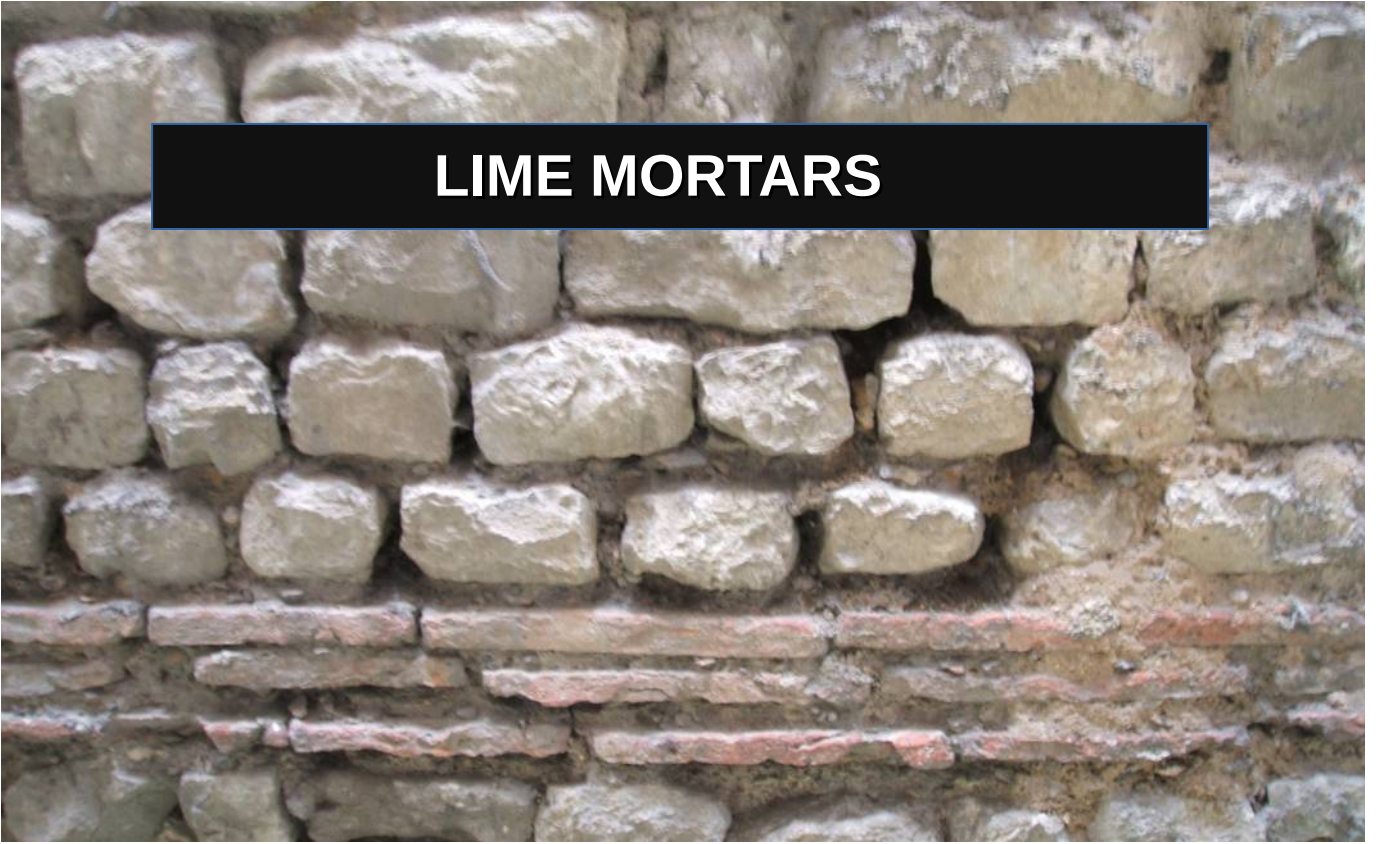




LIME MORTARS

INTRODUCTION

Lime is the material produced from the heating or ‘burning’ of limestone and its subsequent ‘slaking’ with water. It can be combined with aggregate and water to produce a mortar or plaster, or diluted with water and used for use in limewashes like a paint.

