TECHNICAL GUIDE

Mortars: materials, mixes and methods

A guide to repointing mortar joints in older buildings

David Young

HERITAGE COUNCIL OF VICTORIA | HERITAGE COUNCIL OF NEW SOUTH WALES | HERITAGE SOUTH AUSTRALIA
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We acknowledge the Traditional Owners of Country throughout Australia, and their continuing connection to land, sea and community, and pay respects to them and their cultures, and to their Elders – past, present and emerging.

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Cover photo: Close-up of lime mortar in the circa-1840 stables at Cooma Cottage, near Yass, NSW. Large lumps or ‘knots’ of lime are apparent in a lime-rich mix. This texture is common in traditional mortars and is due to the way they were made – directly from quicklime, by sand-slaking (hot-mixing). Despite the intervening 180 years, the mortar is in good condition, retaining evidence of its struck finish. Importantly, because it is elastic and permeable, it is compatible with the soft, low-fired clay bricks.

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A note about the photographs: Photographs which show the inside of historic mortars have been made possible because of the use of abrasive cleaning (by others) which has removed surfaces, exposing the interior of joints. Cleaning methods have included high-pressure water blasting, sand blasting and grinding. Most of these treatments are damaging and can significantly reduce the life of traditional masonry.

Abbreviations

AS	Australian Standard
AS/NZS	Australian/New Zealand Standard
ASTM	American Society for Testing Materials (standard)
BCA	Building Code of Australia
BS	British Standard
DPC	damp-proof course
EDX	energy dispersive X-ray (sometimes EDS)
EN	European Standard (literally European 'Norm')
FTIR	Fourier transform infrared (spectroscopy)
g/L	grams per litre
GB	blended cement
GGBFS	ground granulated blast-furnace slag
GL	general purpose limestone cement
GP	general purpose cement
HE	high early strength cement
ICPOES	inductively coupled plasma optical emission spectrometry
IRA	initial rate of absorption

Abbreviations (cont.)

kg/L	kilograms per litre
LH	low-heat cement
NHL	natural hydraulic lime
μm	micron
mm	millimetre
MIP	mercury intrusion porosimetry
NCC	National Construction Code
PVA	polyvinyl acetate
SBR	styrene butadiene rubber
SEM	scanning electron microscope
SCM	supplementary cementitious material
SR	sulfate-resisting cement
TDS	total dissolved solids
UV-VIS	ultraviolet-visible spectroscopy
XRD	X-ray diffraction

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‘

… how is it that mortar is often such perishable stuff, that new buildings often require pointing after a few years? Almost invariably the reason is, that loam is used in order to economise the lime, whereas good mortar consists essentially of lime and siliceous sand alone, the lime in the state of hydrate.

‘The difference in the expense and trouble of making mortar which will last for centuries, and each century become harder; and useless rotten stuff, that would not last twelve months, is so trifling, that it must be from ignorance alone the mistake is now made. …

‘The lime should be fresh, the sand a sharp grit and quite clean, and the water pure and free from salt. The sand is made into the form of a basin, into which the lime is thrown in a quick state; water is then thrown upon it to slake it, and it is immediately covered up with sand; after remaining in this state until the whole of the lime is reduced to powder, it is worked up with the sand, and then passed through a wire screen, which separates the core. More water is then added, and it is well worked up or larryed for use.’

Precautions in building, The Australian Town and Country Journal, 4 December 1875

PART 1

Introduction and the basics

The guide begins with a summary of the key information, particularly as it relates to repointing. Readers with insufficient time should at least read the Introduction and Chapter 2 'The basics' which has some common questions and answers, some important dos and don'ts, and an outline of the main points that need to be considered for successful repointing of lime mortar joints in stone and brick masonry.

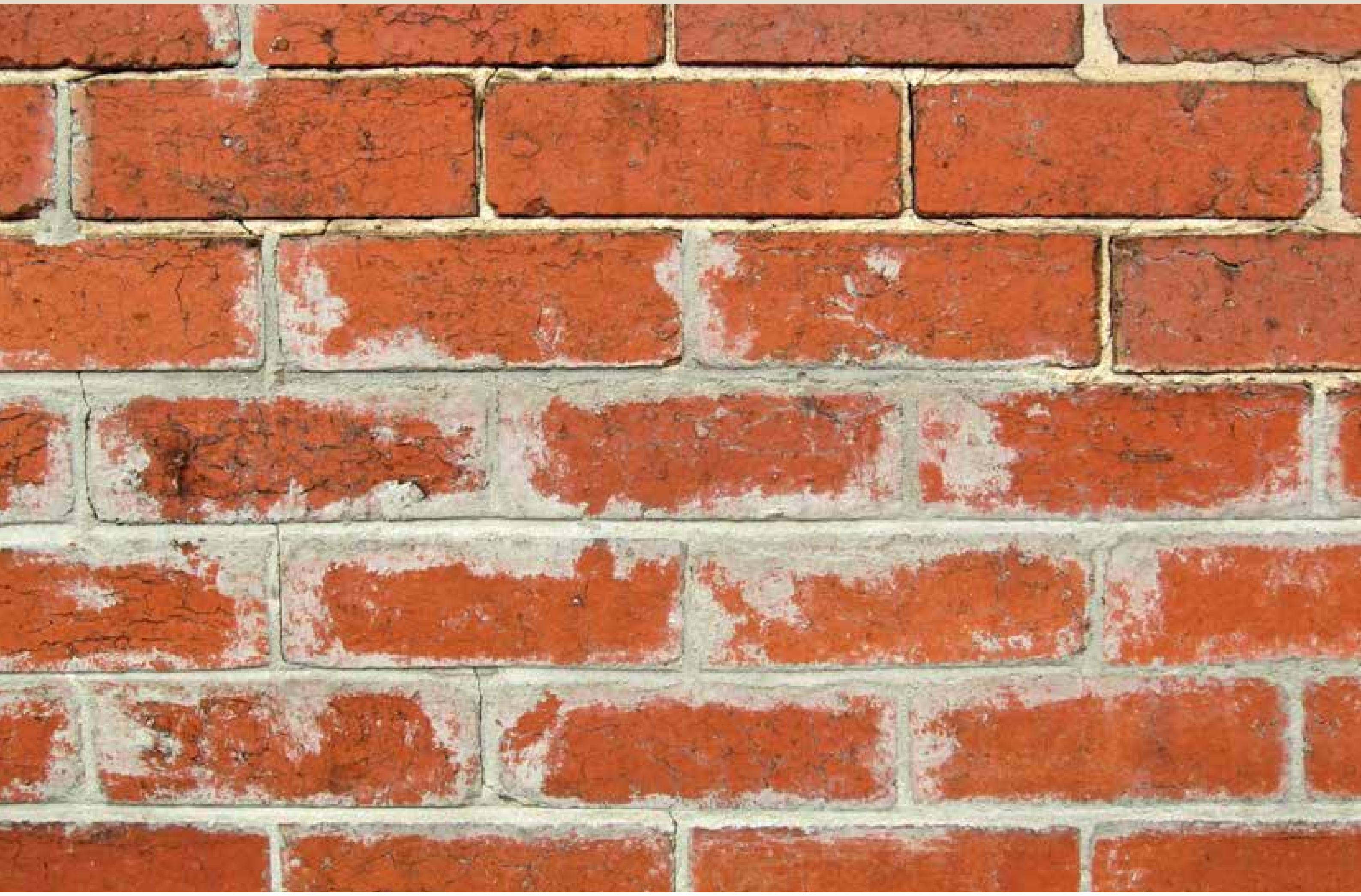


Figure 1: How not to repoint a wall. As well as being unsightly, this example breaks all the rules. Repointing should match the colour, the materials and the finish of the mortar joints. The original lime mortar had deteriorated due to salt attack and rising damp, and its repairer should have recognised the need for the wall to dry out through the joints and for salts to be controlled. Responding to all these factors means using a lime mortar with a clean, well-graded sand. By using a stiff, yet plastic, mortar (which is essential for all repointing), and by placing it with tools that fit within the joints (caulking or finger trowels), repointing can be undertaken without any mortar smears on the face of the brickwork. The cement mortar used here will be too inelastic to allow for small movements and too impermeable to permit drying through the joints. The bricks can be expected to decay.

1 Introduction

In building constructions there are few things of more importance, and thought less about, than the mortar, either as to the quality of the materials or the manner of mixing them …

Hodgson, 1907

This guide does not cover earth mortars, where the principal binder is clay, nor earth mortars that were stabilised with lime.

The focus of this guide is on mortars in older Australian buildings, and consequently there is an emphasis on traditional lime mortars. These were widely used until the middle of the twentieth century, when major changes in building practices (after World War II) led to cement becoming the principal binder. Cement began replacing lime from the late nineteenth century, though the use of composition mortars (cement and lime in varying proportions) was soon adopted and remains common practice.

Mortars: mixes, methods and materials is in three main parts. Part 1 is an introduction and provides a summary of the key information, particularly with regard to repointing. The chapter on The Basics should be read before dipping into other parts of the guide.

Part 2 aims to provide a thorough understanding of mortar materials and mixes, including the binders (limes and cements) and the sands and other aggregates that are the raw materials of mortars. Subsequent sections explain the range of mortar mixes and the circumstances in which they might be used, as well as the investigation and analysis of existing mortars to aid in their repair.

Part 3 is the 'how to do it' part of the guide and covers the practical aspects of repointing, which is the process of replacing the outer part of a mortar joint. Though focused on lime mortars, the recommendations can also be applied to cement-lime (composition) mortars. The guide concludes with a chapter outlining the topics that should be covered when specifying repointing work.

Key terms are explained in the next section, and there is a fuller glossary at the end of the guide. A bibliography of further reading includes references to Australian Standards and some standards from overseas. Boxes that explain particular topics are distributed through the text.

The technically minded may want to read this guide from the beginning. Those involved in repointing work may prefer to read the basic material in the next chapter and then go to Part 3 for the practical details of repointing, referring back to Part 2 on materials and mixes as needed.

Describing proportions in mortar mixes

There are two ways of describing the proportions of materials in a mortar mix: one begins with the binder (e.g. 1:3 binder to sand) and the other begins with the sand (3:1 sand to binder). This guide adopts the binder-to-sand convention, beginning with any cement component, which is generally kept at one part. Thus a 1:2:9 mix means one part of cement, two parts of lime and nine parts of sand. Where only two components are shown (e.g. 1:2), the binder could be cement or lime, and should be identified (e.g. 1:2, lime to sand).

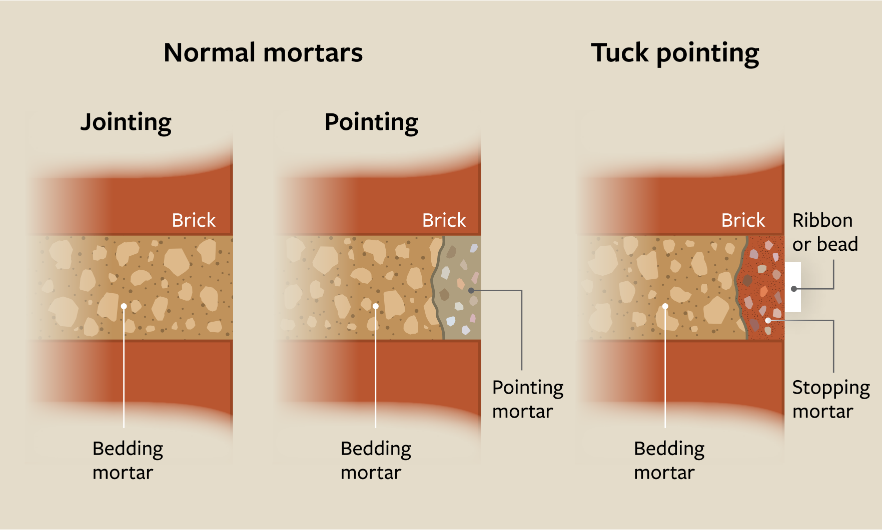
1.1 Key terms used in this guide

This list provides basic definitions, in the order that they appear in the guide, to help you get started; for the full definitions of these terms see the Glossary at the end of the book.

binders and aggregates	Mortars are made from a binder (such as lime or cement) or a combination of these (composition mortar or 'compo') and an aggregate, which is generally sand but may include some crushed stone. Water is used to make the mortar plastic until it stiffens and hardens.	
limes	Lime binders come in several forms, and it is important to be clear about the differences between them and the sometimes confusing terminology. Limes may be non-hydraulic or hydraulic.	> See Chapter 5 'Limes'
non-hydraulic limes	Non-hydraulic (or pure) limes were the most commonly used limes in Australian building. Generally described just as lime, the term 'non-hydraulic' means they do not harden by reacting with water, in contrast to hydraulic limes and cements, which do. Non-hydraulic (or pure) limes come in three distinct forms: • quicklime, which is slaked with the sand • a wet putty, described as slaked lime putty or just lime putty • a dry powder, known as hydrated lime, or builder's lime: 'dry hydrate' is sometimes used to distinguish it from putty.	> See Section 5.2 'Non-hydraulic (pure) limes and the lime cycle'
hydraulic limes	Hydraulic limes can be thought of as a cross between non-hydraulic limes and cements. Some of the chemicals in a hydraulic lime harden by reacting with water (like cement) producing a stronger binder than non-hydraulic limes. There are natural hydraulic limes and artificial ones, depending on the source of their raw materials.	> See Section 5.7 'Hydraulic limes'
cements	Cements differ from hydraulic limes in consisting mainly of hydraulic materials. Like hydraulic limes, there are natural and artificial cements. There was some use of natural cement in Australia in the nineteenth century, until Portland cement (an artificial cement) became more widely used.	> See Chapter 6 'Cements'
pozzolanic materials	Pozzolanic materials have little or no binding power of their own, but when mixed with non-hydraulic lime they make some of it hydraulic and so increase the strength of the resulting binder.	> See Chapter 7 'Pozzolanic materials'
void ratio	The void ratio is the amount of voids (or air) in a measure of dry sand, and it is an important factor determining the correct proportioning of a mortar mix and hence its workability and water retentivity.	> See Section 9.6 'Void ratio and its impact on mixes'
compatibility	Whether for repairs or new building, mortars should always be compatible with the adjacent masonry. This means having appropriate physical properties, such as strength, elasticity, porosity and permeability. Repair needs may dictate that these properties should be different from those of the original.	> See Section 13.5 'Choosing the right mix – compatibility'
workability	This describes the relative ease with which a fresh mortar can be spread and worked. It is not a single, measurable property but a combination of several properties, particularly plasticity and water retentivity.	> See Chapter 14 'Workability'
repointing	Repointing is the process of replacing the outer part of a mortar joint. It may be applied to joints that were originally laid and finished in a single mortar (jointing), or to joints that were finished in two stages by raking out some bedding mortar and adding a pointing mortar (pointing). It is commonly undertaken in response to loss of the existing material.	> See Part 3 'Repointing mortar joints'

2 The basics

Figure 2: Mortar terminology. Jointing is the process of laying masonry (bricks or stones) and finishing the mortar joints with a single bedding mortar. In pointing, the joints are finished by raking out some of the bedding mortar and inserting a separate pointing mortar. Note how the pointing is termed 'stopping' in tuck pointing. The repair of tuck pointing (Figure 30) is not covered in this guide. See also Figure 56, 'Common Australian joint profiles'.



2.1 What makes a good mortar?

The following are the key qualities and characteristics of a good mortar:

> See Chapter 14 'Workability'

- **workability** – it should flow from the trowel when used for laying. Workability requirements vary depending on the application. A bedding mortar should spread readily, so the bricks or stones can be properly placed and the joints completely filled. A pointing mortar should have a much lower water content and be stiffer, yet still plastic.

