the mortars require analysis. Based on the results, restoration mortars specific to each building can be planned. The researcher and planner should have the possibility to study in depth the special characteristics and repair possibilities of the object before drafting a repair plan. It is not recommended to copy the repair work specification and its mortar formula from another object.

Some shared properties can, however, be expected from all restoration mortars:

– Frost resistance (when used outdoors)

– Workability

– The right type of binder composition

– Modifiable appearance so as to resemble the old mortar.

A restoration mortar to be used outdoors must be sufficiently ***frost-resistant***. This is the most difficult qualification for a lime mortar, but not impossible. The frost resistance can be influenced by e.g. the granularity distribution of the aggregate (see chapter 5 for more detail).

The frost resistance of fat mortars (mortars with a lot of binder) depends on the carbonation rate of the mortar, quality of the binder and coat thickness. Frost resistance is also substantially influenced by the professional skills of the plasterer or mason.

There should be no problems with the ***workability*** of the mortar, and the mortar should also function as stiff mortar.

The chemical ***composition*** of the mortar, i.e. binder type, must be similar to that of the mortar to be conserved. Certain quality requirements should be compiled for lime binder, lime hydrate (preferably as wet lime) and pit lime, but unfortunately this has yet to be done. The quality of the hydraulic lime, i.e. the strength class, must also be verified, as there are several grades of hydraulic lime.

Additives like plasticizers, dispersing agents and pore-forming agents should be avoided. Dosing them correctly is also difficult on site. There might be additives in industrially prepared lime mortar or hydraulic lime mortar. They must not cause salt formation, must not act hydrophobically in hydrophilic parts of the masonry, and should not alter the shade of the mortar.

A repair mortar must merge with the old masonry structure. Thus it should be easily ***modified*** to resemble the old mortar. It can be tinted with pigment, brick powder or special sand. The maximum granule size of the aggregate must correspond to that of the old mortar.

There are many ways to prepare good lime mortars for repairing an old building. A good final result can be obtained when the plasterer or mason understands the properties of the mortar he will be using on different bases. If he has lengthy experience with e.g. the functionality of an old pit lime with a certain aggregate, he is also able to modify his mortar to suit the circumstances. Some such skilled masons exist but many more are needed, especially those interested in restoration.

Nonetheless failure can occur even with sound advice, appropriate raw materials and good working methods. This is something one has to be prepared to accept, because some of the factors that influence the functionality of the new repair mortar alongside the old mortar and masonry structure may be unknown. Failure also provides more information that may help to correct the mistakes.

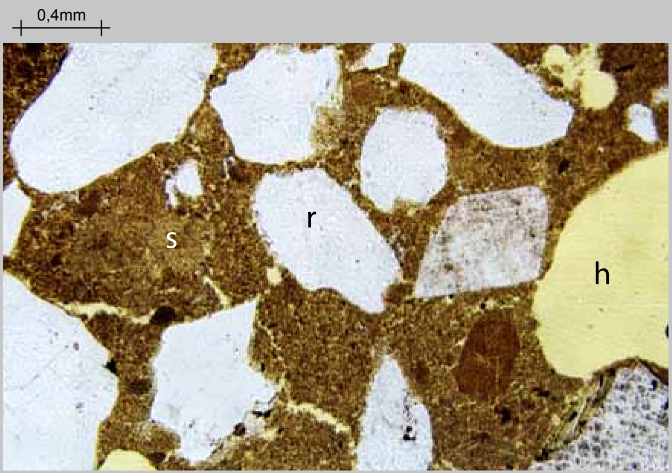
In general it is always better to make as small repairs as possible rather than big changes. Some difficult repairs can also be left for future generations to puzzle over and fix.

Restoration of the façades of Joensuu Manor is still ongoing.

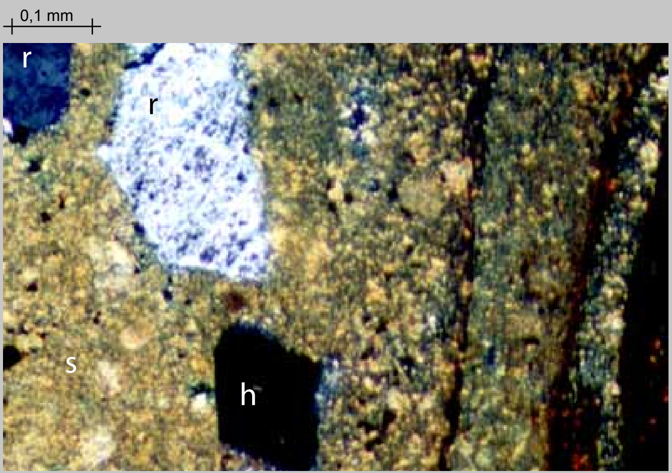
Plaster repair of a log manor

The middle part of Joensuu Manor is a log structure. Initially the logs were plastered with lime mortar in 1811-1813. This was later changed to lime cement plasterwork including a very cement-rich adhesion mortar. It has been suggested that this compact mortar is one of the reasons for the decay of some of the logs. During an extensive repair project in 2005 the old cracking repair mortar was removed, the dowelling repaired, and pins added. A mesh was fixed to the wall and plastered with lime mortar. Hydraulic lime was then added to the adhesion and filling mortar. The new plaster mortar is considerably more airy and permeable to humidity than the earlier repair mortar, which should allow the humidity in the logs to dry off well. The surface mortar is a pure lime mortar.

Original lime plasterwork that is still in good condition has been left on almost the entire eastern log wall and on the northern brick masonry. The lime plasterwork on the log wall has been coated with lime paint only.



The original lime plasterwork of the east wall of the manor is 50 mm thick. The wall has been plastered twice with the same type of mortar. The plaster mortar is very homogeneous and compact, with hardly any cracks. Photomicrograph magnification x4, X-nicol



Top layers of the same plasterwork. Lime slurry and lime paints are visible on the right. Photomicrograph magnification x10, X-nicol

Old insertion pins, dowel rods, plastering mesh and adhesion mortar on one of the log walls.

Merja Nieminen

Finishing coat of the façade repaired with lime mortar.