Lime was commonly used as the binding agent in the historic mortars of traditionally constructed buildings and structures until the beginning of the 20th century, when it was largely replaced by Portland Cement. It can be found in very old structures (6,000+ years old at the pyramids at Giza). It is used for both construction (foundations, bedding, pointing and flooring mortars) and finishing (plasters, renders and limewash).

Its fairly simple to prepare and use, and can be very durable if prepared correctly and maintained.

PRODUCTION OF LIME

There are two types of lime:

1. **non-hydraulic lime** which is in the form of a putty and sets by *carbonation* in the air.
2. **naturally hydraulic lime** which is in the form of a powder and sets by *hydration* with water.



Both forms of lime are produced by burning limestone (calcium carbonate, CaCO_3) at 850°C .

The heat drives off the carbon dioxide held within the lime to produce calcium oxide (CaO), a highly reactive solid known as ‘quicklime’.



Slaking lime



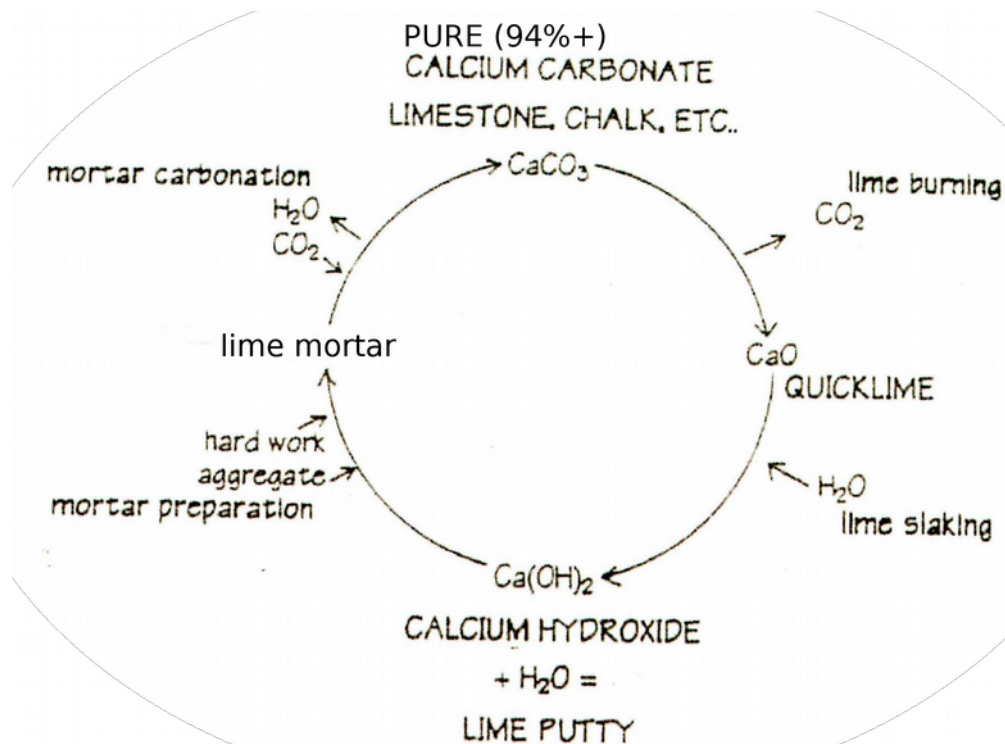
Slaking lime

Adding water to the CaO results in a highly exothermic reaction that produces calcium hydroxide – $\text{Ca}(\text{OH})_2$ - a putty material called **slaked lime**.



Slaked lime

If the limestone used has at least 94% calcium carbonate and few impurities then more water is added during slaking to make a **non-hydraulic lime** putty (a powder form of it is called 'hydrated lime'). This is mixed with sand to make a mortar and the Ca(OH)_2 will react with CO_2 in the air to form CaCO_3 by 'carbonation'. The series of reactions is known as **the lime cycle**