> See Section 14.2 'Water retentivity'

- **cohesiveness** – good mortars should pass the trowel test by sticking to an upturned trowel. Mortar that is too wet will not be cohesive: it won't hang together. The water will tend to separate out, or 'leak', leaving run-down stains on the masonry and a mortar with poor durability.
- **sufficient strength** – to bind the individual masonry units (bond strength), support the overlying masonry and building structure (compressive strength) and resist dynamic loads such as wind and minor movements (bond and flexural strengths).
- **not too strong** – mortars should always be weaker than the masonry units, so any cracking that develops in the wall will be expressed in the mortar joints where it is much less obvious. It is much easier to repair the mortar than to replace bricks or stones.

> See Chapter 3 'Role of mortars in traditional construction'

- **permeability** – mortars should be more permeable than the masonry units. This is so walls will breathe through the mortar joints, allowing them to dry rapidly after rain.

> See Box 9 'Compatibility'

- **be sacrificial** – the mortar should always fail before the masonry units. This is a combination of the two previous points. Deliberately sacrificial mortars are commonly specified for the repair of masonry damaged by high concentrations of soluble salts.
- **reasonable durability** – it should resist the action of wind, rain and other forces, but it should not be more durable than the adjacent masonry. Mortars should not be designed solely on the basis of the exposure conditions. Instead their design should ensure that they will be compatible with the masonry units.

- **compatibility** – a compatible mortar will comply with the previous four points in terms of its relative strength, permeability, durability and capacity to act sacrificially. For porous materials (such as many sandstones, limestones and older, handmade and low-fired bricks), this means relatively low-strength mortar with good elasticity and relatively high porosity and permeability. In contrast, mortars for use with modern exposure-grade bricks, which have very high strengths and low porosities, will need much higher bond strengths to be compatible.

> See Box 9 'Compatibility' and Section 13.5 'Choosing the right mix – compatibility'

2.2 Mortar materials and mixes

This guide focuses on lime and cement binders, though earth bedding mortars are commonly found in older Australian buildings – weather protection was achieved by pointing the face of the joints in a lime-sand mortar or by limewashing the exterior. There is a range of limes used in building including non-hydraulic and hydraulic varieties. These form a continuous chemical spectrum with cement: non-hydraulic limes merge into hydraulic limes, which in turn merge into cements.

> See Section 8.1 'The lime–cement spectrum'

Lime was the principal binder in mortars and plasters of Australia's early colonial buildings and continued in use in domestic construction until the middle of the twentieth century. Although some Portland cement was used in the mortars of larger buildings in the late nineteenth century, its widespread use began with the advent of substantial local production in the early twentieth century. Composition mortars consisting of cement, lime and sand also became common early in the twentieth century.

> See Chapter 4 'Mortars in Australia – then and now'

There were major changes in industry and building practices after World War II. Small-scale lime burning for quicklime declined, and it was superseded by large, mechanised kilns and plants producing hydrated lime. Quicklime and lime putty were mostly replaced by hydrated lime in a bag – for convenience – while the faster hardening and greater strength of cement led to its predominant use in all mortars and the consequent loss of knowledge of traditional lime practices. Lime is a relatively weak binder, but it has the considerable advantage of good workability, particularly in the sand-slaked and directly slaked putty forms. Although much stronger, cement is harsher and more difficult to work with a trowel.

> See Chapter 5 'Limes' and Chapter 6 'Cements'

The change from lime to cement was followed by a change from sharp sands that were free of clay to clay-rich fine-grained sands in order to regain some lost workability. There is no point reverting to the use of lime unless good sands are used. **Using soft bricklaying sands with high clay contents is bad practice**. Instead of using clay, the workability of clean but 'hungry' sands can often be improved by adding ground limestone or marble fillers.

> See Chapter 9 'Sands and other aggregates'

Traditional mortar mixes are frequently stated as being one-part lime to three-parts sand (1:3), but the truth is more nuanced than this simple ratio suggests. Analysis of historic mortars shows much richer mixes, commonly in the range 1:1.5 to 1:2.5. Part of the explanation is that traditional mix proportions were in fact 1:3 quicklime to sand, which results in a mix of about 1:2 lime to sand, because the quicklime expands on slaking.

> See Section 13.1 'Traditional mixes'

Also relevant is the quality of the sand, particularly its size grading and particle size. A 1:3 mix is appropriate for a well-graded sand, but richer mixes (like 1:2.5 or 1:2) may be required for poorly graded, or uniform sands. As the size of the sand grains gets finer, their surface area increases (for the same volume of sand) and the proportion of lime binder must be increased to compensate. Very fine sands may require mixes as rich as 1:1.5 or 1:1.

> See Chapter 9 'Sands and other aggregates', particularly Section 9.6 'Void ratio and its impact on mixes'

Many late-nineteenth-century cement mortars were specified to be 1:2 or 1:3 cement to sand. This was in an era when Portland cements were quite different and much weaker than they are today. A modern cement mortar made with washed, well-graded sand in these proportions will not only be difficult to work with; it will also be too strong, too brittle and too impermeable for most masonry materials.

> See Section 6.3 'Portland cement through time' and Chapter 8 'Comparison of lime and cement binders'

> See Section 13.2 ‘Composition mortars’

Composition mortars have been widely used by those seeking to combine the advantages of cement (faster hardening and greater strength) and lime (workability). However, recent research and field trials have shown that weaker mixes (such as 1:3:12) are not as durable as pure lime mortars and that cement inhibits the curing of the lime by blocking pores in the mortar.

> See Section 5.7 ‘Hydraulic limes’ and Chapter 7 ‘Pozzolanic materials’

This guide recommends the 1:3:12 mix no longer be used. There are several alternatives to this mix if greater strengths than those provided by pure lime mortars are required: the use of natural hydraulic limes (NHLs) or of pozzolanic materials, which are added to pure lime mortars to produce results similar to hydraulic limes.

> See Chapter 4 ‘Mortars in Australia – then and now’

One of the challenges of repairing older buildings is that their materials are often very different from those in common use today. For example, bricks today are generally much stronger, denser and less porous than those used in the nineteenth and early twentieth centuries. Yet most people working on buildings, whether as specifiers (such as architects and engineers) or as contractors and tradespeople (such as bricklayers and stonemasons) have been trained to use contemporary materials, and they may not be aware of the damage they can do by using modern materials on older walls.

The Building Code of Australia now forms part of the National Construction Code: see Box 10 ‘Mortars and Australian Standards’ and Box 11 ‘Mortars and the Building Code of Australia’.

Uncritical adherence to the Deemed-to-Satisfy Provisions of the Building Code of Australia (and on the Australian Standards on which parts of them are based) can compound this problem, as they reflect contemporary practice and materials. Bricks and mortar are made differently today, but old bricks and stones (like sandstone and limestone) haven’t changed – they need mortars, and construction and repair practices, that are compatible with their relatively porous nature.

Box 1: Mortar basics – materials

Some of the materials used to repair the mortar joints of older buildings are not commonly used in contemporary building practice:

- Mature lime putty is a dense, wet putty that has considerable advantages over the more-common dry-powder form of hydrated lime. Its fine particle size makes it more workable and more reactive. It is used in mortars, the set coat of plasters and in limewashes.
- Natural hydraulic lime (NHL), which is only available in dry powder form, can be thought of as a cross between pure lime and cement. However, it has advantages that are not achieved by mixing cement and pure lime together. Figure 4 shows bags of NHL from various European manufacturers.
- Good sand is an essential element of any mortar. Figure 5 shows a sand that has been sieved through progressively finer mesh sizes and separated into different grades. That there is a range of particle sizes shows that it is well graded, and that means it will make a workable mortar, despite the presence of the coarser grains. Well-graded sands washed free of clay are a key component of good repair mortars.

Figure 3: Mature lime putty.

Figure 4: Natural hydraulic limes.

Figure 5: A well-graded sand.

2.3 Repointing mortar joints

> See Chapter 13 ‘Mortar mixes’

Mortar joints that were originally made with lime mortar should be repointed with lime mortar. The use of cement mortar or cement-lime composition mortar (compo) to repoint lime mortar joints is bad practice and may lead to irreversible damage to the adjacent masonry.

Though not difficult, repointing with lime mortars requires skills some people may not have and a level of care and attention to detail to which some may not be willing to commit. It also requires appropriate tools, including caulking or finger trowels that fit snugly within the joints, so that the mortar can be tightly compacted into the back of the joints.

Figure 6: Jointing tools. Some of the jointing tools used by master brickmason Dr Gerard Lynch. Caulking or finger trowels that fit within the joints are essential tools for successful repointing. With a range of widths and lengths to suit different joints, these tools enable neat placement and tight compaction of relatively stiff (yet plastic) mortars without smearing any material over the face of the brick or stonework. See Figures 67, 68 and 69 for examples of some of these tools in use.

> See Section 5.6 ‘Setting of lime mortars’, Chapter 22 ‘Pre-wetting’ and Chapter 24 ‘Protection and curing’

Curing of lime mortars is critical. Lime hardens by absorbing carbon dioxide from the atmosphere, in the presence of water. If the work is allowed to dry out prematurely, hardening will cease, leaving the mortar weak and prone to decay. It is essential to thoroughly pre-wet raked-out joints and maintain damp curing conditions for at least four weeks. The Australian climate can make this difficult, so you need to consider how this can be best achieved.

2.4 Questions and answers

Q **Shouldn’t I add some cement to make sure the lime will go off?**	A No. Lime mortars do not need any cement to make them go off. Their hardening occurs slowly, by absorbing carbon dioxide from the atmosphere.
Q **Why should I use or specify lime when cement is so much stronger?**	A Strength is often not an issue, particularly when repointing, as lime mortars have adequate strength for traditional brick and stone masonry. On the other hand, modern, cement-based mortars can be too strong, leading to cracking in the bricks or stones, rather than through the joints where it is less obvious and more readily repaired. Mortars should always be weaker than the adjacent masonry. Also, walls need to breathe: any moisture in the wall should dry out through the joints, which need to be more permeable than the adjacent masonry. Lime mortars are much better at allowing breathing than are mortars made of cement, or cement-and-lime compositions.
Q **When should I use cement?**	A If the building was constructed with cement in the mortar, then it may be appropriate to repair it with cement. However, the proportion in the mix will need to be considerably reduced to account for the high strength of modern cements and to make the new mortar compatible with the masonry. In some circumstances, it may be better to use a hydraulic lime or a lime and pozzolan mix. Some repairs to lime-mortared buildings (such as undersetting for salt damp) require early hardening and justify the use of cements. In such instances, the quick-setting characteristics of natural cement may be advantageous.
Q **Why should I use coarse, sharp sands? Bricklaying sands are so much easier to work.**	A Bricklaying sands, which are fine grained and rich in clay, produce weak mortars with low bond strengths and poor breathing characteristics. In contrast, well-graded, coarse, sharp sands produce strong and durable mortars that bond well to the adjacent masonry. By using lime, you can regain the workability lost with the change to cement. The workability of lime, cement and composition mortars can be improved with the correct use of mineral fillers (e.g. ground limestone) and water-retaining and air-entraining admixtures.
Q **When I tried using lime putty, a milky stain spread over the brickwork. How can I stop this happening?**	A Your mix may have been too wet or the putty insufficiently matured. Always use dry sand and lime putty that has been matured for at least four months. Drain the putty or carefully pour off the watery material from the top and use only stiff putty that will stand like feta cheese rather than run like thin cream. There is enough water in a stiff putty to make mortar for repointing. Do not add more. When the mix is stiff (yet still workable), the lime will not bleed (‘leak’) over the face of the brickwork, and so staining should not occur.
Q **Why all the fuss about curing? I’ll bet they didn’t worry about curing 100 years ago when they built this place.**	A Well they did actually, or at least some of them did: expressing concern that hot weather was bad for new brickwork. Also, there is a big difference between building a wall and repointing it. When the wall was built, porous bricks or stones were soaked or dipped in water to ‘kill’ their excessive suction and so the whole wall was wet through. The wall dried slowly, and the moisture in the bricks and stones helped the curing of the mortar. When we come to repoint them, most walls are relatively dry, so we need to add water before (by pre-wetting), during and after the work to prevent premature drying.

2.5 Repointing lime mortar joints: 11 key points

These are the key points to consider for successful repointing of lime mortar joints in stone and brick masonry.

1. Match previous mortars

- Binder: if the original was lime, use a similar type of lime.
- Sand: try to match the colour, grain size, grain shape and grading.
- Match the finished appearance of the original joint profile (such as flush, struck or tuck pointed).
- Match the mix proportions: traditional mixes were commonly 1:2–3 quicklime to sand.

2. You may need to modify the mortar mix

- The nature of the available limes or sands may differ from the originals.
- It may need to be made weaker (sacrificial) to protect the adjacent bricks or stones.
- It may need to be more permeable to promote better evaporation (breathing).
- It may need to be made slightly stronger by adding pozzolanic or hydraulic materials.
- Sacrificial mortars should be in the range 1:3 to 1:5 (lime to sand), depending on circumstances.
- Adjust the mix by adding lime (not water) to make poor sand more workable or to allow for finer-grained sand (e.g. 1:3 to 1:2.5 to 1:2 to 1:1.5 as sands get progressively finer).

3. Some mortars should not be matched

- Hard, cement repointing of an original lime mortar may need to be replaced in lime.
- Where good breathing is needed, mason's putty may be too impermeable.

4. Lime mortars are best made with slaked lime putty or quicklime

- Slaked lime putty is more workable – more plastic or buttery – than hydrated lime.
- Maturing putty before using it results in a finer particle size, faster curing and better working properties: these are even more important for plaster and limewash.
- Lime putty mortars can be stronger and will be more elastic than those made with hydrated lime mortars.
- The workability of hydrated lime can be improved by running it to a putty in water 24 hours before use – this is not slaking, but soaking – and do ensure the lime is fresh.
- Excellent mortars can be made by the traditional practice of sand-slaking quicklime.

5. Sands should be washed clean, and be sharp and well graded

- Washing sands clean removes clay, salt and organic material.
- Sharp sands – i.e. that are angular in shape – ensure a good bond to lime and to adjacent masonry.
- Well-graded sands provide a range of coarse, medium and fine particle sizes.
- Sands of a uniform grain size (whether coarse, medium or fine) lead to higher void ratios, requiring more lime to fill the voids.
- Dry sand makes for a better bond between lime putty and sand.
- Damp sand may produce too wet a mix for good repointing work.
- A proportion of porous aggregates (e.g. crushed porous limestone) can be beneficial.

6. Mixing mortars from matured putty

- Lime putty mortars are best made by pounding and chopping the putty into the sand with the broad end of a mattock handle in a bucket or with a mason's hoe ('larry'), a forced action (screed) mixer, a handheld helical-bladed mixer or a roller pan mixer.
- Conventional rotary cement mixers can be used, but need the addition of heavy stone or steel balls (such as milling balls) to force the lime and sand together.
- Pointing mortars need much less water than laying or bedding mortars.
- Lime putty should be drained of any free water and only dense, stiff material used.
- Do not add water to the mix: there is enough in the putty.
- Add more putty, not water, if needed to improve workability.
- Pure lime mortars can be mixed well ahead, kept sealed and then knocked up for use.
- The benefits of maturing the mix are greater than maturing the putty separately.
- Slaking quicklime with the sand (sand-slaking) produces mixes with excellent workability, good strength and other desired characteristics.
- After maturing, knock up the mortar with similar tools used in the original mixing (mattock handle, larry, or forced action, handheld, or roller pan mixer), but do not add water.