The inner walls of Joensuu Manor still have plenty of original lime mortar layers covering the original clay plaster. For the repair of the inner walls, a combination of clay and lime plastering was designed based on the original plasterwork. The logs were pinned with wooden pegs and the wall was plastered with clay mortar. The next three plaster layers were prepared with factory-made dry lime mortar, which was prepared according to a special formula. Before use this dry mortar was matured for a couple of months mixed in water. Quartz filler and quartz sand were added to the adhesion mortar to help it adhere better to the clay plasterwork.The new partition walls were also built according to the old system: wooden frame, boarding, mesh, clay mortar and lime plastering.

Old log wall with insertion pins and a new clay mortar plaster on top.

Plasterer Tommi Vilkanen coating the adhesion layer with a matured mortar...

…and spreading the finishing coat exactly on the level of the old plastered and painted inner surface.

Merja Nieminen

Lime mortars maturing in tubs. Before use, the mortars were allowed to mature for a couple of months during which they were mixed weekly.

Injection of loose areas of lime plaster mortars in the inner surfaces of Ulvila Church.

Materials in the conservation of plaster surfaces in brief

The materials and methods used in conservation must not damage the original material.

The materials used must function similarly to the original material.
The composition, condition and water absorption properties of the material to be conserved should be analysed before starting the work (Sonninen 2004).

Injection mortar is used where the original plaster surfaces (with lime paintings) have come loose from their base. The old lime plaster to be fixed must to be strong enough to withstand the injection treatment.

Properties and function of the injection mortar

The mortar must be injectable and have suitable viscosity (fluidity).
The adhesion and gluing ability of the mortar must be good.
The mortar must have good absorption into and distribution within the object to be injected.
The hardening time of the mortar should be reasonable: it must not harden while being injected.
However, the hardening time should be fast enough that the support structures are not kept in place for long.
The mortar must be able to harden in a space that is airtight or nearly so.
The mortar must be non-toxic or nearly so (work safety).
The mortar must not damage the material to be injected.
There should be very little drying shrinkage of the mortar.
The mortar must not act as a sealant; movement of humidity in the wall should not be disturbed.
The thermal and moisture expansion of the mortar should be close to those of the original material so that no tensions are generated and the conserved surface does not crack.
The amount of water-soluble salts in the mortar must be as small as possible.
The mortar must not cause microbial growth.
Low density of the mortar is useful. A light injection mortar will not generate excess weight on the material to be conserved or fixed. (Sonninen 2004)

The most suitable injection mortar for this purpose is based on lime, as are the old plasters. The binder must also include hydraulic material that will harden under the plaster in an airtight space. The mortar should be very fine-grained; the best filling agent is quartz filler (maximum aggregate size less than 0.2 mm), which gives good workability and improves the adhesion properties of the mortar.

Mixing of mortar

Hydraulic lime powder is mixed carefully into the quartz powder. Wet lime must be screened and totally lumpless. It should be beaten thoroughly for about 10 minutes, for example with a small paint beater. Dry ingredients are added and mixing is continued.

The flowability of injection mortar is adjusted by adding water. A couple of drops of dishwashing liquid can also be added, which disperses the mortar and increases its flowability.

The functionality of an injection mortar should be ascertained with a small test before use. The adhesion and durablility of the mortar depend strongly on the amount of water used. The greater the amount of water, the weaker the strength of the mortar. However, when it is soft, mortar soaks better and does not block the thin injection syringe.

Injection method

Small holes 3 mm in diameter are carefully drilled into the plaster surface to be treated. Water is sprayed into the holes and allowed to absorb for about an hour. Mortar is then injected with a syringe behind the plaster through the drill hole. The plaster area to be patched is pressed carefully back onto its base. Larger plaster bases must be held with a supporting framework while the mortar is setting.

Tiina Sonninen

Fixing plaster from a scaffold.

Injection mortar formula

2 parts by volume of wet lime (matured for 2-3 months and screened)

1 part by volume of hydraulic lime (NHL 5)

3 parts by volume of quartz filler (KV-NFQ 0-0.2)

Water is added until a suitable plasticity is obtained.

The functionality of the injection mortar must be ascertained by a small test before use. The adhesion and durability of the mortar depend strongly on the amount of water used.

Tiina Sonninen

Consecration cross mural in Ulvila Church.

Tiina Sonninen

Fragments of a mural in Ulvila Church.

Bibliography:

Sonninen, T., Ulvilan kirkon sisätilojen kalkkilaastien irtonaisten kohtien injektointilaasti ja halkeamien injektointi. (Unpublished source)

Example cases

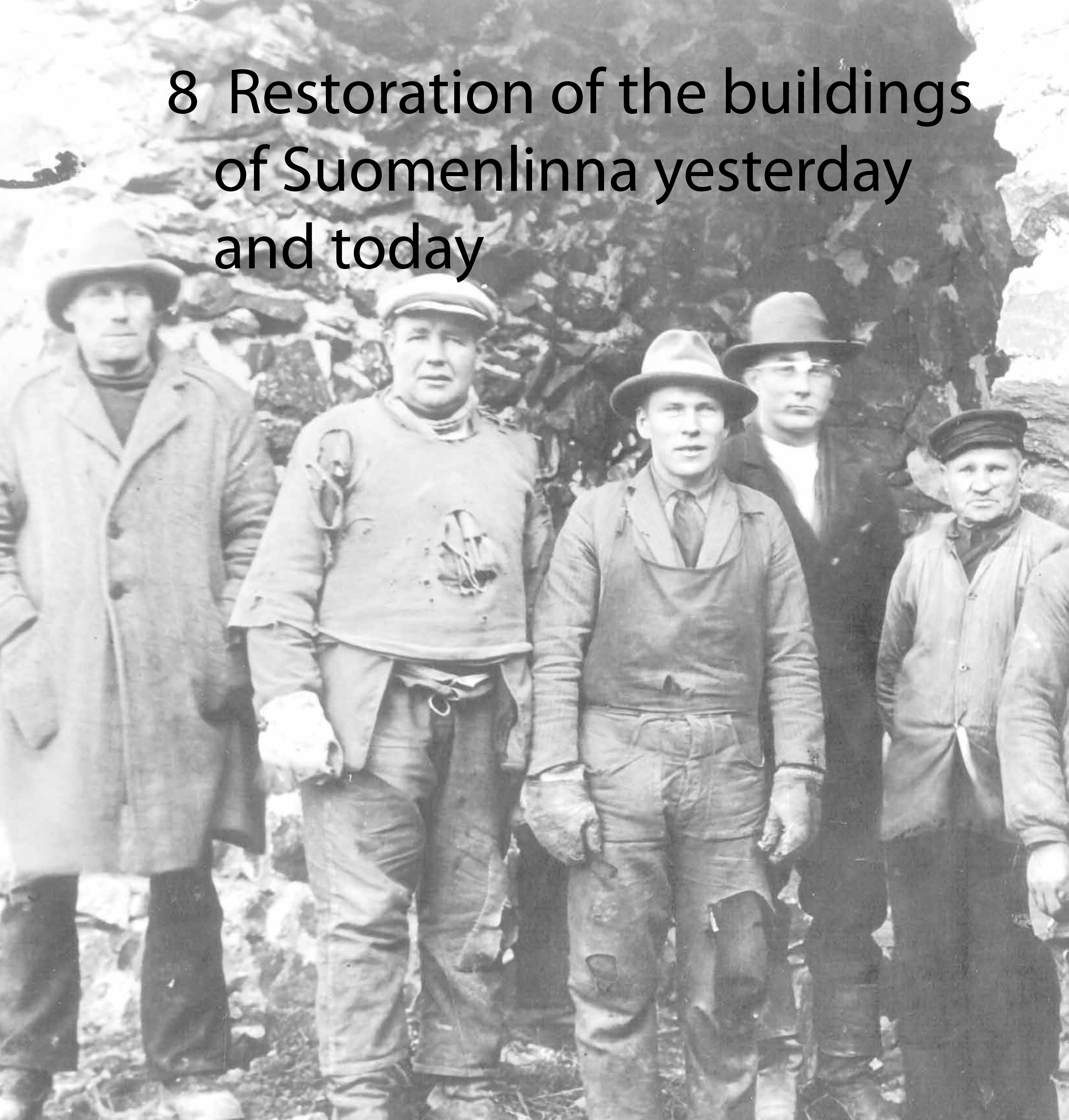
Problems encountered and factors influencing the selection of a repair mortar.