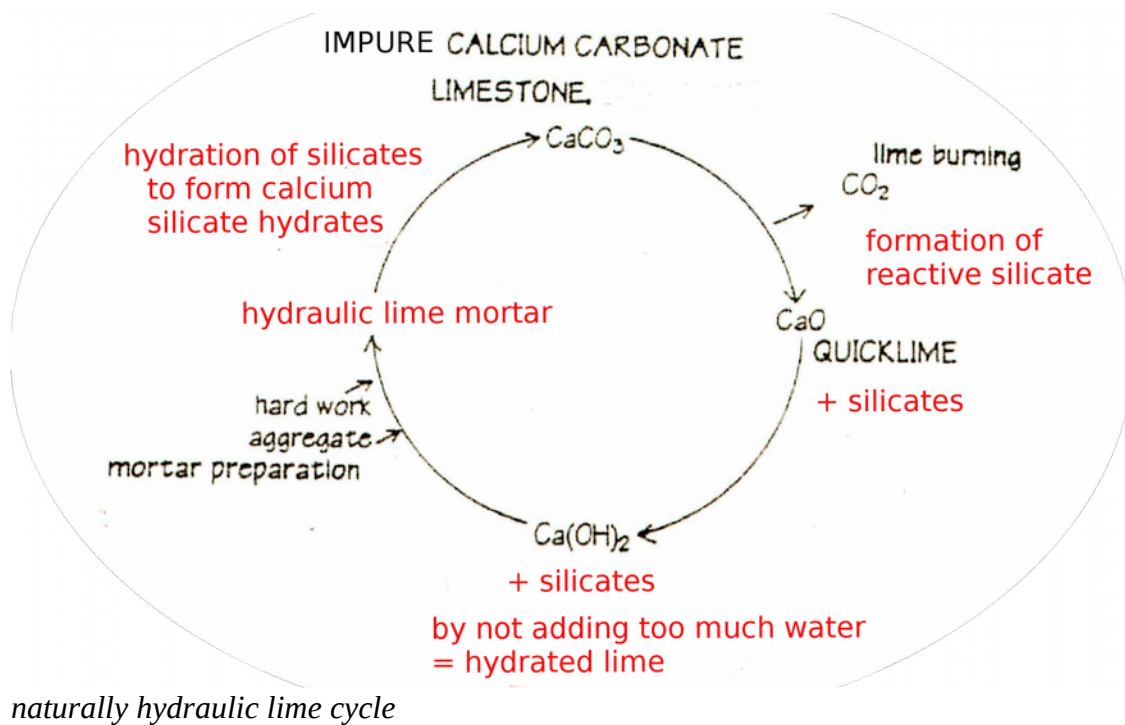
non-hydraulic lime cycle

This simple **non-hydraulic lime** cycle is based on the use of pure limestones to make the non -hydraulic ‘lime putty’. When it sets the lime mortar essentially returns to a form of limestone as chemically it is the same, CaCO_3 .

The production of **non-hydraulic lime** from limestone via the lime cycle is an ancient technology, with examples of lime kilns (for burning limestone) going back at least 2000 years in Iran or to the Romans. There are reports of slaked lime being used with rice to make a ‘sticky rice mortar’ for the Great Wall of China 1500 years ago.

Although the lime cycle has remained largely unchanged for thousands of years, some modifications to the raw material have evolved over time. **Hydraulic lime** were developed to make the lime set quicker.

Hydraulic lime production is made from limestones that contain reactive impurities such as in silicate or clay based limestones proceeds via a more complex cycle to produce ‘**naturally hydraulic limes**’ (NHLs) which is what we used in the workshop. They are made from less pure limestones of between 94% to 75% or so CaCO_3 .



NHLs set in a hydration reaction occurring between the silicate and aluminate impurities that combine with water and calcium hydroxide. In NHLs there always be an amount of ‘free lime’ present that will need to

carbonate – free lime is the calcium hydroxide in a hydraulic lime mortar which is not involved in the hydration reactions with silicates and aluminates.

This ‘chemical’ setting enables the use of **NHLs** in wet conditions, where non-hydraulic lime mortars would fail to set. **NHLs** are typically stronger and with slightly less moisture permeability than non-hydraulic limes.

USES OF LIME



Historically lime has been used for both fresco and secco wall painting – fresco is a technique of wall painting where paint is put on a freshly laid or wet lime plaster. Secco is where the paint is applied to a dried lime plaster as here in Leonardo da Vinci's *The Last Supper* from 1495.





As well as being used in the Renaissance in Italy a form of secco is found in the murals at the Mogao Caves at Dunhuang on the Silk Road from the 4th Century.

As well as its use in cultural heritage, lime is used for industrial processes such as steel fluxing and waste water treatment, and for agricultural purposes.