7. Raking or cutting out old mortar

- Rake the old mortar out to a depth at least 2½ times the joint width, leaving the ends square.
- Never widen original joints, no matter how narrow they are.
- Oscillating-blade tools (mortar saws or multi-tools) can be very useful for removing lime mortars.
- Use a small-diameter angle grinder to cut a slot in the centre of hard cement mortars, then use a sharp, tungsten-tipped chisel to remove the mortar from bricks or stones.
- Clean out joints with a vacuum cleaner and low-pressure water sprays.

8. Pre-wetting

- Pre-wet masonry thoroughly, to control suction and prevent premature drying of the mortar, which leads to inadequate hardening and poor durability.
- For most old (porous) walls, it will be necessary to wet them the day before and then several times on the day, the last time immediately before placing the new mortar.
- Walls should be thoroughly dampened, but not have water glistening on the surface.

9. Repointing

- A relatively stiff, dryish mortar mix is much better than one that is too wet.
- Mortar must be compacted tightly into the joints to achieve a bond with the masonry.
- Always fill any deep voids first, grouting if necessary before final repointing.
- Never use backing rods: they prevent good adhesion and stop the joint breathing.
- Use the correct tools: caulking or finger trowels that fit snugly in the joints, or plasterer's small tools for wide joints in rubble stone walls.
- For narrow joints, use a stiff, dry mix with care, or use masking tape on either side.

10. Finishing the joint

- Match the previous finish (such as struck or ruled); otherwise, use a plain flush finish.
- Don't overwork by dragging the tool: this brings too much lime to the surface.
- Dampen the joint with a fine water spray as soon as possible after placing the mortar.
- After initial stiffening, lightly scrape off any excess mortar with a trowel or small tool.
- Tamp the joint with a stiff-bristled brush to prevent shrinkage, expose sand and increase the surface area. Do this when it's still just possible to push a fingernail into the mortar.
- Tamping produces an aged appearance. The amount of tamping will be determined by the need to match any existing mortar and by the need for good breathing characteristics (the more tamping, the better the breathability).
- Spray the joint with a fine water spray as soon as tamping is complete.

11. Protection and curing

- Good protection and curing are essential aspects of making durable lime mortars.
- Water must be present for the hardening reactions – carbonation and hydration – to occur.
- New mortars must be protected during application from rain, heat, frost and particularly wind, to prevent rapid drying, and for at least four weeks afterwards.
- Misting systems may be needed to control humidity within tightly enclosed scaffolds, or cover work with removalists' blankets (or carpets) that are kept wet.
- Ideally, work only when the temperature is between 5°C and 30°C, and stage the job to avoid hot sun on new work.
- Keep new lime mortars quite damp for a week, then allow a week of damp 'drying', then a week of wetting and then damp 'drying' for the fourth week.
- Improved results can be achieved by additional cycles of wetting and drying, which should be specified for hot, windy or exposed environments.

2.6 The dos and don’ts of repointing mortar joints

Dos

Do consider whether the joints really need repointing. Unless they are allowing water to leak through the wall, slightly eroded joints may not need attention in the short-to-medium term. Deeply eroded joints risk excessive moisture penetration and should always be repointed.

Do match the original materials, colour and texture as closely as possible. This means matching the colour, grain size, grain shape and grading of sands as well as binders. It also means matching the finished appearance of the original joints (e.g. flush or struck), if appropriate. Often an aged look is needed to blend the new work in with the existing.

Do use lime mortars when repairing joints that were originally made with lime. Sand-slaked quicklime or slaked lime putty will make more workable mixes than hydrated lime.

Do soak hydrated lime in water for 24 hours before using it. This will improve its performance, but it will never be as workable as traditionally slaked lime putty. Ensure the hydrated lime is fresh.

Do consider that you may need sacrificial mixes to manage excessive salt accumulation in the masonry, particularly where the need for repointing is because of mortar loss due to salt damp.

Do use jointing tools (such as caulking or finger trowels) that fit snugly within the joints and apply considerable pressure to tightly compact the mortar into the back of the joints.

Don’ts

Don’t use cement to repoint joints that were originally made with lime. As well as being historically wrong, there are good technical reasons for not doing so: cement is too hard and too rigid and it blocks pores, preventing the mortar from breathing well. Where salts are present, they may damage the adjacent masonry instead of the mortar. The greater thermal expansion of cement mortars can also damage adjacent bricks or stones, spalling their edges or arrises.

Don’t use high proportions of reactive pozzolans in lime mortars to repair old masonry. Modern pozzolans like ground granulated blast-furnace slag (GGBFS) and fly ash are quite reactive and, like cement, will tend to block pores. Use these materials at 10% by volume of the lime if moderate strength is required; 5% by volume of the lime will be enough for much repointing. Less-reactive pozzolans (such as trass) can be used in higher proportions.

Don’t use the higher classes of natural hydraulic lime (NHL 3.5 or NHL 5) when the lower (NHL 2) will suffice, particularly where the original mortar was essentially non-hydraulic. The higher the class of NHL, the more blocked will be the pores, though much less so than with cement.

Don’t carry out repointing when the temperature is more than 30°C. The new work will dry out too quickly and the mortar won’t harden. Strong winds in cool weather can be equally damaging. Protect walls with tightly enclosed scaffolds, and work around a building away from direct sun.

Don’t use acids and high-pressure water jets to clean mortar spills off brickwork. Repointing can be done without leaving mortar smears on the surface. Mixes should be made with a low water content and be relatively dry and stiff. If mortar is correctly placed with tools that fit within the joints, there should be no mortar on the face of the brickwork.

Don’t even think about sealing older walls with water-repellent coatings: they can trap water and salts and disrupt the surface. Most permanent anti-graffiti coatings will also trap water.

PART 2

Mortar materials and mixes

This part of the guide aims to provide a thorough understanding of mortar materials, including limes, cements and pozzolans, as well as sands and other aggregates before discussing how they are combined in mortars. Mixes for six mortar types are suggested for a range of applications. Further chapters cover workability, mortar mixing and the investigation and analysis of existing mortars. The part begins with some background on the role of mortars in traditional masonry and some key changes in Australian construction practice.

Figure 7: Traditional lime burning. A lime kiln at Susac Lime Supply, Carabooda, north of Perth, Western Australia. This may be the last such lime kiln operating in Australia: most had ceased production by World War II.

Photo: Alan Kelsall.

3 Role of mortars in traditional construction

As well as contributing to the appearance of a wall, mortar performs four important roles:

- providing a cushion – an even bed – for the overlying masonry units
- bonding the masonry units together
- weatherproofing the wall
- providing a drying wick: a moisture path that promotes drying.

The first three of these roles are commonly understood. The fourth is particularly important for older, solid walls, which are normally more porous and permeable than modern ones.

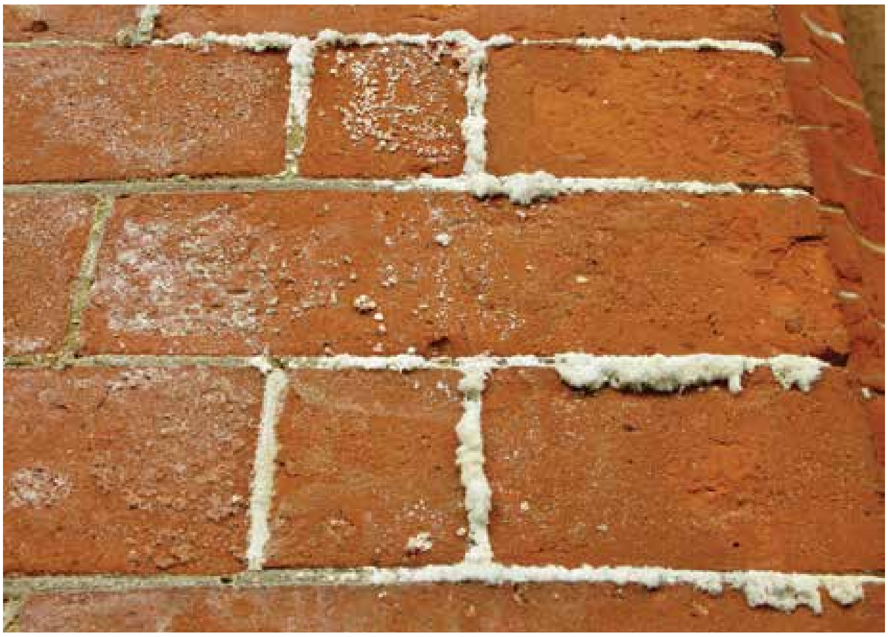
Bricks, stones and blocks are collectively described as masonry units.

The drying wick or moisture path through a wall is essential to allow it to dry rapidly after rain. When rain strikes a wall, some runs off down the wall surface and some soaks in through the network of fine capillaries that is the pore structure of the masonry units and of the mortar. When the mortar is more permeable than the masonry units, much of the drying can take place through the joints, speeding up the drying process and reducing the risk of water penetrating deeper into the wall.

At first it may seem that weatherproofing a wall and also providing a moisture path through it are contradictory aims, but this is not so. The explanation lies in the relative sizes of the voids and pores in a wall. Large voids, such as gaps between brick and stones, that would let substantial water through a wall are filled with mortar to make it weatherproof. On the other hand, small pores in the masonry (stone, brick and mortar) allow some moisture to move through the wall, but it does so slowly and generally the wall will dry before the moisture reaches the other side. Porous masonry behaves like a giant sponge, absorbing moisture during rain and giving it up in dry periods. The quicker that a solid wall can dry the better, as it reduces the likelihood of moisture reaching internal spaces. Permeable mortar is the key to promoting rapid drying and good breathing of older walls.

Traditional masonry walls are a system in which the permeable mortar plays an important role in concert with the bricks or stones. Figure 8 illustrates this: moisture moving through the wall is carrying a lot of salt, which predominantly crystallises at the more permeable mortar joints (see also Box 9 'Compatibility').

Figure 8: Permeable mortar. Salt crystals extruding from joints indicate that the lime mortar is more permeable than the bricks. By decaying in preference, and so protecting the bricks, the mortar is said to be sacrificial. Were the salt to be trapped in the less-permeable bricks, the damage to them would be very much greater than it is.



4 Mortars in Australia – then and now

Lime was the principal binder in mortars and plasters of nineteenth century Australian buildings, and continued in this role in domestic construction until the mid-twentieth century.

Most of the lime used in Australia was the more common non-hydraulic variety, though there was some local production and also importation of hydraulic limes. Hydraulic limes were used in engineering works and other highly specified structures, but the full extent of their use in Australia is not yet clear and needs further research. The boundary between non-hydraulic limes and hydraulic limes is gradational (see Section 8.1 'The lime–cement spectrum') and some of the older limes that would be classified as non-hydraulic are likely to have had a small proportion of hydraulic components.

Portland cement was first imported in the 1850s but, along with the earlier, natural cements, would, on account of the higher cost, have been reserved for limited use on the more exposed parts of buildings (such as renders, mouldings and cast work). Portland cement began to be used in the mortars of larger buildings in the late nineteenth century. Its more widespread use came in the early twentieth century with the advent of large-scale local production.

Major changes in building practices after World War II led to the predominant use of cement in mortars, as cement-and-lime composition (compo) mortars. A key reason for this was that cement hardened much faster, which enabled more rapid construction. Increasing industrialisation also saw the decline of small-scale lime burning (see Figure 7) and its replacement by larger operations producing hydrated lime. As a result, sand-slaked lime mortars (and lime putties for plasters and limewashes) were replaced by dry hydrated lime, with the added convenience of its supply in paper bags, like cement. Today, building is only one of many uses for hydrated lime, which is made from relatively pure limestone and may be quite different to the limes used in the past.

Earth mortars, in which clay is the binder, were widely used for laying masonry in early buildings. Their joints were made weatherproof by pointing with lime and sand.

Table 1: Principal binders used in Australian mortars

Houses & small buildings	Year	Large buildings & engineered structures
composition	2000	composition
composition	1950	composition cement
lime composition	1920	cement composition
lime composition	1900	cement composition
lime clay	1880	cement hydraulic lime lime
lime clay	1850	lime hydraulic lime
clay lime	1800	lime clay

Note: The larger the type size, the more dominant the usage. This is provisional information and needs further research: exceptions and local variations are to be expected. Note that cements used in the late nineteenth and early twentieth centuries were very different to modern cements (see Section 6.3 'Portland cement through time').

The change from lime to cement meant a change from plastic, workable mortars to materials that were more difficult to work with a trowel. To regain lost workability, there was also a change in the use of sands in many areas, from sharp and well-graded sands that were free of clay to soft sands that are fine grained and clay rich. Clay-rich bricklaying sands produce poor-quality mortars of low durability. Despite this, they are used today with cement because they bring workability advantages: clay is even added to some sands with poor working properties.

In some areas, the only available sands were of poor quality. Those using them adjusted their mixes to suit. See Section 9.11 'Making do with poor sands'.

The challenge for repairers of older buildings that were constructed with lime is to:

- **revert to the use of lime binders in place of cement**
- **revert to the use of good-quality building sands**
- **ensure everyone involved understands these materials.**

All three must be progressed in unison for the results to be successful.

Ensuring that everyone understands the use of lime binders and good-quality building sands is particularly important. Anyone working on buildings today, whether as a specifier (such as an architect or engineer) or as a contractor or tradesperson (such as a bricklayer or stonemason) will have been trained to work with contemporary materials and may not be aware of the often very different properties of traditional masonry materials.

Old bricks can be quite porous – 25–35% porosity is common for low-fired bricks from the mid-nineteenth century – whereas modern, general-purpose extruded bricks are more highly fired and have porosities around 7%, while exposure-grade bricks can have less than 5% porosity. A strong, cement-based mortar suitable for use with a modern, exposure-grade brick will lead to irreparable damage if used with a soft, porous brick, while a mortar appropriate for such a brick will have insufficient bond strength for the low suction of a modern brick.

Suction is determined by pore size and distribution, as well as total porosity.

With the change in materials has come a change in work practices. Traditional practices included pre-wetting the masonry units by hosing the stack and this was often followed by dipping them in a bucket of water, just prior to laying. The aim was to reduce or 'kill' the suction of the brick or stone so it would not draw too much moisture from the mortar. If this was allowed to happen, the mortar would dry prematurely leaving it friable, of low strength and poor durability. With pre-wetting, the natural workability of the lime allowed the use of mortars with a low water content.

> See Chapter 10 'Water', Section 14.2 'Water retentivity', and Chapter 21 'Pre-wetting'

In contrast, contemporary practice with modern bricks of low suction – with a low initial rate of absorption, or 'IRA' – is not to pre-wet the bricks but to lay them using mortar that has a maximum water content (consistent with good bricklaying practice) so that the bricks absorb some water and pull some cement in with the water, to create a good bond.

When repointing older walls made of porous materials, work practices need to be appropriate for them. Also, some materials still in use today are very porous (particularly sandstones, limestones and recycled older bricks). Mortars for these materials need to be traditional porous mixes to be compatible with them, and so produce walls that work as systems (as Chapter 3 explains).

5 Limes

Originally, the word ‘lime’ was used for sticky materials (such as glues and pastes). Today the word has a variety of meanings, and in relation to mortars it is used for both quicklime (calcium oxide) and for slaked or hydrated lime (calcium hydroxide). There are different types of limes including non-hydraulic limes and hydraulic limes and it is important to be clear about the distinction between them.

To complicate things further, there are calcium limes and dolomitic limes. Dolomitic limes contain both calcium and magnesium and have more complex chemistries than calcium limes. This guide does not cover dolomitic limes because they are not common in Australia, though they are widely used overseas, particularly in North America and parts of Europe.

Don’t confuse building limes with agricultural lime (ag-lime), which is just ground limestone and has no binding power.