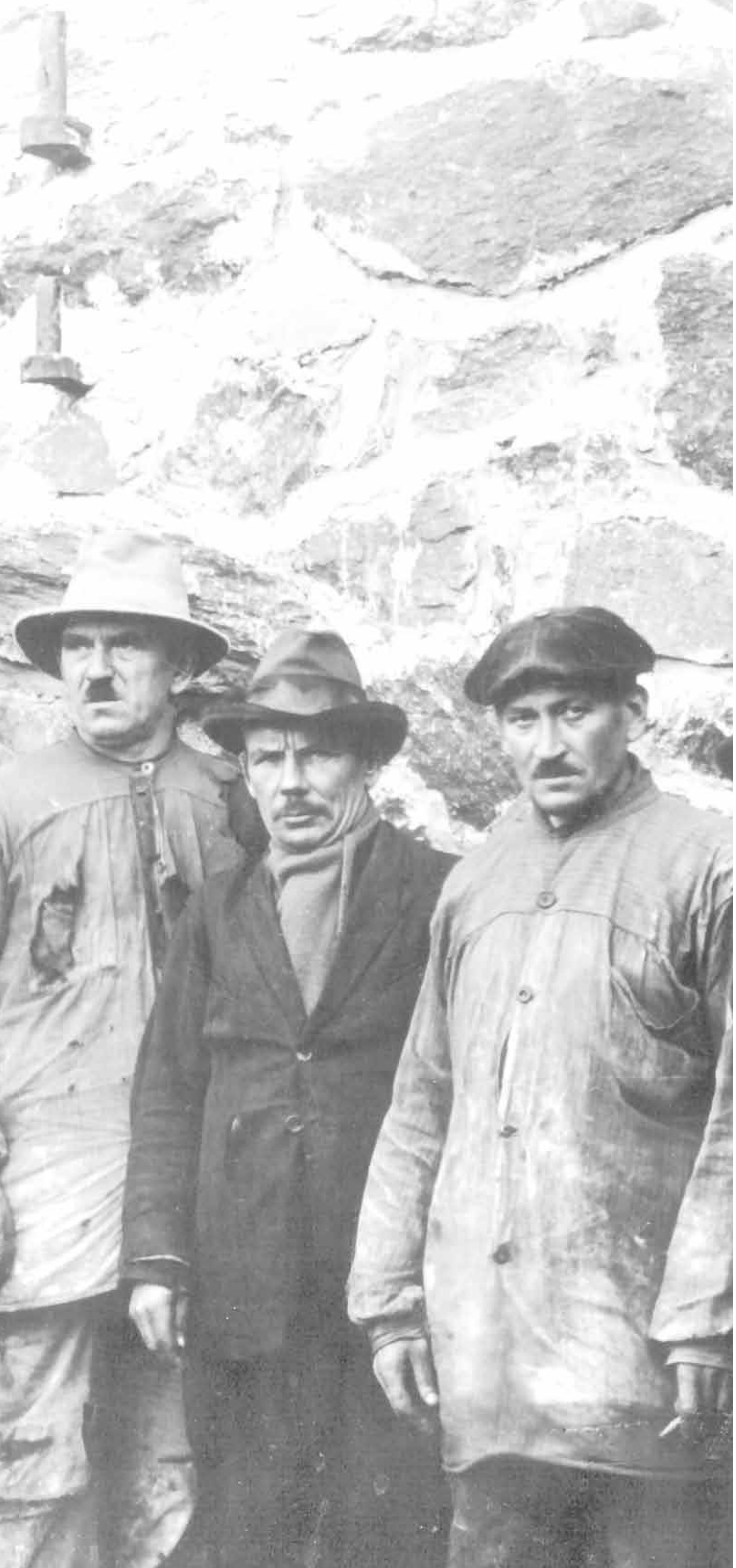
Object 1	**Climatic conditions**	**Base**	**Situation before repair**	**Problems**	**Mortar type**	**Properties of the repair mortar (function)**	**Composition of the repair mortar**
Plastered house, built in 1898	Coastal climate: – wind – rain – frost from the environment	Brick masonry	Plaster repairs from different ages	Aesthetic	Plaster mortar	Lime mortar that is durable enough considering the environment	Lime mortar K 100/650 Volumetric ratio 1:2.5
		Great variation of brick quality	2/3 of the plastering has fallen off	Some of the new mortar repairs have been made with a mortar with a high cement content	Masonry mortar: for replacing damaged bricks with new ones	Mortar choice based on the old lime mortar to match as closely as possible the architectural image of the building	
			In places still the old lime plasterwork	Plastering extends very close to the ground		Aggregate granularity: suitable for frost-resistant plaster mortar	Lime-hydraulic lime mortar KKh 70/30/650 2:0.7:7.5

Problems encountered and factors influencing the selection of a repair mortar.