However as a building material lime is no longer used on a large scale, having been replaced by cement. Actually cement, or more correctly, Portland Cement, is produced from limestone in a similar way to lime but is manufactured under much higher temperatures with reactive clays added during its production - this is why cement sets much more quickly in the presence of water and hardens to a much greater compressive strength than lime.

The inventor of Portland Cement in 1824, Joseph Aspdin, allegedly claimed that the product could produce an artificial stone as good as Portland stone (the finest limestone of England). In the 20th Century cement was further developed and now its extremely versatile for engineering and architecture where a high compressive strength, low permeability, or an underwater set is required.



However, cement is generally unsuitable for use on stone monuments as its high strength, lack of permeability and its tendency to crack due to its inflexibility make it too incompatible – the image shows how moisture has not been able to evaporate out through the joints has come out through the softer stone causing its decay.

TYPES OF LIME

Lime is the generic name given to calcium hydroxide, Ca(OH)_2 , although there are many different types with different physical properties and performance characteristics.

In conservation the most common types are:

Non hydraulic lime

Non hydraulic limes, also called ‘fat limes’ or ‘air limes’, are natural limes formed from the burning of limestone that is considered to be ‘pure’, i.e. that does not contain any silicate or aluminate ‘impurities’. In conservation usually used in the form of a lime putty.

When used in a mortar, non hydraulic limes set and harden only through carbonation and drying. Carbon dioxide from the air is essential for the progression of this reaction. They are not considered to set quickly enough nor to be sufficiently durable for conditions where there is much rain and wind. In hot climates they can dry out too quickly and carbonation fails to take place.

Lime Putty

When a lime putty has been produced by slaking quicklime in water it is typically allowed to mature, or ‘fatten up’, for at least 48 hours prior to use in a lime mortar. The maturation or ‘fattening up’ of putty results in the formation of increasingly finer lime particles over time. It is this maturing that makes putty the most soft, permeable and flexible of all the types of lime. Leaving lime putty in metal baths buried and covered in the ground for at least 3 years is not uncommon.

Hydraulic limes

Hydrated limes with hydraulic properties are typically referred to as ‘hydraulic limes’.

There are naturally hydraulic limes – as we used – and hydraulic limes where additives have been used but are not generally used in conservation as the CaCO_3 content is low and additives such as cement are used.

Natural hydraulic lime

Natural hydraulic lime (NHL) is produced from limestone that contains a proportion of reactive minerals, such as silicate and aluminate, which allow the lime to chemically set in the presence of water, with some setting also due to carbonation. Because they generally chemically set hydraulic limes can be used in wetter conditions than non-hydraulic limes.

The chemical composition of the limestones varies and as such, produces limes of differing strengths or, more accurately, has different hydraulic properties or hydraulicity. NHLs are sold as a dry hydrate under a standard classification system:

NHL 2	Feebly hydraulic	(6-12% reactive impurities)
NHL 3.5	Moderately hydraulic	(12-18% reactive impurities)
NHL 5	Eminently hydraulic	(18-25% reactive impurities)

‘Feebly hydraulic’ lime that are softer and particularly good for work on fragile stone and wall painting conservation. They have up to 94% calcium carbonate content.

‘Moderately hydraulic’ limes are formed from reasonably ‘pure’ limestones with around 85% calcium carbonate and are moderately strong.

‘Eminently hydraulic’ limes are generally too strong for conservation.

It is important to note that the NHL classification system is not truly accurate as the ultimate strength of a lime mortar can vary according to lime type, mix proportions, conditions and application practices including after care.

With reference to the Hydraulic Lime Cycle diagram, NHLs are produced by adding just enough water to convert the calcium oxide (CaO) to calcium hydroxide (Ca(OH)_2), but not enough to initiate the chemical set of the silicate or aluminate impurities through hydration.

Despite their perceived high strength relative to lime putty, most natural hydraulic limes have good water vapour permeability and the ability to accommodate movement.