5.1 Types of lime: non-hydraulic and hydraulic

Non-hydraulic limes have been the most commonly used limes in Australian building construction and are generally described just as lime. ‘Non-hydraulic’ implies they do not harden by reacting with water; instead they react with carbon dioxide in the air, and for this reason they are also known as air limes. Non-hydraulic (or pure) limes come in three distinct forms:

- as quicklime, in various particle sizes, such as rock, pebble (nut) or powder
- as a wet hydrate or putty, commonly described as slaked lime putty or simply lime putty
- as a dry hydrate or powder, known as hydrated lime, or builder’s lime.

The term ‘air lime’ is common in Europe and is used in the European standard for building lime (EN 459) as the general name for all non-hydraulic limes.

Hydraulic limes (or water limes) are more complex materials containing a hydraulic component and a non-hydraulic component. The hydraulic component hardens by reacting with water (as do cements), producing a stronger binder than non-hydraulic limes. The non-hydraulic component hardens by reacting with air, as for non-hydraulic limes. As noted in Chapter 4, the gradational boundary between non-hydraulic and hydraulic limes means that some non-hydraulic limes will contain a small proportion of hydraulic material.

> See also Section 8.1 ‘The lime–cement spectrum’

Following sections explain the manufacture and properties of the various limes. This guide focuses on non-hydraulic limes, as these were the materials used most in Australian building. They remain widely available but in the modern form of relatively pure hydrated lime. There are also several manufacturers of slaked lime putties. Although hydraulic limes were used here, they are not currently made in Australia and are imported from Europe, where there are several manufacturers.

Although most non-hydraulic limes today are pure limes, some early mortars were made with lean limes.

5.2 Non-hydraulic (pure) limes and the lime cycle

The raw material for making lime is calcium carbonate, generally in the form of relatively pure limestone or chalk. Marble, which is a metamorphosed (altered) limestone, is another source. Other sources include seashells and coral, which the early British colonists used to make lime in Australia. Some sands are naturally composed of calcium carbonate (as worn-down seashells) and these can also be used for making lime. They are known as lime sands, as distinct from quartz (silica) sands.

Lime burning (calcination)

The first stage of producing lime is to heat the limestone (or the other materials) in a kiln to about 950°C. The heating, which is technically described as calcining (and is commonly but incorrectly known as burning) converts the calcium carbonate, giving off carbon dioxide gas and leaving behind calcium oxide, which is quicklime.

> The chemistry of lime burning and the other reactions in the lime cycle are explained in Box 2.

Lime slaking (hydration)

Quicklime (also known as rock lime or lump lime) is a highly reactive material that stores the energy involved in making it. When combined with water, it reacts vigorously and generates a lot of heat. The process is known as slaking (technically hydration) and the product is calcium hydroxide, or slaked lime.

> See Box 16 'Health and safety with mortars'

The energy liberated by the reaction depends on the purity of the limestone raw material and on the calcining temperature, but it can be sufficient to boil the water (see Figure 9) or cause a steam explosion if not handled correctly: when slaking, highly reactive quicklime is always added to water, never water to quicklime. Soft-burnt quicklimes – those that have been calcined at temperatures below about 950°C – are more reactive and are preferred to those calcined at higher temperatures (hard-burnt quicklimes).

Figure 9: Slaking quicklime to produce lime putty. The reaction releases the stored energy in the quicklime and can produce sufficient heat to boil the water, as seen here, though ideally the temperature should be kept just below boiling point. When making putty, quicklime is always added to water: adding water to highly reactive quicklime risks a hazardous steam explosion. Anyone working with quicklime must understand the risks involved and must be able to describe and apply the necessary safety precautions.

In traditional production, quicklime was slaked in more water than needed for the reaction, resulting in the formation of a wet hydrate or putty known as slaked lime putty or just lime putty. In modern hydrating plants, an old practice has been mechanised: just enough water is added to the quicklime to produce the dry powder known as hydrated lime, or builder's lime. In theory, lime putty and hydrated lime should be the same (after allowing for the water in the putty) but in practice there are important differences, which the next section explains.

Lime hardening (carbonation)

Lime putty and hydrated lime are binder materials that are mixed with aggregates (principally sands) to make mortars, plasters and renders. The hardening (or curing) of non-hydraulic lime binders involves the slow absorption of carbon dioxide from the air and the conversion of the calcium hydroxide back to calcium carbonate in a process known as carbonation.

There are actually two stages to this reaction. In the first stage, carbon dioxide from the air dissolves into the mixing water remaining in the pores to form carbonic acid. In the second stage, the reaction of the carbonate in the acid with the lime (calcium hydroxide), which dissolves into the acidic water, produces calcium carbonate, which precipitates out to form a mass of small crystals that bind to each other and to the aggregate.

> The hardening of lime mortars is further discussed in Section 5.6.

While the hardening of a non-hydraulic lime is with carbon dioxide from the air, the reaction will only take place in the presence of water. This why lime mortars must be kept damp (well cured) during hardening.

Box 2: Chemistry of non-hydraulic limes

The chemical reactions that take place during the burning, slaking and hardening of non-hydraulic limes are set out here.

Burning (calcination)

Limestone (or marble, seashells or coral) is heated in a kiln to drive off carbon dioxide and produce quicklime:

$CaCO_3$	+	heat (950°C)	=	CaO	+	CO_2	(1)
Limestone (calcium carbonate)	+	heat	=	quicklime (calcium oxide)	+	carbon dioxide (gas)	

Slaking (hydration)

The quicklime is then combined with water in the process known as slaking:

CaO	+	H_2O	=	$Ca(OH)_2$	+	heat	(2)
Quicklime (calcium oxide)	+	water	=	slaked lime (calcium hydroxide)	+	heat	

The reaction is strongly exothermic – it produces a lot of heat – and can be hazardous.

Hardening (carbonation)

Pure limes harden by slowly reabsorbing the carbon dioxide from the air, in a process known as carbonation:

$Ca(OH)_2$	+	CO_2	=	$CaCO_3$	+	H_2O	(3)
Lime (calcium hydroxide)	+	carbon dioxide	=	calcium carbonate	+	water	

In fact, there are two stages to this reaction, which is more correctly shown here. In the first stage, carbon dioxide dissolves into the mixing water to form carbonic acid:

CO_2	+	H_2O	=	H_2CO_3	(3a)
Carbon dioxide	+	water	=	carbonic acid	

In the second stage, the lime dissolves into the acidic water and reacts to produce calcium carbonate:

$Ca(OH)_2$	+	H_2CO_3	=	$CaCO_3$	+	$2H_2O$	(3b)
Lime (calcium hydroxide)	+	carbonic acid	=	calcium carbonate	+	water	

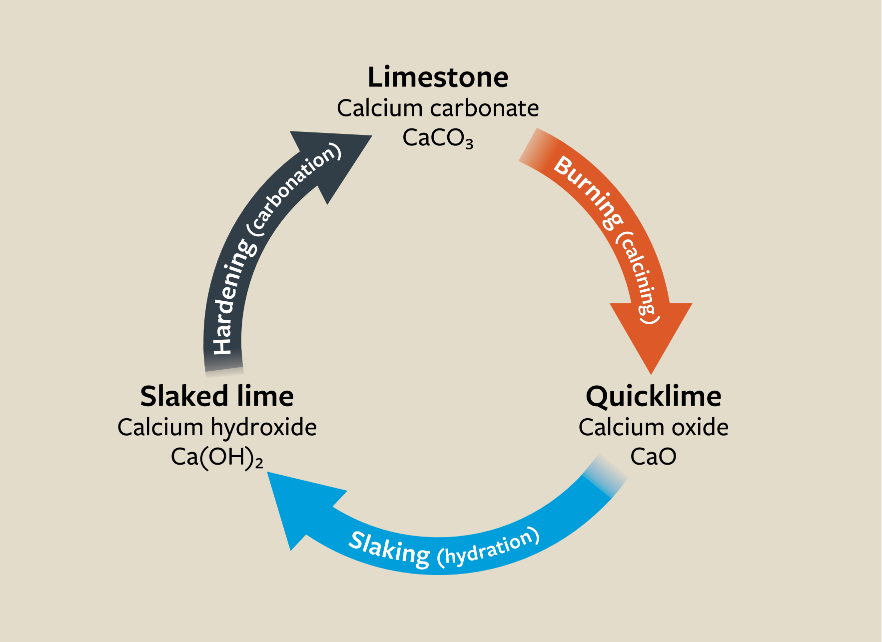
The calcium carbonate precipitates out to form a mass of small crystals that bind to each other and to the aggregate, while the excess water evaporates.

The lime cycle

Because the hardened product (calcium carbonate) is chemically the same as the limestone raw material, the production and hardening of lime is known as the lime cycle. Figure 10 shows the three stages of the cycle:

- the burning (calcining) of limestone to make quicklime
- its slaking (hydration) to form slaked lime
- the hardening (carbonation) of the lime back to calcium carbonate.

Figure 10: The lime cycle.



So far, we have looked at lime made from relatively pure sources of calcium carbonate. These produce what are known as pure or high-calcium limes. Many limestones contain other minerals (such as sand, silt or clay) in appreciable quantities. Though geologically described as impurities, these additional minerals may be beneficial in that they may react in the kiln to produce calcium silicates and calcium aluminates which are stronger binders than lime. These are hydraulic limes, which are discussed in Section 5.7.

The underburnt centre (core) of some lumps of quicklime may remain as calcium carbonate. Unless removed, they effectively become part of the aggregate (see Box 13 'Lime lumps').

Some materials remain unaltered in the kiln and contribute nothing to the product. These underburnt or inert lumps are often removed by screening before the lime is used. A lime with appreciable inert material is known as a 'lean lime', in contrast to a pure, high-calcium or 'fat' lime. These terms give an understanding of their workability and sand-carrying capacity:

- a fat lime is readily worked because of its buttery or creamy consistency and has a high sand-carrying capacity
- a lean lime is less workable and needs to be used with a smaller proportion of sand to make a mortar with similar workability to that of a fat lime. Lean limes are less common today.

5.3 Lime putty and hydrated lime

Though they apparently have the same chemistry, there are noticeable differences between a mortar made with lime putty and one made from hydrated lime. Some differences result from their initial formation, others from maturing (or ageing) of putties, while others may occur during storage and use. Here it is important to be clear about terminology. Lime putty and hydrated lime have both been hydrated by reaction with water. The term lime putty is used for material that has been directly slaked (from quicklime) in an excess of water to form a wet putty, while hydrated lime is (paradoxically) used to mean the dry powder form. Hydrated lime can be run to a putty in water, but this is soaking, not slaking, and its properties will differ from those of a putty that is directly slaked from quicklime.

Provided it is protected from carbon dioxide in the air (by sealing it under a layer of water or in a lidded pail or drum), lime putty can be kept indefinitely, as it will not harden. On the other hand, if not tightly sealed in an airtight bag, dry hydrated lime can absorb carbon dioxide from humid air and can partially carbonate, leading to a less workable material with reduced binding power because some of it has hardened before use. A similar problem happens with bagged cement, though in that case the reaction is with water in the atmosphere, not with carbon dioxide.

Slaked lime putties have finer particle sizes than soaked hydrated limes. The fineness increases with prolonged maturing of the putty: the particle size gets smaller and the shape of the particles change as they break down – hexagonal columns cleave into tiny plates – leading to a significant increase in plasticity, as the tiny plate-like particles slide past each other more readily than do the coarser columns. Lime putty is often specified to be matured for at least four months, but in practical terms the desirable maturation period depends on the application: limewash calls for the most mature lime putty, then plaster and render, then pointing and repointing, and finally bedding mortar for the least-mature putty.

> Plasticity, a key aspect of workability, is discussed in Chapter 14 ‘Workability’

Provided that it has settled out to a dense putty, a few weeks maturing may be sufficient for laying bricks or stones; four months will make a pointing mortar more workable; and limewash will be improved by at least a year’s maturing to reduce its particle size and increase its reactivity by increasing the effective surface area of the particles. Premixed mortars of lime putty and sand can also be matured, and the benefits of doing this are greater than those of maturing the putty separately.

> See Section 15.3 ‘Off-site preparation and maturing of mixes’

Directly slaked lime putties (known as irreversible colloids) consist of fine particles of calcium hydroxide surrounded by water, which, if they are allowed to dry out, will never recover their former properties. This is because the drying process leads to small particles clumping together into much larger particles, which cannot be broken down simply by adding water. The same clumping (also known as agglomeration or crystal coarsening) occurs during the manufacture of hydrated limes, and it is a reason why mortars made of the latter are not as workable as those made from putties.

The workability of mortars made from hydrated lime can be improved by mixing the lime powder to a putty consistency in water (soaking it) and storing it for at least 24 hours before using it. For the reasons explained above, further maturing will have limited workability benefits, but may be needed to allow time for the putty to settle out and become sufficiently dense.

Researchers have differed on whether lime putty makes stronger mortar than hydrated lime. Some research indicates similar strengths for both types; other research shows significantly greater early (28 day) strength for lime putty. Mortars made with hydrated lime will certainly be weaker than those made with lime putty if the hydrated lime has partially carbonated before use. ‘Going-off’ in the bag can be minimised by using only freshly manufactured material.

Differences between types of sand (aggregate) may produce greater variations in strength than differences between limes (see Section 9.9 ‘Other aggregates’ and Section 9.10 ‘Mineral fillers’).

There is no reason why a lime mortar cannot be made of a blend of lime putty and fresh hydrated lime. Indeed, this may be a useful compromise in situations where some workability can be sacrificed for the low weight of hydrated lime, with consequent savings in transport costs.

5.4 Densities of lime putties and hydrated limes

The densities of lime putties and hydrated limes can vary widely, both within and between the two types. Despite the water content, a dense, matured putty will contain more lime than the same volume of dry hydrated lime. If this is not understood, and appropriate adjustments made, the resulting mortars may not meet specification and will commonly have insufficient lime.

Lime putty (made from a high-calcium limestone) should have a bulk density of least 1,350 g/L (1.35 kg/L). At this density, the lime will be a little under half the weight of the putty (about 600 g in a litre of putty), while water will be a little over half the weight (about 750 g in a litre of putty) and about three-quarters of the volume of the putty.

Freshly made putties of lower densities will contain more water and less lime. Consider, for example, a density of 1,270 g/L. This might seem close to 1,350 g/L, but such a putty will have only three-quarters of the lime of the latter. These differences will have a significant bearing on the actual proportions of binder to aggregate in a mortar mix: in this case, a 1:3 mix would actually be a 1:4 mix, if putty of the lower density were used.

While 1.35 kg/L is the minimum density for lime putty, the ideal is closer to 1.4 kg/L when the lime content will be about 675 g/L. Such a putty contains 50% more lime than one with a density of 1.27 kg/L.

Commercially available Australian putties are generally less dense than 1.35 kg/L. They should be drained before use to ensure only stiff putty remains, although the lime slurry from on top should be retained, because it has potential uses, which Section 19.1 ‘Batching’ explains. In cooler and damper climates, lime putty is stored in woven polypropylene bulker bags, to allow it to drain. This is less practical in the hotter, drier Australian climate as the putty would prematurely dry out and carbonate.

> See Section 19.2 ‘Mixing’ for more details about managing the water content of putties and mixes

Hydrated lime has a bulk density of 350–640 g/L – the wide range reflects variability of the raw materials, as well as bulking of the dry powder. Fine, dry powders can bulk up, increasing their volume substantially and giving a misleading impression of the actual amount of material present. In a hydrated lime with a density of 400 g/L, there is only two-thirds of the amount of lime present compared to a matured, dense putty (which is 600 g/L). For this reason, mix proportions may need adjusting when using hydrated lime (see Section 19.1 ‘Batching’). A mix made with hydrated lime may need to be as rich as 1:2 to be comparable with a 1:3 mix made with lime putty.