Object 2	Climatic conditions	Base	Situation before repair	Problems	Mortar type	Properties of the conservation mortar (function)	Composition of the conservation mortar
Wall plasterwork with lime paintings in a medieval church	Inside air with varying humidity and temperature	Old brick masonry Original lime plasterwork remaining	Plasterwork under the paintings is loose and damaged in places Plasterwork humid in places Lime painting peeling off	Fixing of the old plasterwork Humidity increases damage Water-soluble salts damage the lime paintings	***Injection mortar*** for fixing the plaster surface	Fluid, injectable Good adherence to the base and the plasterwork to be fixed Inorganic, without sealing materials Must not form a water-soluble salt Must harden in an airtight space	Mortar that includes lime and hydraulic lime Aggregate is quartz powder 2 parts of wet lime 1 part of hydraulic lime 3 parts of quartz filler (parts by volume) Water is added until suitable plasticity obtained
		Plasterwork has been repaired with lime cement mortar		Later lime cement plaster seals the surface and slows down drying of the wall	New lime plaster mortar replacing lime cement mortar	Lime mortar, similar composition to the old lime mortar	K 100/500 volumetric ratio 1:2 mortar sand has good aggregate proportion

8 Restoration of the buildings of Suomenlinna yesterday and today





The first restorations of the masonry walls of Suomenlinna were carried out in the late 1920s and early 1930s as relief work for the unemployed.

8.1 The first restorations and repair work

The fortified islands of Kustaanmiekka, Susisaari and Särkkä were classified as historic monuments as early as 1920. The first restoration projects were carried out at the turn of the 1920s and 1930s as relief work for the unemployed. In those days the mortar contained a high quantity of cement and the repaired wall became as hard as stone. No restorations were made on Suomenlinna during the Second World War and the 1940s. An article in the Ilta-Sanomat newspaper from 1962 described the restoration work of Suomenlinna as "Repairs from the 1960s that are intended to last for centuries and withstand the destructive powers of nature." The use of cement mortar and reinforced concrete was seen as a means to ensure long-lasting results. Reinforced concrete slabs were used to protect the waterproofing on parapets (Lind 2001).

In the 1970s a so-called deep-grouting method was used for rescuing badly deteriorated walls that had not yet collapsed. A mortar called Parmu, containing cement as a binder and lime filler as part of the aggregate, was used for this purpose. Grouting mortars were often mixed with a substantial amount of an additive that would increase the porosity of the mortar and at the same time make it easier to pump. Despite these efforts, this mortar was neither the desired porous mortar nor the "weak link" inside the old masonry construction. Quite the contrary; the Parmu mortar made the structurally important weak part of the wall as hard as artificial stone, entirely changing its function as part of the construction. The hard repair mortar blocked the evaporation of rainwater moisture absorbed by the original weak, porous lime mortar, keeping it humid. On the other hand it is not fully known how Parmu mortar acts as a grouting mortar for a rubble wall. During later repairs it has been noticed that adjacent to a Parmu repair only sand remains of the old lime mortar, probably also due to the degradation of lime mortar in the harsh climate.

Façade plastering has also been repaired with Parmu mortar, but considering how the plaster should work as part of the entire construction, the Parmu repairs are too dense and hard for repairing a lime mortar surface.

Parmu mortar was gradually replaced by lime-cement mortars in the repairs of façade plastering. The repairs were made with mixes similar to those used in modern construction, i.e. the adhesion layer contained a lot of cement (LC 20/80), the filling contained slightly less cement, and the finishing coat normally contained equal amounts of lime and cement. In some cases the finishing coat was made with lime mortar. The mixes were made on site by adding a few shovels of cement to wet mortar. Sometimes also lime putty was added to the mix of the finishing coat.

During the restoration works of the 1990s, the cement was replaced with Jura lime imported from Denmark. This continued until 2005, when production ended. Jura lime is not a hydraulic natural lime, but closer in consistency to natural cement. Initially there were some problems with Jura lime, as frost damaged the joints. However, since the proportions of the aggregate were changed the mortar has worked well, and its resistance in harsh weather conditions has been good.

8.2 Restoration mortars since 1997

The first plaster restoration with pure lime mortar was carried out in 1999 on a building on the island of Pikku Mustasaari, right by the sea. Since then, lime mortar has been used in the restoration of plasters in a similar manner (pure, without cement) or hydraulic lime has been added to the mortar. Hydraulic lime mortar has been used mainly for repairing decorative corner rustications originally made with cement-rich mortars in the early 20th century. Almost all façade plaster repairs have been made with lime mortar. The "brick powder mortars" from the Russian era have been repaired with mortar containing brick powder; this kind of mortar was used for repointing the brick façade of Tenaille von Fersen in 1997.

Restoration mortar aggregates

The grain size distribution of the restoration mortars has been outlined both according to the composition and grain size of the original mortar, according to the weather conditions to be expected at the restoration site, and according to the desired "life cycle" of the repaired structure. The climate of Suomenlinna is harsh almost everywhere on the islands, and the mortars used outdoors should match the weather conditions. The indoor plaster does not have to withstand frost, but a solid base for wallpapers or paint surfaces is required.

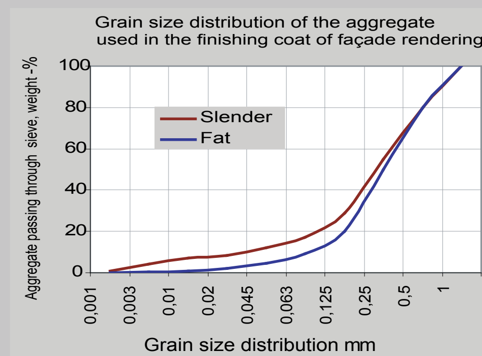
A wide spectrum of aggregates has been used. Initially, the sand used for restoration mortars was selected from commercially available sands and fillers like those provided by the Rudus company. Different grain sizes were proportioned in order to obtain a suitable distribution curve. Each sand type was individually weighed on site and mixed with lime to make the mortar. Factory-proportioned sands have been used since 2001; this has made measuring at the building site much easier. Mixtures have been provided in large-size bags by CT-laastit Oy.