PROPERTIES OF LIME

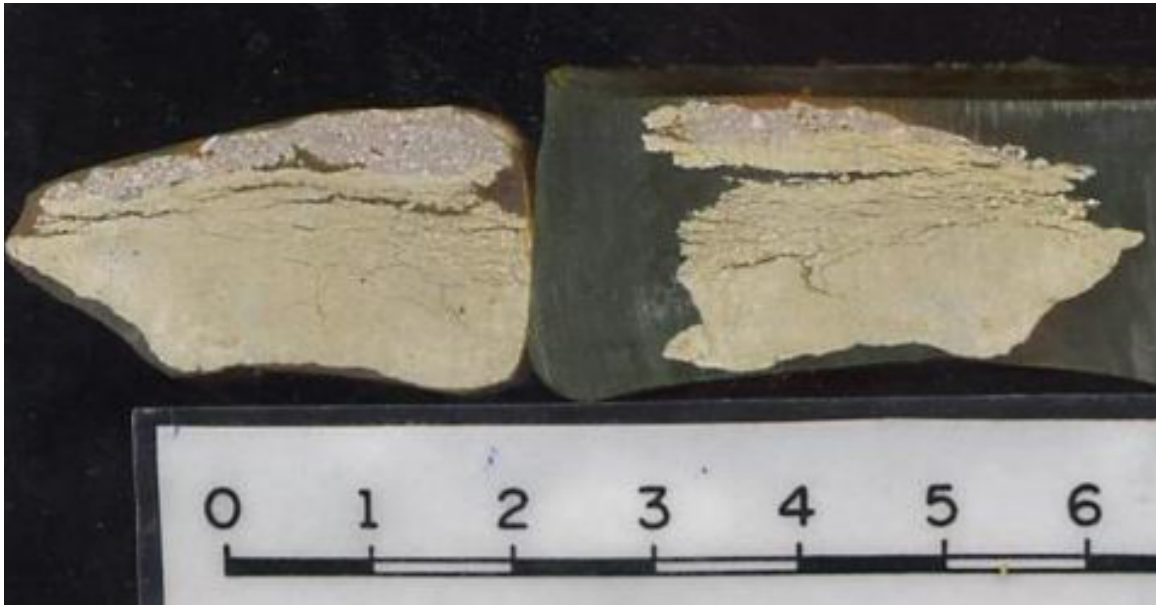
Vapour permeability: The relatively high vapour permeability of lime allows moisture to move through it. The absorption and evaporation of moisture through lime helps protect the stone structure from moisture-associated damage. Vapour permeability of lime generally decreases as compressive strength increases

Flexibility: The 'elastic' nature of lime enables it to absorb minor structural movement associated with the expansion and contraction stresses that are undergone due to changes in temperature and humidity. This means it is less vulnerable to crazing and cracking than are many cement-based products. Flexibility typically decreases as compressive strength increases.

Environmentally friendly: natural lime contains no volatile organic compounds (VOCs), petrochemicals, lead or other contaminants. In addition, the alkalinity of lime helps to inhibit the growth of mould and other pathogens.

Aesthetics: Lime finishes complement the appearance and visual qualities of natural stone. Lime fast earth pigments can be used to colour match the stone to which lime mortars are applied.

When used correctly, lime mortars act sacrificially to prevent the stone they are applied to from deteriorating. The relatively high vapour permeability of lime enables the diffusion of moisture through it – it allows the stone to 'breathe'.



Inappropriate repair of historic stone using less vapour permeable materials, such as cement or epoxy/polyester resins, can inhibit the movement of moisture through stone resulting in problems such as scaling and loss. In the cross section here an epoxy resin was used and the underlying stone has fractured because the resin has failed to allow moisture transport in and out of the stone.

TECHNICAL CONSIDERATIONS

Lime mortars are a mixture of lime binder, aggregate and water. Despite this apparently simple formulation, there are an infinite number of variations that can be created by altering mix proportions and water content, as well as aggregate and binder type.

Lime mortar mixes (both hydraulic and non-hydraulic) are often mixed using a 1:3 lime:aggregate ratio by volume or weight.

Lime as a binder is required to fill the spaces between aggregate grains and bind them together. Free lime in lime mortars can perform a continuous cycle of carbonation, dissolution and re-precipitation, sealing any microscopic cracks in a process known as ‘autogenous’ or ‘self’ healing. In conservation, this is a positive attribute of the material but it is a long-term cycle and should not be seen as a substitute for remedial action after failure.

It is the free lime in a lime mortar that, due to its relatively high solubility, can leach where stone is continuously damp or wet and so needs adequate protection after initial application.