Australian Standard 1672.1 assumes that a given volume of putty contains an equal volume of hydrated lime: the implied densities are 1.285 kg/L for putty and 480 g/L for hydrated lime (see Box 10 ‘Mortars and Australian Standards’).

Densities of putties and dry hydrates can be straightforwardly measured by weighing their known volumes. For example, take a container that will hold a suitable volume that can be accurately measured: say, 1 or 2 litres. Weigh the container empty. Fill it with lime putty or hydrated lime, level it off carefully and weigh it again. Subtract the weight of the container and then divide the result in grams by the volume in litres. As noted above, lime putty should be at least 1,350 g/L (1.35 kg/L). Transferring hydrated limes to the container will inevitably lead to some bulking of the dry powder, but after tapping the sides of the container to reduce the bulking effect, their compacted densities will typically range from 450–640 g/L.

Figure 11: Density matters! In addition to its water content, a matured, dense lime putty will have about 600 g/L of lime. The same amount of lime in dry, hydrated form can occupy one and a half times the volume of the putty, and may, depending on the source and bulking, be closer to two times the volume of the putty. It is important to take account of these differences when batching mortars. One way to do this (and avoid bulking concerns) is to run the hydrated lime to a putty in water (see Section 19.1), let it stand to allow the putty to settle and then use only the denser material, as is done with directly slaked lime putties. Because they clump (as mentioned in Section 5.3), soaked hydrated limes will never achieve the same densities as directly slaked putties.

5.5 Quicklime mortars

An alternative to using putties and hydrated limes is to make mortars in the traditional way, directly from quicklime. The quicklime is slaked with the sand, not separately. This sand-slaking (or dry-slaking; also hot-mixing) was the way most lime mortars were made until well into the twentieth century. Traditional mixes were based on run-of-kiln lump quicklime, whereas modern quicklime may be in chip or powder form with densities ranging from 900–1,200 g/L, depending on particle size and degree of burning.

As with putties and hydrated limes, density differences between quicklimes must be taken into account.

Sand-slaking can be a way of safely controlling the energy released from the quicklime. Also, the heat generated by the slaking cleans up the sand and leads to better contact with the lime. Section 19.2 explains how quicklime mortars are made by sand-slaking. These mixes can be stored in sealed containers and allowed to mature before use, which improves their workability.

> Sand-slaking and the related hot lime mortars are further explained in Section 15.1 'Traditional mixing'.

5.6 Setting of lime mortars

The setting of lime mortars is a two-stage process: stiffening, then hardening.

The initial stiffening and drying of a newly laid mortar is due to the suction of the adjacent masonry units, which draws the mixing water from the mortar into the pores of the bricks or stones. Some drying is also due to evaporation. This first stage – developing an initial set as the mortar loses its plasticity or workability – involves no chemical reaction. It is due to forces related to surface tension, the same forces that cause damp sand to increase in volume (to bulk up) and allow it to stand as sandcastles on a beach.

The second hardening (or curing) stage is when chemical reactions occur and the binder hardens around the sand to form a solid mortar. These two stages happen to all mortars, whether cement- or lime-based, but are particularly relevant to lime mortars (including hydraulic limes) because of their slower hardening. Slow hardening of lime mortars is well documented, with cases of lime deep inside thick walls that have never properly cured. Lime mortars need thorough curing if they are to harden properly.

> Lime mortars need thorough curing if they are to harden properly, see Chapter 24 'Protection and curing' for practical details.

Lime mortars should be kept quite damp for a week, during which time there will be little or no carbonation (except at the surface), only the slow dissolving of carbon dioxide into the mixing water. Then, as the mortar slowly dries, carbonation will begin to occur as the lime dissolves into the now-acidic mixing water and reacts to produce calcium carbonate (as explained in reactions 3a and 3b in Box 2). The ideal curing conditions (after the initial week of wetting) are a temperature of 15–20°C and relative humidity of 60–70%. These conditions are unlikely in the hotter and drier months in Australia, and indeed for much of the year. Consequently, it is usually necessary to modify the environment around a curing mortar.

Excessive hot weather is bad for brickwork. The best conditions for good work are in winter, when the atmosphere is damp. The slow setting of the work is always to be aimed at.

Haddon, 1908

Experience has shown that periodic wetting and drying will improve the hardening of lime mortars. Cycles of wetting and drying can be deliberately applied as part of a planned curing process, but such cycles might also happen naturally where rain periodically strikes the wall. This is one reason why some sides of a building can be better cured than others. The effect is commonly seen on chimneys which are more exposed to the weather: the weather side is often better cured. Deterioration on the lee side of a chimney might be partly due to incomplete hardening, but there might be other factors at work, particularly salt attack (see Figure 34).

Recent laboratory research has demonstrated that repeated cycles of wetting and drying can ensure thorough carbonation of a lime mortar, which can increase its strength to nearly double that of an untreated sample. The same research showed additional cycles of wetting and drying further increased the mortar's strength to about two and half times that of the untreated mortar. Importantly, as well as further carbonation, the additional cycles also resulted in dissolution and recrystallisation of the newly formed calcium carbonate, producing a better-interlocked binder matrix that should be stronger and more durable. This confirms the effectiveness of the traditional practice of repeatedly wetting lime mortars, plasters and washes to accelerate their hardening.

> The steps needed to ensure thorough hardening of mortars are explained in Chapter 24 'Protecting and curing'.

5.7 Hydraulic limes

Don't confuse hydraulic limes with hydrated limes – they're different. Although hydraulic limes have been partly hydrated, the term 'hydrated lime' is normally used only for pure (non-hydraulic) limes.

Hydraulic limes can be thought of as a cross between pure (non-hydraulic) limes and cements. Like cement, a component of a hydraulic lime sets by reacting with water in a process known as hydration, caused by the presence of silica and/or alumina, either in the limestone raw material or added later. The materials produced on hardening – principally hydrated calcium silicates – are quite different binders to the calcium carbonate of non-hydraulic limes. Hydraulic limes can be natural or artificial.

Natural hydraulic limes

Natural hydraulic limes (NHLs) are so named because their limestone raw material naturally contains silica or alumina (as amorphous silica, or as aluminosilicate minerals in clays) in the correct proportions for the binder. Such materials are called argillaceous (if clay bearing) or siliceous (if silica bearing) limestones. Geologically, these limestones are described as impure, yet it is the impurities which are the key to making hydraulic limes.

The impure limestones are burnt at temperatures of about 1000–1100°C which produces a reaction between some of the resulting quicklime (from the limestone) and the silica (or alumina) to produce calcium silicates (or calcium aluminates). The resulting mix of calcium silicate (or aluminate) and calcium oxide is then slaked with just enough water to hydrate the calcium oxide (but not so much as to cause a reaction with the hydraulic component), leaving a dry powder which is then ground (if required) and bagged.

> See Box 3 for an outline of the chemistry of hydraulic limes.

It is important to be clear that there are two active components in a bag of natural hydraulic lime: a hydraulic component (calcium silicate and/or calcium aluminate) and a non-hydraulic component (calcium hydroxide, i.e. hydrated lime). Two reactions occur when the natural hydraulic lime is mixed with water: the hydraulic component hardens in a reaction known as hydration; the non-hydraulic component hardens by carbonation, which Section 5.2 explains.

As it reacts, the hydraulic component consumes some of the mixing water and grows as interlocking needle-like crystals. This leads to a stronger but less-permeable mortar than one made with non-hydraulic lime.

> See Figure 12

The classification of hydraulic limes is explained in Box 4 and the spectrum from pure limes through hydraulic limes to cements is discussed in more detail in Chapter 8 'Comparison of lime and cement binders'.

The proportions of the hydraulic and non-hydraulic components can vary, leading to a series of natural hydraulic limes with a range of strengths and other properties that sit between non-hydraulic limes and cements. European Standard EN 459 currently recognises three classes: NHL 2, NHL 3.5 and NHL 5. NHL 5 is the most hydraulic – the strongest and fastest hardening – while NHL 2 is the closest to pure (non-hydraulic) lime. Some argue for the introduction of an NHL 1 class, which would sit between NHL 2 and pure limes.

Because hydraulic limes react with water, they are only available as dry powders and come in paper bags, like hydrated lime and cement (see Figure 4). As with those materials, the dry powder can bulk up. It is important to be aware of their normal, compact density and use an initially weighed amount as a basis for calculating proportions when batching mixes (see Section 19.1 'Batching').

Typical compacted (that is, not bulked up) densities of lime powders are:

- non-hydraulic (hydrated) lime: 450–640 g/L
- natural hydraulic lime (NHL 2): 475–565 g/L
- natural hydraulic lime (NHL 3.5): 440–650 g/L
- natural hydraulic lime (NHL 5): 690–700 g/L.

The ranges above reflect variations in raw materials as well as in manufacturing processes.

Compared to cement, hydraulic limes harden relatively slowly and can take up to two years to achieve their ultimate strength. This needs to be allowed for in construction, but is generally not an issue for repointing, so long as the ultimate strengths are clearly understood. Hydraulic lime mortars should not be designed on the basis of 28-day strengths; 90 days gives a more characteristic value, but it should be remembered that the strength may eventually exceed 150% of the 90-day value.

As with pure limes, hydraulic limes need careful protection and curing if they are to perform as intended (see Chapter 24 ‘Protection and curing’).

Repeated wetting and drying (as explained in Section 5.6) also improve the hardening of hydraulic limes.

Artificial hydraulic limes

Artificial hydraulic limes can be made either by burning limestone and silica or clay together in the required proportions, or by combining (cold) non-hydraulic lime (as putty or dry hydrate) with reactive siliceous materials known as pozzolans (see Chapter 7 ‘Pozzolanic materials’). The nature and proportion of the pozzolan used determines the hydraulicity, strength, porosity and other properties of the resulting binder.

A pre-packaged mix of hydrated lime and pozzolan would be classed as a formulated lime according to EN 459.

Box 3: Chemistry of hydraulic limes

The chemistry of hydraulic limes is more complex than that of non-hydraulic limes, so for simplicity only reactions with silica are shown below. Most hydraulic limes contain silicates, while some contain appreciable aluminates.

Burning (calcination)

Siliceous limestone is heated in a kiln, driving off carbon dioxide and producing quicklime (as for non-hydraulic limes, see reaction 1 in Box 2). Some of the quicklime reacts with silica to form calcium silicate:

$$2CaO \quad + \quad SiO_2 \quad + \quad \text{heat (1,000°C)} \quad = \quad Ca_2SiO_4 \qquad (4)$$

Quicklime (calcium oxide) + silica + heat = di-calcium silicate

Di-calcium silicate is the mineral belite, which is also found in Portland cements (see Box 5 ‘Cement chemistry’).

The resulting mix of belite (di-calcium silicate) and quicklime (calcium oxide) is then slaked with just enough water to hydrate the calcium oxide (as in reaction 2 in Box 2) but not so much as to cause a reaction with the silicate.

Hardening (hydration and carbonation)

Two separate reactions occur as a hydraulic lime hardens. The hydraulic component (di-calcium silicate) reacts with water in a reaction known as hydration, producing a complex hydrated calcium silicate:

$$Ca_2SiO_4 \quad + \quad H_2O \quad = \quad \text{C–S–H*} \qquad (5)$$

Di-calcium silicate + water = calcium silicate hydrate

* Because the chemistry of this material is very complex, cement chemists use a simplified notation: C–S–H indicating calcium silicate hydrate; see Box 5 for details.

The non-hydraulic component (hydrated lime) hardens by carbonation, as in reactions 3a and 3b in Box 2.

The resulting binder is a mixture of calcium silicate hydrate and calcium carbonate.

Box 4: Classification of hydraulic limes

Natural hydraulic limes (NHLs) have been classified in various ways, beginning with the early-nineteenth-century work of Vicat who identified three classes or grades (later to be known as Feebly, Moderately and Eminently hydraulic limes), based on their setting times in water and on the proportions of active clay and silica in the limestone. Some have used the relative proportions of the component oxides to derive a Hydraulic Index and later a Cementation Index. Others argue that classification should be based on the proportion of active silica and clay actually combined in the hydraulic component, rather than the proportion in the raw material (which may include a portion that remains inert).

European Standard EN 459 uses a different approach, based on the compressive strength of a mortar made from the NHL. There are three classes and while they can be roughly equated to those of Vicat, they cannot be directly compared because modern NHLs are stronger than those of Vicat's time, as Figure 14 shows.

Table 2 shows the strength and free lime (non-hydraulic) requirements of EN 459. It also shows the range of free lime contents of typical materials. NHL stands for natural hydraulic lime – not to be confused with non-hydraulic lime.

Table 2: Classification of natural hydraulic limes

EN 459 notation	Compressive strength at 28 days (MPa)		Free lime (%)* EN 459	Free lime (%) typical
	Minimum	Maximum	Minimum	Range
NHL 2	2	7	≥ 35	35–60
NHL 3.5	3.5	10	≥ 25	25–50
NHL 5	5	15	≥ 15	15–30

* EN 459 uses the term 'available lime expressed as $Ca(OH)_2$'.

Caution: these compressive strengths should not be used for design purposes. They are derived from testing special rich mortar mixes using a standard sand and very low water contents, and are solely for classification. Mortars used in actual practice will be significantly weaker than the specified minimums at 28 days. Also, testing at 28 days (which is derived from testing cement) is not appropriate for determining the ultimate strengths of lime mortars as they cure more slowly, often not achieving their final strengths for one to two years.

An issue with the EN 459 classification is that 28-day strengths in the range 5–7 MPa conform to all three classes, apparently leaving no way of distinguishing between them. Similarly, the required minimum free lime content may also fail to separate them, as can be seen from the right column of Table 2. However, it is important to understand that EN 459 also provides conformity criteria for manufacturers, which effectively narrows each of the strength ranges to the point where there is minimal overlap between them. The compliance ranges are 3.5 ≥ NHL 2 ≤ 5.8, 5.6 ≥ NHL 3.5 ≤ 8.3 and 8.2 ≥ NHL 5 ≤ 12.5 MPa.

EN 459 also provides for two other categories of lime with hydraulic properties:

- formulated lime (FL), which may include disclosed additions including cement or pozzolans to a natural hydraulic lime and/or to a pure lime
- hydraulic lime (HL), which contains lime and other materials and for which there is no requirement to disclose its composition.

Natural hydraulic limes are appropriate for use in heritage conservation and more broadly to repair older buildings. Formulated limes may also be used, provided their components are fully disclosed and their properties understood.

Note: Recent research in the United Kingdom has shown widely varying test results between brands of NHL and between classes from the same brand. Specifiers should seek up-to-date test data before deciding on a particular product.

6 Cements

Cements differ from hydraulic limes by consisting predominantly of hydraulic materials. As with hydraulic limes, there are natural and artificial cements; and again, these terms relate to the source of the raw materials. Natural cement is made from a single raw material, sometimes known as cement stone, while artificial cements (such as Portland cement) are made by combining several raw materials in carefully controlled proportions.

6.1 Natural cement

Natural cements are made from argillaceous (clayey) limestones that contain just the right proportions (about 30–40%) of clay, so that on firing at moderate temperatures (about 1,000˚C) they produce a material that contains calcium silicate and calcium aluminate but little or no free lime. After grinding to a fine powder, natural cement reacts with water to form hydrated calcium silicates and calcium aluminates.

The presence of relatively high levels of calcium aluminates in the cement leads to rapid hardening, and this is exploited for a variety of purposes. These include casting decorative elements and mouldings, and making quick-setting repairs where time is limited (such as in the intertidal zone).