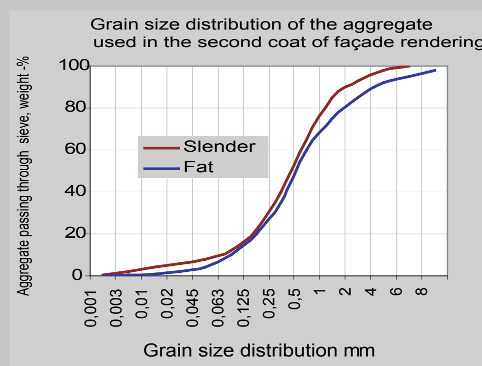
Binding agents in restoration mortars

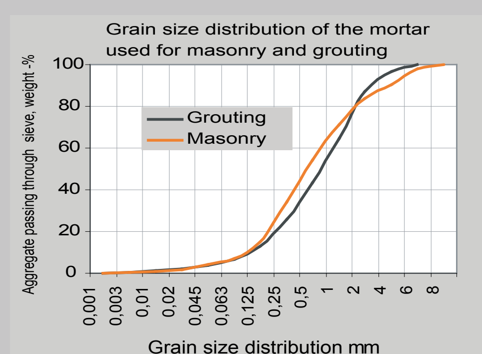
The binding agent used between 1995 and 2001 was Danish *Rödvig Kulekalk*, a factory-slaked lime stored in a lime pit for 2 years. *Rödvig Kulekalk* proved to be good, but was later replaced by cheaper "industrial lime". Since 2001 the lime used in Suomenlinna has been "simmered", i.e. made of calcium hydrate SL 90 T by soaking in water for approximately 2 months before use. This lime is equivalent to *Rödvig Kulekalk* as a binding agent in mortars and lime paint.

Average grain size distributions of restoration mortar aggregates used in Suomenlinna

The grain size distribution values of the aggregates are depicted below as curves. The upper curve shows the grain distribution of a "slender" mortar (i.e. containing a large portion of aggregate) and the lower curve the grain distribution of a "fat" mortar (containing a large portion of binding agent). These grain distribution values have been specifically derived for masonry- and plasterwork in Suomenlinna and cannot be adapted elsewhere.







Grain size distributions of mortar aggregates used in Suomenlinna.

Portland cement has been used in reparations only on concrete surfaces. In 1998 it was replaced by hydraulic lime (Jura). Since 2004 façade plaster (and since 2005-06 masonry reparation) has been made with St. *Astier* NHL5 (naturally hydraulic lime).

Some restoration mortars are dry-mix mortars "tailor-made" by mortar factories. The additives (dispersants) of these mortars enable complete soaking of even the tiniest parts of the aggregate while mixing the mortar. Almost all mortar recipes also contain a portion of fine-grain aggregate, or "filler", with a grain size smaller than 0.2 mm, either limestone or quartz. The addition of "filler" increases the amount of micropores and enhances the plasticity of the mortar. Most restoration mortars are mixed on site with a vertical-shaft mixer.

8.3 The Suomenlinna mixing plant

Mortar is used at almost every restoration site on Suomenlinna. A total of 50 - 100 tonnes of mortar, measured in dry components, is used annually for reparations. A special building for mixing restoration mortar is going to be designed to store all the components under one roof, including binder as well as various kinds of aggregate. Measuring the components of a mortar and mixing the mortar in a vertical-shaft mixer can be done more accurately in a hall than outside in the wind. The wet mix mortar is delivered from the hall to the restoration site by tractor.

In the future the hall will also house a mortar laboratory for trying out various kinds of mortar mixes and monitoring their usability in practice. Shading lime paint will also be tried out. The hall is thus planned to be a place for designing, testing and mixing mortars for various restorations and transporting them to the building sites.

This mortar mixing plant, located in a fortress that is included in the UNESCO World Heritage list, will be one of a kind.

Reparation of a façade rendering with lime mortar

The façades of the Old Pharmacy in Suomenlinna (building D11) were repaired mainly with lime mortar in 1999. The new rendering had to meet the following requirements: resistant to weathering and frost, drying out quickly after heavy rainfall, good plasticity, and binding agent proportions similar to the original mortar.

The recipe was selected from the assortment of lime mortar mixes that proved most successful in a test carried out by von Konow in 1997. The desired grain distribution of this mortar was acquired by combining five different types of sand. The dry mix was made by the Fescon Company, which followed the grain distribution curve in proportioning the aggregate. Quartz filler was finally added to the mix at the building site.

Plastering was completed in late September. All the façades were covered with tarp, and during the winter the still vulnerable lime mortar layers were heated with hot-air blowers. The tarp was removed the following spring.

The lime and cement plaster of the south façade of the Old Pharmacy is carefully removed. The fragments of original surface plaster are left intact.

The pointing was repaired with LLh 60/40/450 containing brick powder. The aggregate used for narrow joints was Haaja sand (0-2 mm) and for broad joints a mixture of Haaja sand and sand used for concrete (0-8 mm). The binding agent was Rödvig kulekalk. Jura was used as the hydraulic lime.

Pointing a brick wall with hydraulic mortar containing brick powder

The façade of Tenaille von Fersen (B17c) has been repointed several times. The reddish mortar is from the Russian era and contains a large amount of brick powder. The mix of the repair mortar was based on this mortar. In 1997 the deteriorated mortar joints were scraped away to provide a solid background surface. The deepest holes were filled with mortar and the cleansed joints thoroughly filled with brick powder mortar. The excess mortar was cut away with the tip of a trowel.

The L 100/670 lime mortar used at the Jetty Barracks (C1) was mixed on site. The maximum grain size was 3 mm for the filling and 1.5 mm for the surface plaster.