Limes of different hydraulicity have different free lime contents; the higher the hydraulicity, the lower the free lime content, so NHL2 has a higher free lime content than NHL5.

AGGREGATES FOR LIME MORTARS

Aggregates affect the appearance and performance of a lime mortar. Historically there was an almost infinite number of variations, depending on what was available locally, typical materials being river or beach sand or crushed shell. Stone dust is also commonly used from the host rock to which the mortars will be applied.

The type of aggregate required is largely dependent on the intended use of the mortar. However, a good aggregate for a lime mortar should be 'sharp' - that is, consisting of angular grains - and free of contaminants such as salt and organic matter. This is why in conservation we wash and dry the sand to free it of any salts or other contaminants.

Using a sharp sand ensures that the grains interlock in the mortar, producing a stronger bond within the material. Rounded, or 'soft', grains might increase workability as the grains roll over one another, but this can result in poor adhesion.

The aquarium sand we used in the workshop was more rounded and will have a lower bond strength – however this can be good to make sacrificial fills, that is fills that fail before the stone, rather than fills that cause the stone to fail.

AGGREGATE GRADING

The term 'grading' refers to the size distribution of aggregate grains and is determined by passing samples of aggregate through sieves of a specified size.

For larger scale works on historic buildings and monuments aggregate in which the majority of grains are of similar size is termed 'poorly graded' and aggregate with a wide spread of grain sizes is 'well graded'. Typically a well graded sand has grain sizes between 0.125 to 2-3mm, with the largest proportion of grains at the mid-size. In whatever use, the largest grain sizes should generally be no more than one third of the width of the crack or joint that is to be filled, so, for example, a very fine graded sand or stone dust is more suitable for very fine pointing or crack filling.

In historic works matching of aggregate in a repair mortar to that of the existing mortar may be required on conservation projects, and in such cases an analysis of the existing mortar is appropriate.

When using lime mortars on sculpture, texture and colour are overy important to maintain the visual integrity of the art work. An aggregate can impact upon the colour of the mortar as well as its physical properties and stone dust is often used in cases where a colour match to stonework is required. For colour matching natural earth pigments are often used.

A mortar with too much lime binder may be liable to shrinkage and cracking during drying. And a mortar with too little binder will be weak and friable as there is insufficient lime to bind the grains together. And sand with a high clay or silt content will affect the performance of a lime mortar and can cause cracking and shrinkage. If no technical data exists then a simple 'jam jar' test can be done to determine the level of clay and silt in a sand:

1. Mix up a salt solution using 1 teaspoon of salt per 0.5 litre of water.
2. In a jar, shake up a sample of aggregate in the salt solution.
3. Allow the material to settle.
4. The constituent parts of the aggregate will settle out and the clay and silt content settling at the top of the aggregate can be roughly measured.

ADDITIVES IN LIME MORTARS

The qualities of a lime mortar can vary depending on numerous factors including the composition of the lime binder, type of aggregate, mix proportions and care during curing. Additives play an important part.

Pozzolans

Pozzolans are materials that contain reactive silica and alumina which can be added to non-hydraulic lime mortars such that the silicates and aluminates present become hydraulically reactive.

Pozzolans take their name from the town of Pozzuoli in Italy where the local volcanic ash was used by the Romans to produce a binder that is harder than lime putty, and which was found to set under water. The generic name Pozzolan is now applied to any reactive material used with a lime putty, and includes brick dust, ground tile/pottery, Pulverised Fuel Ash (PFA), Granulated Blast Furnace Slag (GBFS) and some processed clays (metakaolin), plus other similar materials.

Other additives

Both historically and in conservation natural additives are sometimes added to mortars to change its behaviour:

Tallow comes from beef or sheep fat and was historically added to limewash to improve water resistance. *Linseed oil* was also sometimes added to lime mortars and limewash to improve their water resistance. It has also been found to increase frost resistance and resistance to salt crystallisation. Its use was most common for mortars on stone buildings in Europe particularly in the 19th century.

Casein is a protein found in milk that was sometimes added to mortars and grouts that required an enhanced level of plasticity. Casein also increases the durability of lime materials and is most commonly used in limewashes.

Animal hair has been added to lime plasters, and sometimes to mortars, for centuries to provide an enhanced level of tensile strength and to reduce the risk of shrinkage. In conservation hair is often boiled to kill pathogens etc.