Parker's so-called Roman cement is a natural cement commonly found in nineteenth-century buildings in Australia. It was imported from the UK. It has a distinctive brown colour and can be found internally (as the dado in entrance halls) and externally (as renders, moulding and stucco work). It was not commonly used as a mortar.

For information about Roman cements and their conservation, see Gurtner et al. 2012. *Manual on best practice in the application of Roman cements.*

6.2 Portland cement

Today, most hydraulic cements are artificial. The principal one is Portland cement, so named by its inventor Joseph Aspdin because he thought it resembled Portland limestone, one of the UK's main building stones.

Raw materials for Portland cement include limestone, clay or weathered shale, and small amounts of silica and iron. Limestone (or chalk, coral, marble or sea-floor shell deposit) is the principal raw material, accounting for about 80% of the blend. The mixture is ground and then burnt at a temperature around 1,450˚C, substantially higher than the temperature for limes and natural cements. The resulting, partially fused cement clinker is ground with about 5% of gypsum, which is added to retard setting and provide enough working time for normal use.

Box 5 'Cement chemistry' briefly outlines a very complex subject. There are four principal components of ordinary Portland cements, and one or two of them are also found in hydraulic limes. The chemical links with hydraulic limes, which in turn are related to non-hydraulic limes, lead to an understanding of a continuous spectrum from pure lime through to cement.

> See Section 8.1 The lime–cement spectrum

On reacting with water, cement produces complex hydrated calcium silicates and calcium aluminates. The needle-like crystals of the silicates tightly interlock with adjacent particles and give cement its great strength. The network of needles fills the space between particles previously occupied by the mixing water, blocking pores and reducing permeability, as Figure 12 shows.

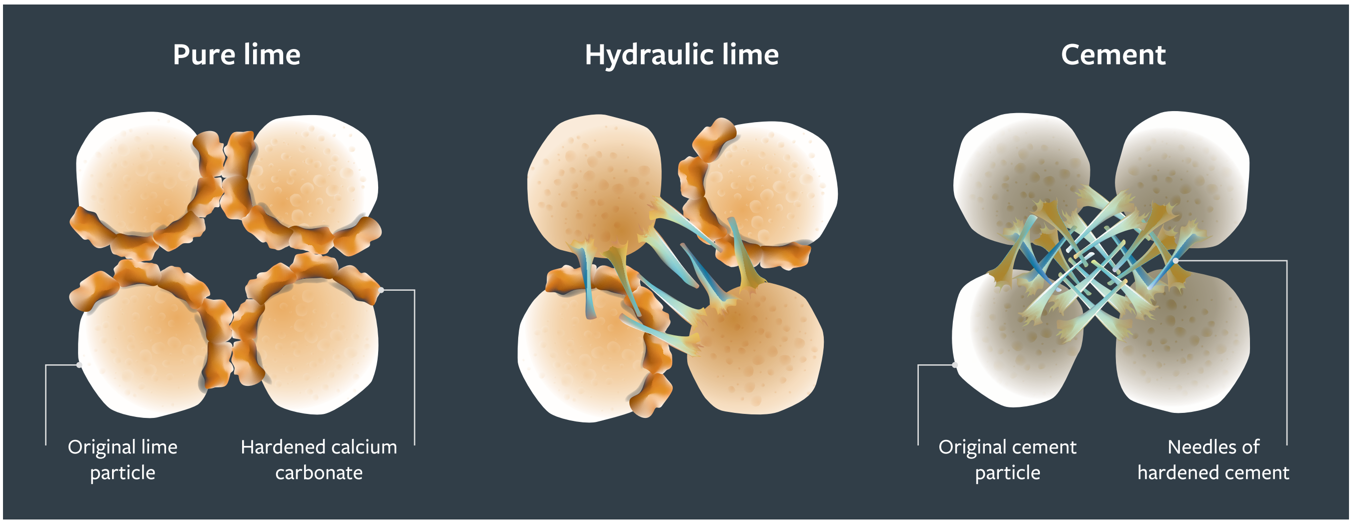


Figure 12: Hardened binders and pore blocking. Schematic representation of particles of hardened pure lime (left), hydraulic lime (centre) and cement (right). The illustration on the right shows how needle-like crystals of cement largely fill the pore space between particles, significantly reducing permeability. This is in contrast to pure lime, in which much of the pore structure remains open. The degree of partial blocking of pores by natural hydraulic limes depends on their class: NHL 2 mortars are more permeable and NHL 5, less permeable.

Box 5: Cement chemistry

To simplify a complex subject, cement chemists use a shorthand notation based on the first letter of the oxides: C = CaO (quicklime), S = SiO_2 (silica), A = Al_2O_3 (alumina), F = FeO (iron oxide) and H = H_2O (water). The complex calcium silicate hydrates and calcium aluminate hydrates that are the products of the reaction with water are notated by C–S–H and C–A–H respectively, the dashes indicating variable proportions.

The principal components in ordinary (normal) Portland cements and their approximate proportions are shown in Table 3.

Table 3: Principal components of Portland cement

Chemical	Notation	Name	Proportions (%)
Tri-calcium silicate	C_3S	Alite	40–70
Di-calcium silicate	C_2S	Belite	15–35
Tri-calcium aluminate	C_3A	Aluminate	5–10
Tetra-calcium aluminoferrite	C_4AF	Ferrite	5–15

Tri-calcium silicate (alite) is the most important constituent of Portland cements. As well as being the dominant material, it is the one responsible for the early strength development of the hardened cement paste. It is only formed when kiln temperatures exceed about 1,250°C, and so it is not generally found in hydraulic limes, except for a small proportion in the highest class (NHL 5).

Di-calcium silicate (belite) is the second most important constituent. It reacts much more slowly than alite, but it can ultimately lead to similar strengths after about a year of hardening. Belite forms at much-lower kiln temperatures than alite and is a key component of natural hydraulic limes. It is the reason why they develop reasonable strengths, but do so slowly.

Tri-calcium aluminate (aluminate) reacts rapidly with water, which is why gypsum is added to Portland cements to prevent rapid hardening. It is less stable than the silicates, particularly in high-sulfate environments, and manufacturers reduce its proportion when making sulfate-resisting cements. Calcium aluminates are also found in hydraulic limes and natural cements.

Tetra-calcium aluminoferrite (ferrite) is principally responsible for the grey colour of many cements, and manufacturers minimise its proportion when making white and off-white cements. Ferrite contributes little to the overall strength of cement.

6.3 Portland cement through time

Although Portland cement was invented in 1824, there was a period before its manufacture was well understood, and it wasn't until the 1840s that cements resembling today's material were in regular production. Even so, there are big differences between the Portland cements of the nineteenth century and those made today, one being that early cements contained a significant amount of free lime, whereas modern cements contain a minimum.

Because of their significant free lime (quicklime) content, early cements had to be air-slaked to avoid the expansion caused by slaking after application. The hydrated lime that was produced, and the low alite content, meant that early cements were much more workable than modern cements.

Figure 13 shows the progressive increase in the strength of Portland cement since the 1840s. While the basic chemistry of cements has remained much the same, advances in production have included burning at higher temperatures (producing more alite and hence higher and earlier strengths), continuous manufacture in rotary kilns and improved grinding technology, which produces finer-grained, more-reactive materials.

The conservation and repair of buildings and structures made with nineteenth- and early-twentieth-century cements must take into account the substantial differences between the materials used then and those available today.

> See Sections 13.4 to 13.6 'Choosing the right mix'

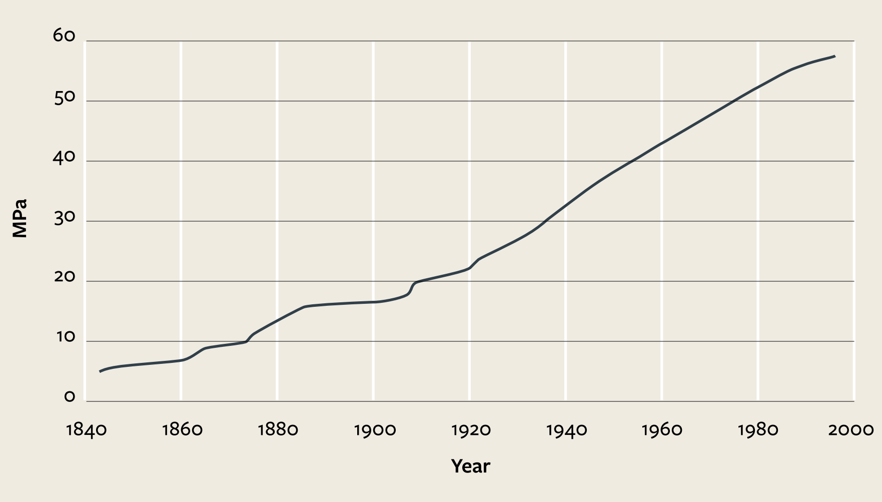


Figure 13: Compressive strengths of Portland cements, 1840–2000 (after Livesey, 2003). Sudden increases in strength indicate advances in manufacture (such as the introduction of rotary kilns in the early twentieth century). Portland cements of the nineteenth century were 4–10 times weaker than today's material, which has important implications for how we approach their repair.

6.4 Types of Portland and blended cements

By controlling the blend of raw materials and other aspects of production (such as the fineness to which they are ground), cements are made to a range of formulations for different purposes.

Australian Standard (AS) 3972 *General purpose and blended cements* provides for general purpose and blended cements, and for a range of special purpose cements. The types of cement the standard identifies, and the two-letter code of each, include the following.

General purpose and blended cements	Special purpose cements
GP – general purpose cement	HE – high early strength cement
GL – general purpose limestone cement	LH – low-heat cement
GB – blended cement	SR – sulfate-resisting cement

General purpose cement (GP) is the common Portland cement that is widely used in concrete construction.

General purpose limestone cement (GL), which may contain up to 20% ground limestone, was introduced in 2010 to reduce cement's carbon footprint.

Blended cement (GB) takes advantage of the fact that while Portland cement consists almost entirely of hydraulic materials, its hardening produces free lime, which makes up about 20% of the hardened cement paste. By adding pozzolanic materials (such as fly ash or ground granulated blast-furnace slag (GGBFS), as Chapter 7 'Pozzolanic materials' explains), the lime is converted to hydrated calcium silicates and aluminates that are similar to those produced by the hardening of the cement itself. Although the early strength may be lower (because of slower-reacting pozzolans), the ultimate strength of blended cement can be significantly higher than that of Portland cement.

By making use of by-products of other processes, blended cements have lower environmental impacts than ordinary cement.

Special purpose cements can be either general purpose (GP) or blended (GB) cements that are modified to meet the requirements of each type.

High early strength cements (HE) are produced by adjusting their chemistry (more alite and aluminate), by grinding them more finely to make them more reactive or by a combination of both. They are used where fast stripping of concrete formwork is required and also in cold weather applications.

Low-heat cements (LH) are in a sense opposite to HE cements: to minimise heat and expansive forces, they harden more slowly and have lower early strengths, but may ultimately achieve higher strengths. Low-heat cements are used in dams and other situations requiring massive concrete sections.

Sulfate-resisting cements (SR) are used where soils, groundwater and masonry are high in sulfate salts and where soils contain minerals, such as pyrite (iron sulfide), that may degrade general purpose cements. They may be general purpose cements (GP) with reduced proportions of aluminate, or blended cements (GB) containing substantial proportions of GGBFS, fly ash or both.

The scientific world has adopted the American spelling of sulphur: hence sulfur, sulfate and sulfide.

White and off-white cements are not separately identified in the Australian Standard, but their manufacture – finer grinding, and minimising ferrite with consequent increased aluminate – often results in materials that also meet the requirements of high early strength (HE) cement.

Slag cements are binders consisting mainly of GGBFS, which is a by-product of making iron in a blast furnace. When combined with Portland cement, the proportion of slag can be higher than 65% and still produce materials that meet the requirements of AS 3972 for blended (GB) cements. Lower strength cements consisting of slag and hydrated lime (and sometimes fly ash) are used in road stabilisation.

6.5 Masonry cements

Masonry cements are proprietary products containing Portland cement and additional materials (such as ground limestone) as fillers. Plasticisers or air-entraining agents are commonly included to improve workability.

> See Chapter 11 'Admixtures and additives'

Masonry cements acknowledge that modern Portland cement, while ideal for reinforced concrete, is too strong for most masonry (i.e. mortar) applications. AS 1316 *Masonry cement* provides for two distinct types of masonry cements:

- **masonry composite cements:** these may contain up to 25% of ground limestone or up to 35% of slag and/or fly ash (with or without admixtures). An advantage claimed for masonry cements is there is no need to add hydrated lime to mixes, as in composition mortars.
- **masonry binary cements:** these are mixtures of general purpose cements (GP or GB) and hydrated lime in proportions that, when mixed with sand, will produce standard composition mortars: that is, cement and lime in proportions of 1:0.5, 1:1 and 1:2. As with masonry composite cements, these have the advantage of a one-bag mix, avoiding the need to mix cement and lime from separate bags while also ensuring the correct proportioning of the two binder components. Another advantage is that pre-packaging allows for the right amount of admixtures to be included, potentially eliminating the common problem of overdosing during on-site mixing.

> See Section 13.2 'Composition mortars'

> See Chapter 11 'Admixtures and additives'

Because of the lower strengths and higher elasticities and permeabilities obtainable with the more lime-rich compositions, masonry binary cements are preferable to masonry composite cements for repairing older buildings, though the potential use of masonry composite cements combined with lime is worth exploring (see Section 6.7 'Which cement?').

Mortars made from masonry composite cement and hydrated lime have been used in Canada, with good test results.

6.6 Rapid-hardening cements

Rapid-hardening cements come in several forms.

Modified general purpose cements may contain additives designed to accelerate hardening. These include calcium chloride and other soluble salts, which are a concern as they may lead to salt attack in the masonry. Some rapid-hardening concrete mixes, which are intended for applications such as setting posts in the ground, contain plaster of Paris. This will add to salt loads, and it risks expansive cracking due to reaction between the sulfate (in the plaster) and the cement. These materials should not be used for repair of older buildings.

Calcium aluminate cements (high-alumina cements) are made from a mixture of limestone and bauxite that is melted at about 1,600°C. Because they are more expensive, their use is limited to specialised applications (such as refractories and applications calling for high chemical resistance or rapid strength development). Rapid-hardening mixes are also made by blending Portland cement with calcium aluminate cements.

Natural cements are also rapid hardening, and are preferable for repairing older buildings where the speed of hardening (but not high strength) is important (see Section 6.1 'Natural cement').

6.7 Which cement?

Common practice when repairing lime mortars has been to use white and off-white cements combined with hydrated lime, the colour being the main reason for the choice of cement type.

With better understanding of the importance of permeability, elasticity and thermal compatibility, as well as the availability of pozzolans and hydraulic limes, it is no longer appropriate to use cements to repair lime mortars, particularly for repointing.

This leads to the question of which cement should be specified for situations where their use is appropriate: that is, typically combined with lime, for repairing buildings originally constructed with cement mortars, or with composition mortars.

A concern with using cements in older masonry is their relatively high soluble salt content. Some salt is unavoidable because of the gypsum (calcium sulfate) incorporated as a retarder, but it can be kept to a minimum by using blended cements with high proportions of slag or fly ash. There are other salts in cements, and these can be reduced by using material with a low-alkali content: that is, low sodium and potassium. Low-alkali cements are not separately identified in AS 3972, but the standard does provide for the alkali content to be reported where required.

There is more information about salts in *Salt attack and rising damp: a guide to salt damp in historic and older buildings*, another guide in this series.