Repairing a façade plaster surface with lime mortar

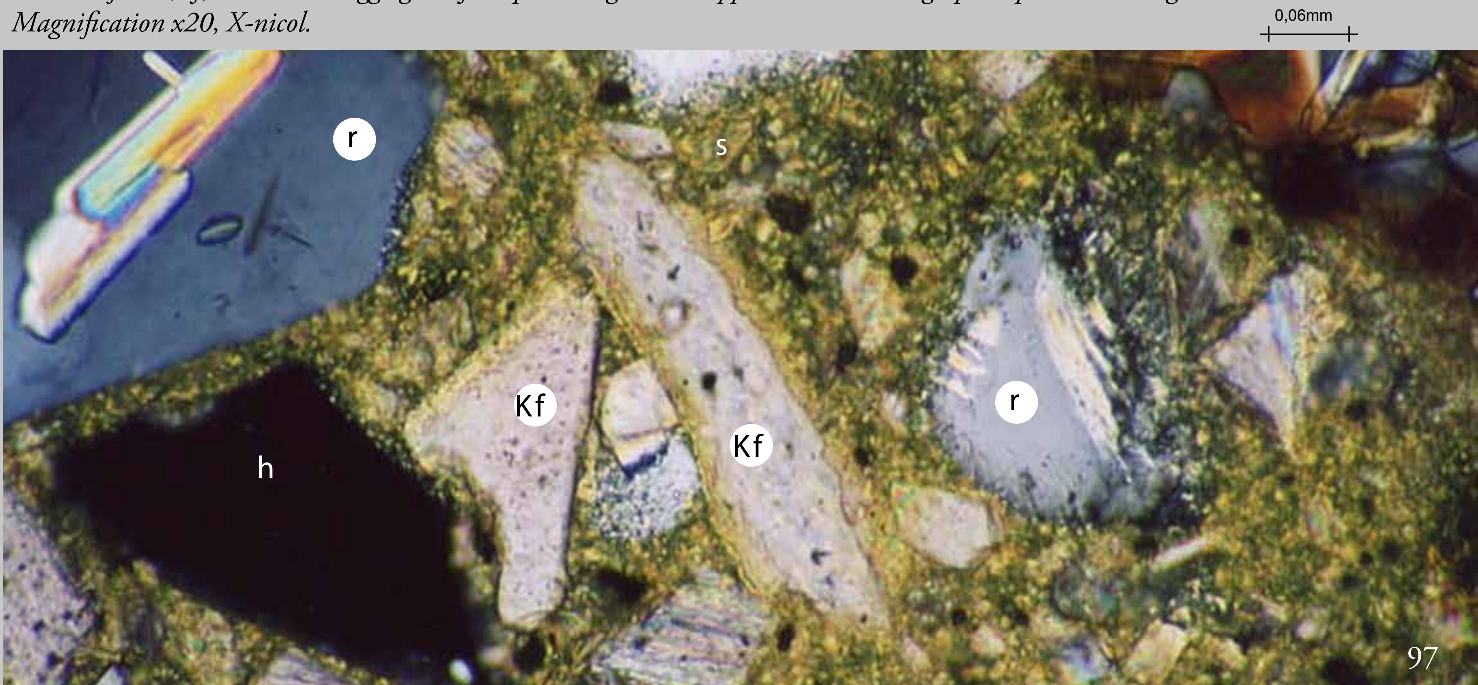
The original lime plaster facades of the Jetty Barracks (C1), from the Russian era, were mostly in good shape before the reparation carried out in 2001. Detached and damaged plaster was removed by careful washing. An unexpectedly large amount of the old plaster could be left on the façade and then completed with a new lime plaster made of wet lime "simmered" on Suomenlinna. The aggregate was mixed according to the recipe at the CT-Laastit factory. The dentils under the window flashings were in good shape; some minor damage was repaired with CT 402a lime and cement mortar (LC 35/65).

Plaster repair of old concrete pillars with lime and cement mortar

Old metal sheet workshop (B 5) from 1917. The concrete pillars were originally plastered. The reparation was done with lime and cement mortar, which suits concrete surfaces better than lime mortar.

The grouting mortar was LC 30/70/350, the filling mortar LC 50/50/600 and the surface mortar LC 70/30/620. The lime was "simmered" wet lime, and the sand mixture was prepared at CT-laastit according to a specific recipe.

The lime filler (Kf) in the sand aggregate of the plastering mortar appears in the micrograph as pastel-colored grains. Magnification x20, X-nicol.



Governing Body of Suomenlinna

The fortifications of Suomenlinna at Kustaanmiekka.

Kaj Holmberg

Holes in the masonry wall of Tenaille von Fersen are grouted with a mortar pump.

Repairing a masonry wall with hydraulic lime mortar

Restoration of the fortifications of Suomenlinna is a long-term process. Loosely attached stones are removed from the wall. Deteriorated mortar and vegetation rooted in the joints is removed mechanically, after which the wall is washed with water. Old wedge stones, completed with new ones if necessary, are preliminarily placed in the wall. Thereafter the mortar is pumped with a grouting pump into the cavities between the stones until the excess mortar flows from the joints. The wedge stones are then hammered into the joints deep enough to touch the surrounding stones. Although the grouting mortar is relatively rigid, its composition allows it to pass through the grouting pump. After hardening for 1 hour the excess mortar is carefully spooled away, and the joints are dressed.

The damaged copings of the walls, which are no longer damp-proof, are repaired. The old insulation layer of birch bark and clay, as well as the deteriorated mortar, is removed. The coping is patched with stones and grouting mortar. The new insulation is made of interlocking birch bark sheets covered with clay, soil and grass turf.

Grout in a mortar pump.

TUREIDA, Thorborg von Konow

PUMPED MORTAR FOR GROUTING STONE MASONRY

LLH 15/85/505   1 : 4.4 : 13

Measurements: parts by volume

		Litres
Binding agent	Wet lime (paste*)	10
	Hydraulic lime NHL 5 (1 sack)	44
Aggregate	Quartz filler **)	6
	Tervakoski coarse sand 6 mm	126

USE RESPIRATOR MASK WHILE HANDLING QUARTZ FILLER

***) SL 90T dry lime, simmered for 2-3 months before use**
****) Quartz filler, KV-NFQ**
Sand: Tervakoski coarse 0-8 mm, screened with 6# sieve

Mixing instructions:

Mix NHL 5 and the filler with a quantity of sand (100 litres). Add approximately 20 litres of water and the wet lime. At this stage the consistency of the mortar is quite loose. Mix for 10 minutes.
Add the remaining sand (26 litres) and continue mixing for 10 minutes. The consistency of the mortar is fine-tuned by adding a small amount of water (1-2 litres).
The grout mortar must have an adequate plastic consistency; it should not be too loose!
Mixing time: 10 min + 10 min
Can be used for approximately 2 hours

Must be moistened with water (e.g. membrane curing) for at least 2 days.

A recipe for pumped mortar, hanging among other recipes on the wall of the Suomenlinna mixing plant.

Bibliography, chapter 8:

Lind, T., Suomenlinnan muurikorjaus; muuraus- ja rappauslaastit ICOMOS Jäsentiedote. Tiili ja laasti 6/2001.