Urine and *beer* have historically been added to mortars to increase workability and improve frost resistance. Additionally, urine is thought to act as a retarder in lime plaster, giving more time for it to be worked and moulded.



Earth pigments

Earth pigments are often used for colour-matching. They are chemically very stable, UV stable, nontoxic, and remain unaffected by moisture or heat. They are mainly oxides of iron (eg. ochre is a clay based iron oxide) and are also 'lime fast' meaning that, unlike synthetic pigments, the alkalinity of the lime will not

affect them and they will not fade over time. Historically they have been used by ancient cultures across the world including in cave paintings.

SPECIFYING LIME MORTARS

Important considerations in specifying the type of mortar to be used include:

What is the mortar being used for?

Understanding what will be required of a mortar is important to determine what the desired or required properties will be.

All mortars should be *sacrificial* – they should fail before the stone and they ideally should have equal or higher water absorption and vapour permeability values than the adjacent stone to prevent problems associated with inhibited moisture diffusion. The relative speeds at which a drop of water is absorbed into the two materials gives an indication of their relative permeabilities and is a simple way of assessing permeability.

For example, *bedding mortars* act primarily as a cushion to support and spread the load of stone in a wall and to a lesser degree as an adhesion medium, holding the stone blocks together.

Pointing mortars, used in between stones on monuments and buildings should allow moisture to pass in and out during cycles of wetting/drying and be breathable, to deal with the diffusion of the often large amounts of moisture to which they are exposed.

Fine mortars for cracks and small fills will need careful aggregate grading, colour-matching, and after-care.

For larger gaps and joints a coarser sand can be used to fill the voids and then finished with slightly finer fills to match the colour and texture of the stone.

What are the environmental or climatic conditions?

The geographical location of the site influence exposure of the mortar to rainfall, wind and humidity and cycles of wetting and drying.

Very exposed areas or parts of the building which stay persistently wet will require a stronger hydraulic mix than will a sheltered area.

Additionally, the specified after-care may need to be adjusted depending on the time of year when the work is to take place to protect the mortar from rapid drying, during periods of heating, and frost damage during colder months.

What type of stone the mortar is being used on?

Some generalisations can be made based on an understanding of limes' interactions:

#Most sandstones and limestones are relatively soft and porous and should not be filled with high-strength mortars.

#More impermeable stone types cannot dissipate moisture effectively. Mortars used on granites and basalts should therefore be permeable and breathable to prevent any potential build up of moisture within the structure that could lead to kaolinisation or demineralization; hard mortars are never appropriate.

For example, the soft and permeable sandstones at Juming suggest that NHL2 is more suitable as a weak hydraulic lime mortar. However the exposed nature of the site makes the environmental conditions a bit more extreme and thus a more durable mortar might be required so NHL3.5 might also be appropriate for long term exposure.

HEALTH AND SAFETY

Lime is a caustic product and can be irritating to eyes and skin. Mixing of dry powdered lime should be carried out in a well ventilated area.

Personal protective equipment is advised for all work involving lime:

Gloves: lime will dry and irritate the skin.

Breathing apparatus/masks: powdered lime dust is highly irritating if inhaled – wear a dust mask.

Goggles/safety glasses: large amounts of lime dust is irritating to eyes.

STORAGE

Dry bagged lime should be kept in a dry, ventilated area which is protected from rain and dampness.

Opened bags should be carefully sealed shut – generally they should not be used after a six months as air moisture will have provoked the onset of hydration making it unusable.

APPLYING LIME MORTARS

Stone preparation

Preparation of the substrate is essential in preventing the failure of lime mortar and there are a number of steps to follow in preparing the stone for application of mortar:

1) Removing existing mortar: where mortar is deteriorated, damaged or has been wrongly applied, it will need to be removed before any new mortar can be applied. Solid lime mortar can be left in place.

Remove all cement to a great a depth as possible.

Where removal of a hard, well adhered cement is likely to cause excessive damage to the stone then it should be left in place.

2) Cracks should be cleaned with soft brushes to remove all dirt, dust and debris – hand blowers and small hand vacuum cleaners with tubes attached can be used; joints can also be washed out with water at low pressure from a hand spray.

Joints must be clean before filling to ensure the mortar adheres to the stone.

3) Dampening down: where mortar is being applied the area should be thoroughly dampened with water sprays before the application of mortar.