As sulfate salts are commonly found in older walls, the use of sulfate-resisting (SR) cement would seem to be an obvious choice. SR cements and low-heat (LH) cements are often similar: both may have high proportions (up to 65%) of slag and fly ash, and some Australian products meet the requirements for both types. These materials are not normally recommended for contemporary use in mortars or renders because of their slower initial hardening times, but this feature may be advantageous where longer working times are required. Longer working times are often useful when doing repairs, so these cements should be considered for such work. However, though they initially harden more slowly, SR and LH cements ultimately produce very high strengths, which may be too high for many masonry materials, even if combined with lime (see Section 6.4 'Types of Portland and blended cements').

An extension of this approach would be to omit Portland cement altogether and use GGBFS combined with lime, as is done in road stabilisation. This has the advantage of producing lower strengths, more like those of nineteenth and early-twentieth-century cements (see Section 6.3 'Portland cement through time').

Longer curing times will be needed where cements are combined with lime (see Chapter 24 'Protection and Curing').

All cements must be properly cured, and this is even more important for slag, LH and some SR cements because of their slower hardening: at least a week of damp curing is needed.

Blended cements (GB) are recommended for situations (such as undersetting treatments for salt damp) that need faster hardening times than slag, LH and some SR cements can provide. Natural cements may be appropriate where rapid hardening is required (see Section 6.1 'Natural cement' and Section 6.6 'Rapid-hardening' cements).

7 Pozzolanic materials

> ***There is also a kind of powder which naturally produces extraordinary results. It occurs in the region . . . around Mount Vesuvius. When mixed with lime and rubble, this powder not only ensures the durability of different types of construction, but even when masonry piers are built with it in the sea, they set hard under water.***
>
> **Vitruvius, c. 30–20 BCE**

Pozzolanic materials are binder additives used in mortars and concretes. They have no binding power of their own, but when mixed with lime they make a portion of the mix hydraulic, increasing its strength.

The name comes from Pozzuoli (near Naples in Italy) where the ancient Romans used local volcanic ash to produce a hydraulic reaction with lime, enabling their concrete to harden underwater. Ashes, pumice and similar volcanic materials (collectively known as *pozzuolana*) have been traditional sources. Trass (formerly tarras) is a German pozzolan derived from tuff, a compacted volcanic ash. The volcanic Santorine (or Theran) earth from the Greek island of Santorini was first used in about 700 BCE, and more recently to build the Suez Canal in the 1860s.

The Romans also crushed clay bricks and tiles for use as pozzolans in their mortars. Modern pozzolans include by-products (such as fly ash from coal-burning power stations and GGBFS), as well as deliberately manufactured materials (such as metakaolin, which is calcined [heated] clay). All these materials contain very fine-grained, glassy particles of reactive silica and alumina. Even though they are mixed cold, they are sufficiently reactive when combined with calcium hydroxide to produce hydrated calcium silicates and calcium aluminates, which are similar to the hardened products of hydraulic limes and cements.

Rice husks are burnt as a fuel in many Asian countries, leaving a silica-rich ash that can be a reactive pozzolan.

Pozzolans are widely used today in blended cements (GB). These cements commonly contain 25–30% of fly ash or GGBFS, to consume the free lime produced during the hardening of the cement.

> See Section 6.4 'Types of Portland and blended cements'

Pozzolans also have a role in the repair of lime mortars. Modern limes are relatively pure and therefore non-hydraulic, whereas some traditional production of lime mortars may have resulted in slightly to weakly hydraulic materials with increased strengths, compared to pure limes. Combining pozzolans with modern limes can be a way of producing materials with similar properties to some of those used traditionally.

The use of pozzolans requires an understanding of their relative reactivities. Pozzolans ranked from most reactive to least reactive include metakaolin, silica fume, fly ash, GGBFS, pozzuolana, trass and brick dust.

This ranking of reactivities is approximate: reactivity depends on several factors including the fineness to which the pozzolan is ground and the inherent variability of the material. For example, variations in clay minerals, firing temperatures and particle size make some brick dusts more pozzolanic than others, while some may not be pozzolanic at all. To be suitable, bricks should be fired at temperatures below about 900°C. Most bricks made in Australia today are fired at higher temperatures, making them unsuitable for use as pozzolans.

AS/NZS 3582.1 *Supplementary cementitious materials* provides for three grades of fly ash, depending on particle size. Coarser (less reactive) grades are preferred.

The more reactive a pozzolan, the more hydraulic will be the resulting binder. This is important when considering mix proportions. While there is currently insufficient research data to confirm the appropriate proportions of common pozzolans when combined with lime, indicative proportions for producing a binder similar to a weakly to moderately hydraulic lime are:

- metakaolin, 5% (1⁄20 part)
- fly ash or GGBFS, 10% (1⁄10 part)
- trass, 20% (1⁄5 part).

Using half these proportions (e.g. 5% of fly ash or GGBFS) will be appropriate for many repointing applications, producing slightly to weakly hydraulic mixes.

Understanding the reactivities of pozzolans is also important when we consider the permeability (breathing characteristics) of the resultant mortar. As with natural hydraulic limes, the more reactive the pozzolan, the less permeable the resulting mortar will be. Similarly, the higher the proportion of pozzolan in the mix, the greater will be the reduction in permeability. As Figure 12 shows, these reductions in permeability occur because the hydraulic components grow into and partially block the pore space between the particles of lime.

Just as with cement, it's important to resist the temptation to add a bit more pozzolan to a mix to make it that little bit stronger. The benefits of moving from cements to limes can be undone by the overuse of reactive and highly reactive pozzolans.

Pozzolans are measured as a proportion of the lime content, not of the total mortar (coarse stuff). To convert to approximate proportions of coarse stuff, divide by the sand content. For example, for pozzolan at the rate of 10% of the lime, a 1:3 mix will have 3.3% of the total. A 1:2.5 mix will have 4% and a 1:2 mix will have 5% pozzolan.

Materials such as crushed bricks and pozzuolana may make other contributions to a mortar mix. While only the finer particle sizes (generally less than about 75 µm) will be pozzolanic, the coarser particles may add colour and a desirable degree of porosity to a mortar. The coarser fractions of these materials should be considered as part of the aggregate, while the finer (reactive) fractions should be considered as part of the binder matrix.

> Section 9.9 'Other aggregates'

Several of these materials are not strictly pozzolans but what are known as latent hydraulic cements. This is because they already contain some lime, which can induce a slow (but inadequate) hydraulic reaction without adding further lime. They include GGBFS and some high-lime fly ashes. Pozzolans and latent hydraulic cements are collectively known as supplementary cementitious materials (SCMs) and are covered in AS 3582.

Like cements, pozzolans contain salts, which may contribute to salt attack decay of masonry. Fly ash may contain sulfates derived from sulfur in the coal. GGBFS may contain sulfide minerals, which eventually oxidise to sulfates after the hydration reaction. Further, gypsum (calcium sulfate) is often added to GGBFS to increase early strength development. In chemical analyses, sulfate concentration will often be expressed as sulfur trioxide (SO_3). For conservation work, pozzolans should contain less than 2% sulfide or sulfur trioxide, or 3% gypsum ($CaSO_4.2H_2O$).

Small amounts of sulfide minerals in GGBFS may produce a blue-green colour after hardening. The colour fades to off-white on exposure.

8 Comparison of lime and cement binders

8.1 The lime–cement spectrum

Although this guide describes non-hydraulic limes, hydraulic limes and cements in discrete categories, there is in fact a continuum (or spectrum) from pure lime through hydraulic limes to hydraulic cement, as Figure 14 shows.

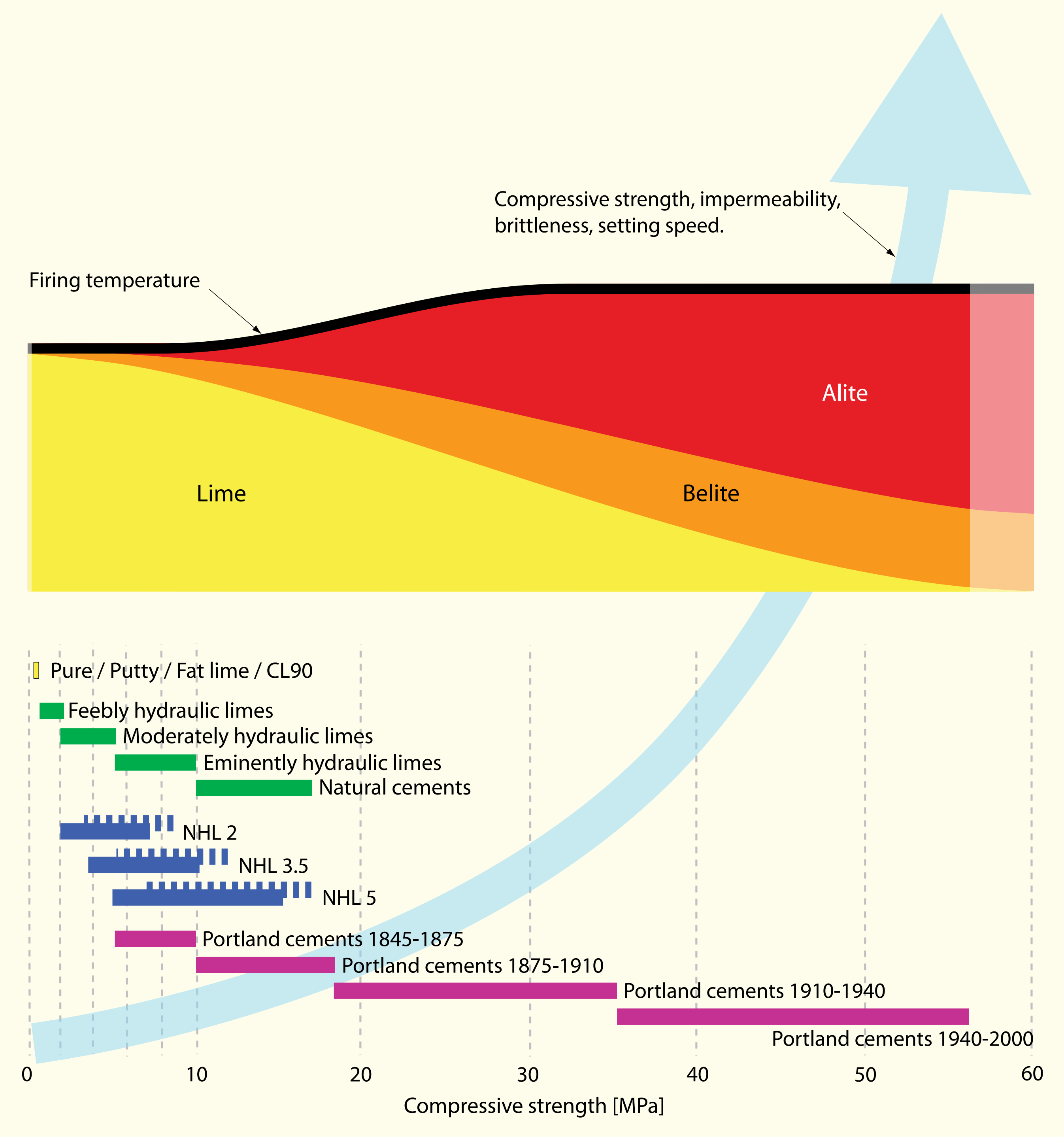


Figure 14: The lime–cement spectrum. The diagram shows the continuous range of materials from pure (non-hydraulic) lime on the left through the hydraulic limes to modern cements on the right. Their increasing strength and other properties are shown against firing temperatures and the changes in their lime and silicate chemistry. The diagram simplifies complex data and boundaries are approximate only.

Diagram: Ian Brocklebank (first published in Brocklebank, 2012).

8.2 Comparison of binder properties

As will be apparent from the lime–cement spectrum in Figure 14, the boundaries between the different types of binder are gradual. Also, each type has a range of properties and a single number cannot be ascribed to a particular characteristic. With this in mind, Table 4 summarises the properties of lime and cement binders, and of the mortars made from them. Like Figure 14, it greatly simplifies a lot of information. The properties in the table are explained below in more detail.

> See Chapter 14 'Workability'

Workability refers to the relative ease with which a fresh mortar can be spread and worked, whether for laying masonry or for repointing. Sand-slaked quicklime and lime putties make the most workable mortars, followed by hydrated limes, which vary depending on the fineness of their particle size. The workability of hydraulic limes varies with their classes: those most like pure limes (NHL 2) are more workable while the highest class (NHL 5) is the least workable. Cements make harsh mortars, which are difficult to work.

Strength ranges from low for limes to very high for cements. The compressive strength of modern Portland cement is too high for most traditional masonry, particularly for the softer materials of older buildings. Though compressive strength is most commonly referred to, bond strength and flexural strength (bending strength) are arguably more important considerations for mortars. Because of their fine particle size, high water retentivities and crystal structures, limes (pure and hydraulic) have relatively high bond and bending strengths as a proportion of their compressive strengths.

Pore structure of the hardened mortars ranges from open (for pure limes) to mostly blocked (for Portland cements). Blocked pores are desirable if an impermeable material is required (such as for a water tank) but are undesirable if a wall needs to breathe, as most old walls do.

Elasticity ranges from relatively flexible (for lime mortars) to brittle (for cement-based mortars). A low-elastic modulus (i.e. high elasticity) means a mortar has some flexibility, which allows a wall to settle without failure as it is being built, and it cushions the masonry units when they are loaded or are under cyclical stresses from thermal expansion and contraction. Brittle materials like cement are less able to accommodate minor movements.

Table 4: Comparison of binder properties

Property	Pure limes	Hydraulic limes	Cements
	Including putties and dry hydrates	Including NHLs and lime + pozzolan mixes	Including Portland and related cements
Workability	Good	Good to moderate	Poor
Strength	Low	Low to moderate	High to very high
Pore structure	Open	Mostly open to partly blocked	Mostly blocked
Elasticity	Flexible	Moderate	Brittle
Thermal expansion	Compatible	Compatible	Incompatible
Hardening mechanism	Carbonation	Carbonation and hydration	Hydration
Hardening rate	Slow	Intermediate	Fast
Pot life when mixed	Indefinite	Intermediate to short	Short
Salt content	Negligible	Negligible to very low	Low to moderate

Note: there is a wide range of properties within each group, particularly among the hydraulic limes, which includes natural hydraulic limes and lime and pozzolan mixes.

Thermal expansion coefficients range from those that are similar to and therefore compatible with stone and brick masonry (for lime), to nearly twice that of masonry (for Portland cement). A high coefficient of expansion coupled with strong, brittle material sets up stresses in the outer surface of the masonry because it heats and cools more quickly than the rest of the wall, leading to spalling and cracking (e.g. Figure 16 in Box 6).

The two different **hardening mechanisms** – carbonation and hydration – have been explained in Chapter 5 'Limes' and Chapter 6 'Cements'. Importantly, hydraulic limes harden by a combination of both mechanisms.

Hardening rates are related to the respective mechanisms. Carbonation is relatively slow, as it involves absorption of carbon dioxide from the atmosphere. Hydration is faster, but the rate varies according to the chemistry of the material: alite in Portland cement reacts much faster than the belite in hydraulic limes. The hardening rate of hydraulic limes, which is described here as intermediate, varies from relatively slow to moderate depending on the hydraulicity of the lime: the more belite (in the higher classes), the faster the rate of hardening. Hardening rates for lime and pozzolan binders depend on the reactivity and proportion of the particular pozzolan.