9 International cooperation in the field of restoration mortars

Arno de la Chapelle

Several international recommendations have been drawn up relating to the conservation and restoration of cultural historical monuments. The most significant is *the Venice Charter* from 1964. In 1994 a meeting was held in Nara, Japan, to discuss authenticity. Every year, ICOMOS[1] holds an international symposium to discuss topical themes relating to restoration, protection of culture and education in the field.

More concrete questions have gradually arisen in the field of restoration, such as those relating to original materials of buildings and the materials needed for reparation. The first international symposium dealing with this issue was organized by ICCROM[2] in 1981 on "Mortars, Cements and Grouts Used in the Conservation of Historic Buildings". The author participated in this symposium, which took place in Rome.

In 1991, after many decades, the issue of lime and its use in restoration mortar was finally brought up at the Eurolime symposium in Karlsruhe. These symposiums have since been organized three times, in 1993, 1998 and 2005. In England and Scotland, interest in the resurrection of lime mortars as restoration material has been so great that the Building Limes Forum was established in 1992 and the Scottish Lime Centre a couple of years later. Both function widely at the practical level, offering education, preparation courses and counselling. Both organisations also have an extensive collection of literature in the field of restoration, including handbooks and publications.

In Sweden in 1984, the history of lime mortars was written about and old working methods were studied. In Finland the first extensive study on lime mortars in historical buildings was carried out in 1983–85 (the study is described in chapter 3). In Denmark the Nordic Building Lime Forum was established in 1999, modelled after the Building Limes Forum in England and the Scottish Lime Centre. The Nordic Forum organizes popular seminars annually for anyone who is interested in lime mortars and paints, users, planners, researchers, historians, and producers of mortar and lime. The Nordic Building Lime Forum has its own website through which people can become acquainted with current restoration works in Scandinavia and methods of burning lime and participate in the discussion forum (www.kalkforum.org).

Not enough is yet known about the restoration of valuable historical buildings and objects, and much is still under debate. Buildings that are defined worldwide as objects of protection are influenced not only by different climatic conditions, but also by earthquakes, eruptions, floods and wars, which can cause catastrophic destruction to both people and buildings. It has also been noticed that various damaging phenomena of old structures that have already been repaired have accelerated in recent decades. Part of the reason is insufficient knowledge about the function of repair mortars and the use of modern mortars in restoration. To find a common language in which to address the topics of damage to masonry structures, the influence of external factors, and historical mortars, an international committee, RILEM[3] TC-COM 167 "Characterisation of old mortars with respect to their repair" was established. When the committee's

The enemies of stone masonry are sometimes also beautiful

1) ICOMOS International Council on Monuments and Sites
2) ICCROM International Centre for the Study of the Preservation and Restoration of Cultural Property

3) RILEM Reunion Internationale des Laboratoires d`Essais et de Recherches sur les Materiaux et les Constructions.

work ended in 2000, it was suggested to establish a new committee, RILEM TCRHM "Repair mortars for historic masonry". This committee started its work in 2003 and is tasked with setting up restoration mortar recommendations for repairs of various masonry structures, by examining both the problems that cause damage and environmental effects.

The committee includes members from 16 European countries, Canada and the United States. Finland and the Governing Body of Suomenlinna are represented by Thorborg von Konow. The work to date has been very challenging. Different countries have different problems and still widely diverging views on how the conditions should be classified, and with what kind of mortars old masonry structures should be repaired. Interestingly, and perhaps surprisingly, the most enthusiastic proponents of lime mortars are found in the Nordic Countries and not in the more temperate climatic zones. The work of the committee is expected to be complete in 2007.

Reports and symposium publications of international committees provide valuable information about restoration. Alongside these publications practical skills are also needed, and are improving in both small and large-scale restoration works being carried out around the world. The restoration of historically valuable buildings is gaining interest among more and more people. Restoration mortar may be a small part of the bigger picture, but it is all the more important.

NORDISK FORUM FOR BYGNINGSKALK

NORDISKT FORUM FÖR BYGGNADSKALK

POHJOISMAINEN RAKENNUSKALKKIFOORUMI

www.kalkforum.org

The Building Limes Forum

www.buildinglimesforum.org

THE SCOTTISH LIME CENTRE

www.scotlime.org

Bibliography (in chronological order)

1981 Mortars, Cements and Grouts used in the Conservation of Historic Buildings. ICCROM symposium 3 - 6.11.1981 Rome.

1983 Vanhanen, R. Rappauslaastit historiallisten kohteiden restauroinnissa. Diplomityö. Teknillinen korkeakoulu, Espoo.

1984 Riksantikvarieämbetet och statens historiska museer. Rapport RAÄ 1984:4 Kalkputs 2 History och teknik – redovisning av kunskaper och forskningsbehov.

1990 Knöfel, D. – Schubert, P., Zur Beurteilung von Mörteln für die Instandsetzung von Mauerwerk. Bautenschutz und Bausanierung. Heft 2 u. 3.

1992–93 Lindqvist, J.-E. et al., Gamla kalkputs med god beständighet – analys och utvärdering. RAÄ, Delrapport 1. ISBN 91-7209-140-1.

1995 Preparation and Use of Lime Mortars. Historic Scotland Technical Advice Notes. Edinburgh.

ISBN 0 9517989-3-6.

1999 International RILEM Workshop on Historic Mortars: Characteristics and Tests. Paisley, Scotland. Edited by P. Bartos, C. Groot and J.J. Hughes. RILEM Publications ISBN 2-912143-15-2.