The amount of water required for this will vary depending on the porosity of the stone and the weather conditions. The stone should be damp but not saturated and there should be no standing water on the stone surface.

Dampening down the stone prevents the mortar from rapidly de-watering through capillary action and suction from nearby dry stone.

De-watering results in failure of the mortar as the rapid drying of the mortar makes it weak and friable.

Preparing the mix

The following principles should be followed in general for making lime mortars:

- Lime and sand ratios - volumes can be used but the ratios used can be inexact. With practice using volume measurements is quite standard as we're after a well mixed mortar which is not over or under-limed – this becomes more easy to judge with experience. Weigh bagged lime and sand for absolute accuracy.

- Using a well graded sharp sand with a void ratio of approximately 30 per cent in a ratio of 1 part lime to 3 parts sand, ensures that all grains of sand are coated with lime, producing a complete mortar.
- Use sand which is washed and free from dirt and contaminants – remember damp sand and dry sand have different weight and bulking values. Make sure sand is thoroughly dry to ensure consistency between sessions of mortaring.
- Only use clean water so as not to introduce ground water salts and/or other contaminants to the mix.
- Add water cautiously, starting with the minimum quantity – mortars will become more plastic and wet as they are thoroughly mixed. Adding too much water can result in failure of the mortar due to increased shrinkage and associated cracking.
- The mortar should be fit for purpose – stiffer, stickier mortars for repointing hard, impermeable stone; more workable mortars for more porous stone.
- Ensure adequate mixing time is allowed for the mortar to reach a workable condition – mix until homogeneous and a consistent mortar is produced especially if using pigments.
- Do not attempt to mix, or apply, mortar to elevations in very cold conditions or in direct sunlight, strong winds or heavy rain, without the use of protection. Failure to protect the mortar from these conditions can result in excessive drying and incomplete carbonation.
- Lime should only be used in temperatures of 5°C or more. Low temperatures will inhibit carbonation and make the mortar more vulnerable to frost damage.
- Lime mortars should ideally be allowed to cure for three months prior to exposure to frost; this allows the mortar to build up a degree of protection against imminent and future episodes of frost.
- A mortar mix can only be used in one session of 2-4 hours depending on the climate – the hotter it is the less time the mortar can be used for. Try not to mix too much at any one time as it cannot be

remixed or re-watered as hydraulic limes hydrate relatively rapidly, and re-mixing of the mortar can break the bonds that form during hydration, which cannot be re-established, resulting in a weaker mortar with lower adhesion.



- Adding earth pigments - damp the stone and mix wet lime/sand and add colour until it matches the wet stone. If you mix the dry lime/sand with colour without water to match the dry stone and then wet it and apply, the mortar will dry too light.
For colour test samples use measured amounts of pigments for later scaling up - usually you need to prepare several samples and choose one or two mixes to use.
- However much you care for the mortar after application they can dry slightly differently in colour. Sometimes they become too light and need redoing – I don't like the practice of using lime paint or even acrylic paint to touch in fills – I aim to make the fill match the general tone of the stone and allow for small variations by having two mixes if possible, and adding little bits of pigment as I apply the mortar.

Aftercare

Many failures of lime mortar are caused by poor after care. Lime mortars require more care than do cement mortars, but by following some simple procedures good results can be obtained:

- After application of pointing, and once an initial set has been achieved, press the mortar back with a stencil brush to create an open texture and promote carbonation. The mortar should not be repeatedly worked, as this can weaken the mortar beneath.
- A smoother finish can be obtained by using a metal spatula but be careful not to draw the lime to the surface as this will result in a lime 'bloom', a white surface. Using paper towels can help prevent this.



Applying different coloured lime mortars to terracotta

- Hydraulic mortars need to be kept damp for a few days to ensure the onset of hydration reactions. Prevent rapid drying of mortar by covering the stone with damp paper towels covered with cling film and taped down to create a micro-environment like a terrarium. Large and coarser fills can be covered with cotton sheets and plastic to protect the mortar while it cures.



Different coloured lime mortars on terracotta after being covered with damp paper towels and clingfilm

Finally lime mortars can be used to model – here's a colour-matched lime mortar 'griffin' (on top of the helmet) made to match the surrounding 500 year old terracotta (Hampton Court Palace, London).



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