2001 External Lime Coatings on Traditional Buildings. Technical Advice Note. The Scottish Lime Centre.

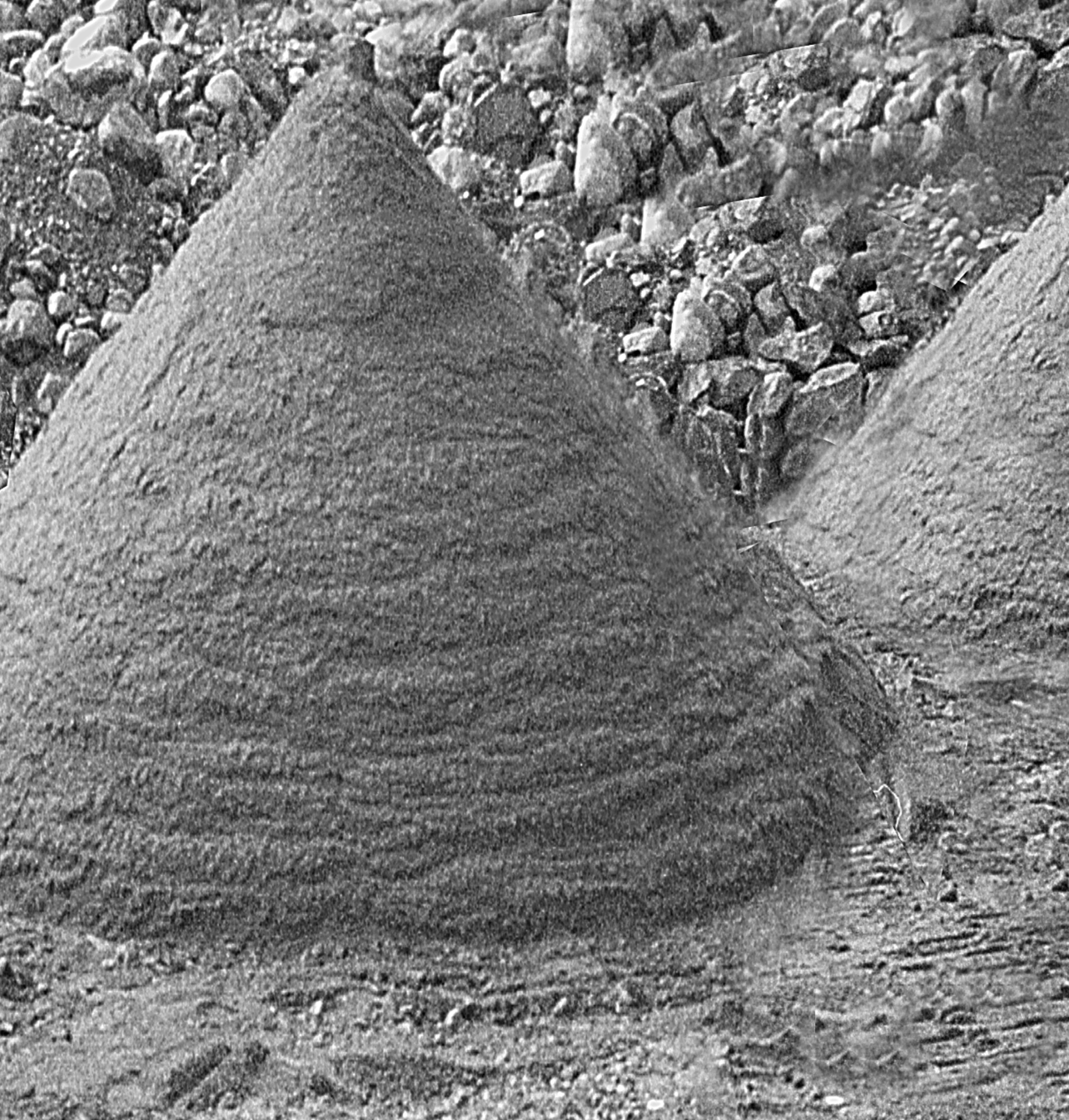
ISBN 1900168-70-7.

2002–03 Claesson, R., Analys av gammal kalkputs. Göteborgs Universitet. Avdelningen för Kulturvård. ISSN 1101-3303.

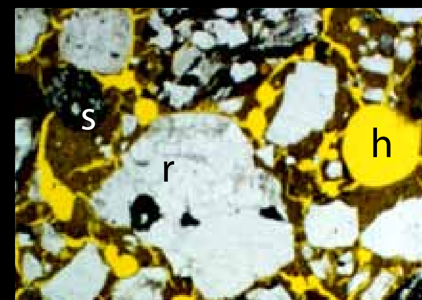
2004 Johansson, S., Hydrauliskt kalkbruk. Göteborgs Universitet. Miljövetenskap. ISBN 91-974985-0-5.

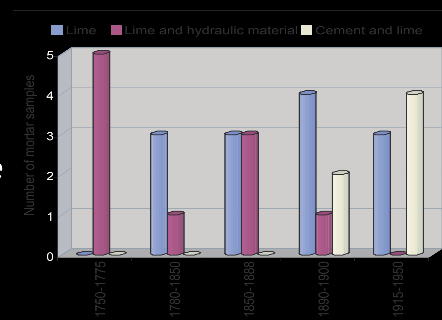
2005 Balksten, K., Kalkputs. Porstrukturens betydelse för beständighet. Chalmers Tekniska Högskola. Oorganisk miljökemi. Sektionen för kemi- och bioteknik. ISSN 1652-943X.

2006 Johanson, S., Hydrauliskt kalkbruk. Produktion och användning i Sverige vid byggande från medeltid till nutid. Doctoral thesis. NMK Företagsförskarskolan, GMV Göteborgs Miljövetenskapliga Centrum, Chalmers Tekniska Högskola och Göteborgs Universitet. Oorganisk miljökemi. Chalmers tekniska högskola. Göteborg 2006. ISBN 91-7346-569-0.



How do mortars in old masonry walls differ from those made today? Why do some mortars crumble and deteriorate faster than others? Based on a long history of Finnish research, this book addresses these questions and is the first Finnish publication to examine the properties of lime mortar in old structures. It is both a manual and a guidebook for anyone attempting to select the best possible restoration mortar - from conservators, restorers and mortar producers to modern-day masons and plasterers. The information in this book will also help property managers assess the maintenance needs of old buildings, analyse damage, and understand the reasons behind it. Designers, engineers, architects and planners will find the wealth of information in this book useful for drawing up specifications for reparation work.





Dr Thorborg von Konow is known internationally for her work on mortar and brick, which she pursued with passion until her death in 2010. Launching her own company, Tureida, in 1994, she consulted widely in the field. For over thirty years she researched the old structures of Suomenlinna.

The fortress has a long history as a restoration laboratory. A Unesco World Heritage Site, Suomenlinna is kept authentic through the use of traditional materials and methods in its restorations. The Governing Body of Suomenlinna, working under the Ministry of Education and Culture, began consistent and comprehensive restoration of the fortress in 1973. The aim of this book is to share some of the resulting knowledge and expertise with those in the field.

TUREIDA

SUOMENLINNAN HOITOKUNTA
THE GOVERNING BODY OF SUOMENLINNA