Pot life is the effective working time after first mixing a mortar. Pure (non-hydraulic) lime mortars (without pozzolanic additives) can be stored indefinitely, provided they are kept in airtight containers to prevent carbonation. Portland cements (GP) have relatively short working times of about one hour. Longer times can be achieved by using blended cements (GB), particularly those with high slag contents (such as sulfate-resisting [SR], low-heat [LH] and slag cements). Hydraulic limes come in between pure limes and cements: their actual working times depend on the weather and storage conditions but can be up to 24 hours for NHL 2, 12 hours for NHL 3.5 and 8 hours for NHL 5. These can be extended by continuously agitating the mix. Working times for lime and pozzolan binders depend on the reactivity and proportion of the particular pozzolan.

Salt content ranges from negligible to very low (for pure and hydraulic limes) through to low to moderate (for cements). Some cements have a higher alkali salt content than others, depending on their raw materials. As Section 6.7 'Which cement?' explains, the amount of gypsum salt in a cement can be minimised by using blends, particularly those with high proportions of slag. The soluble salt content of repair materials should be minimised. Old walls absorb salts during their lives: adding more may tip the masonry over a threshold, leading to salt attack decay.

There is more information about salts in *Salt attack and rising damp: a guide to salt damp in historic and older buildings,* another guide in this series.

Box 6: Problems with cement-based mortars

These photographs and diagrams illustrate some common problems with using cement in mortars. Both examples are from a mid-nineteenth-century sandstone building that was built in lime mortar and repointed in the mid-to-late-twentieth century in a rich cement mortar.

As the image in Figure 15 shows, because the cement repointing mortar is relatively impermeable, moisture from within the masonry is forced to evaporate through the adjacent stones, leading to decay of the sandstone as salts are precipitated within its pores. The diagram on the right shows a section through the wall, illustrating the paths moisture is forced to take because of the dense mortar.

In Figure 16, the inelastic cement repointing provides no cushioning action for the stones, while the high thermal expansion of the cement imposes stresses, producing a pinching effect, as the wall surface heats relative to the body of the wall behind it. Salt attack will be contributing to the spalling action, as it has to the decay on either side of the spalling area, where spalled sections of the stones have already fallen away, taking the repointing with them and exposing the softer, lime-based bedding mortar behind.

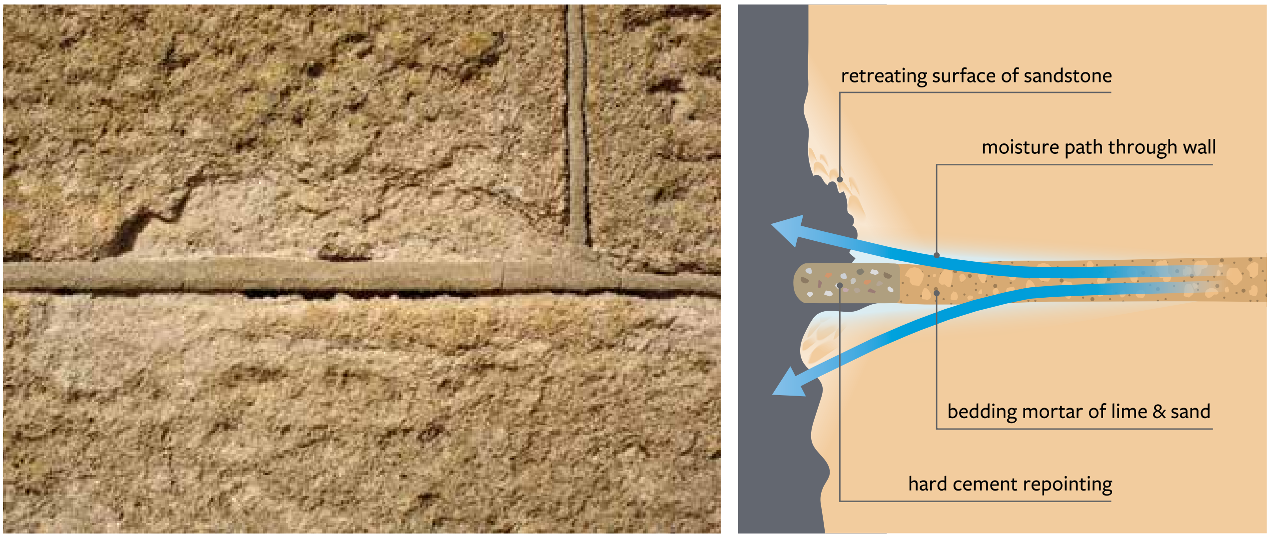


Figure 15: Impermeable mortar causing decay of adjacent stone.

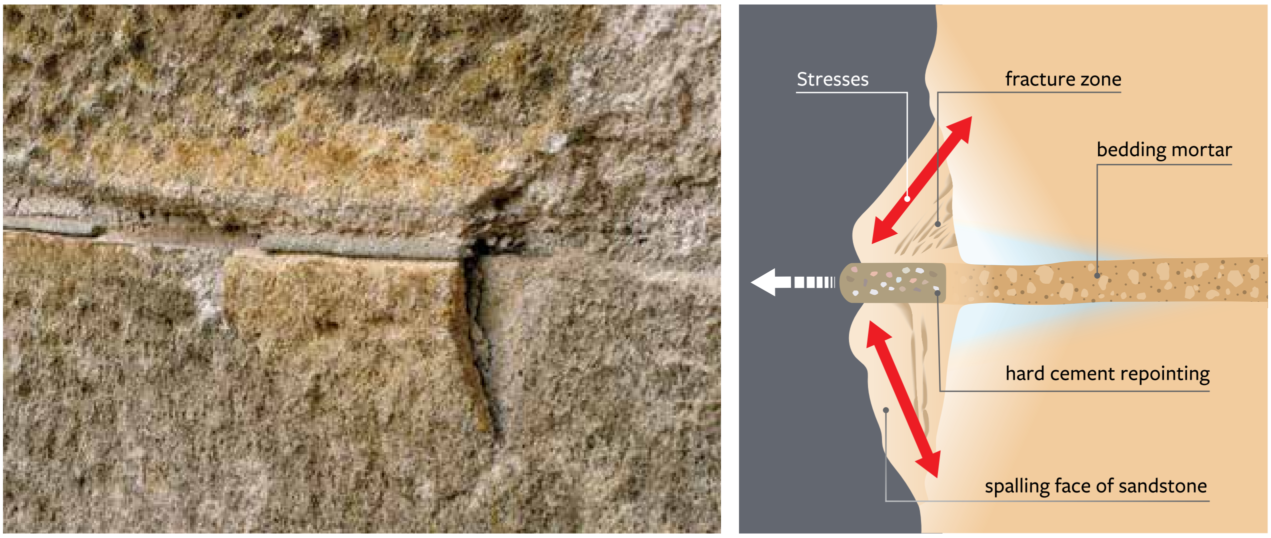


Figure 16: Spalling of edges due to thermal expansion.

9 Sands and other aggregates

. . . no mortar can be good unless the sand has the right qualities. Clean, sharp and coarse sand is always good for mortar, and most other sands are not.

Powys, 1929

Sands make up the greater part of mortars, and their selection can be critical to achieving workable and durable results. Yet the attention paid to sands is often cursory. A thorough understanding of sands is essential to the successful specification and practical use of mortars, particularly those based on lime binders. Testing conducted 100 years ago showed that the strength of a lime mortar could be doubled by the choice of an appropriate sand.

Soft, bricklaying sands that contain clay are not suitable for use with lime binders: washed concrete or plastering sands are preferred.

Sands are technically described as fine aggregates, as distinct from coarse aggregates (natural gravels and crushed rocks) which are used in concrete and other applications. Sands are generally natural materials and are excavated from pits, dunes, riverbeds and terraces. Though natural, they are often highly processed, being passed through sieves of varying sizes (screened) to remove oversized and undersized particles and to adjust their grading. Sands are commonly washed during screening, to remove clays and other unwanted materials. As their name suggests, dry-screened sands are unwashed. Sands from different sources are often blended to produce materials with particular properties.

Before good transport and widespread quarrying for sands became common, many alternative materials were used in mortars. These included road grit (drift), burnt clay, coal ash, coke breeze, shells and sands used for moulding in foundries (see Section 9.9 'Other aggregates').

Some sands are manufactured by further crushing of coarse aggregates produced from hard rock quarries. These quarry or crusher sands can be washed and screened as required.

The properties of sands that affect the quality of mortar include:

- the mineral type (mineralogy) and colour of the sand grains
- unwanted impurities (such as organic matter and salt)
- the surface texture and grain shape: sharp sands are better
- the range of grain sizes (size grading)
- the undesirable presence of clays and fine silts (fines)
- the proportion of voids between grains (void ratio).

Each of these points are explained in detail in this chapter and are followed by a section on assessing sands for their suitability for use in mortars. Then there are sections on blending sands, on other aggregate materials (such as shells, crushed bricks and stones), on the use of mineral fillers (such as ground limestone) and finally, on how to 'make-do' with poorer sands.

9.1 Mineralogy and colour

The most common sand mineral is quartz, which is the principle component of many light-coloured beach sands and has a typical clear or light grey colour, as Figure 17 shows. Quartz is chemically silica (SiO_2) and is very strong and durable. Sands with darker-coloured particles include silicate-based materials that can also be strong and durable (see Figure 72).

Some beach and coastal dune sands are composed of shell fragments, broken up and reduced in size by constant wave action. These sands are chemically calcium carbonate ($CaCO_3$, the same as limestone) and are known as lime sands or carbonate sands. Being softer, the grains tend to be rounder, and their light colours are more opaque. While they are not as inherently strong as silica and silicate materials, they can make excellent mortars. Well-rounded surface textures may be an issue with some lime sands (see Section 9.3 'Surface texture and grain shape'). Aggregates that include crushed limestone particles are known to promote the hardening of lime and to produce stronger mortars because of their similar chemistry and high porosity (see Section 9.9 'Other aggregates').

Although pure quartz is clear, many quartz sands have yellow and red colours due to very small amounts of different iron minerals dispersed through the quartz (Figure 17). However, as Figure 27 shows, the colour of some quartz sands is due to thin clay and iron oxide coatings on the surface of otherwise clear grains. If the coatings are weakly bonded to the grains, the sand will not make a good mortar: washing might be enough to remove the coating, and with it the colour. Some sands require double (or even triple) washing to remove clay coatings. The overall colour of many sands and the mortars made from them is due to the colour of the finer particles.

Standard classification schemes (such as the Munsell Colour system) are used to describe the colour of sands.

Figure 17: Good-quality sand. This is a close-up of a 10 mm wide lime mortar joint in a 100-year-old sandstone wall, showing a good-quality sand. The sand is clean – there is no clay – and the quartz grains have an angular surface texture which would feel sharp if rubbed in the hand. The sand is well graded: there is a good range of grain sizes: from very coarse through coarse, medium and fine down to very fine. Laboratory testing has shown that lime mortars made from sharp, well-graded sands (such as this one) can be twice as strong as those made from soft, fine-grained sands.

9.2 Impurities

Sands should be free of impurities, which commonly include organic matter, salts, friable materials, clays and fine silts. Organic matter (such as leaf and tree litter, loam and humic material from soils) is avoided by carefully selecting the sand during quarrying and by washing and screening it.

Salts are a problem, as they may lead to salt attack decay of the masonry. Sands from beaches and coastal dunes should be washed with fresh water. Sands excavated from the dry beds of ephemeral inland streams can also contain salt. Another source of contamination can be sand containing sulfide minerals, such as pyrite (iron sulfide), which oxidise when exposed to air to form sulfate salts. These can cause aggressive salt attack. Friable materials (such as shale, clay lumps, mud stones and weathered micas) will produce weak mortars and should be avoided. Too many very fine particles will weaken a mortar (see Section 9.5 'Clays and silts – fines').

There is more information about salts in *Salt attack and rising damp: a guide to salt damp in historic and older buildings*, another guide in this series.

9.3 Surface texture and grain shape

The surface texture and shape of the sand grains make an important contribution to a mortar's performance, particularly to that of a lime mortar. Imagine a bedding mortar made of perfectly smooth spheres (such as ball bearings). The mortar would rely totally on the binder to restrain the spheres; without it, the masonry units would tend to roll sideways in relation to the masonry below them. The smooth, round grains would not interlock with each other and the mortar would be relatively weak. In contrast, a good mortar is made of sand with a more angular surface texture: the corners of the grains lock into each other and into indentations in the masonry units. This is important for a strong bond and for slip resistance of one course of masonry over another. The terms used to describe the surface texture of sand grains are: angular, sub-angular, sub-rounded, rounded, well-rounded. Figure 18 shows examples of sands at either end of this range.

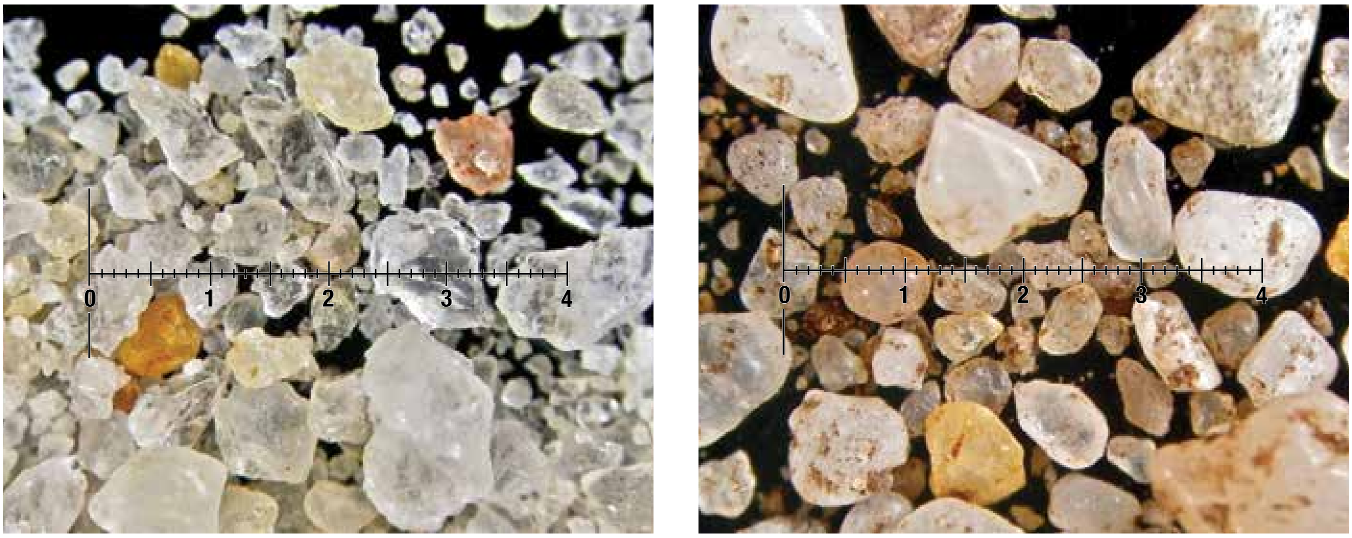


Figure 18: Surface texture of sand grains. The sand on the left has angular to sub-angular (sharp) grains, while that on the right has rounded to well-rounded grains. Sharp sands make strong mortars; rounded sands don't. Another aspect of these sands is that the one on the left has been washed clean, while the one on the right has clay coatings on the grains, which will weaken a mortar made from it (see Section 9.5). Scale bars in millimetres; each small division is 0.1 mm (100 µm).

Sands with angular to subangular surface textures are described as sharp because they feel sharp or abrasive when rubbed by hand. Some sands are described as soft, but that's not the direct opposite of a sharp sand. A soft sand is fine grained and often contains humic (soil) material, and may also be described as loamy. Soft and rounded sands will make weak mortars with poor bonding characteristics. The clay content of soft or loamy sands makes them quite workable, as Chapter 14 'Workability' explains, so they are popular for cement-based mortars. In contrast, sharp sands are more difficult to work, and they may need richer mixes with more binder or the judicious use of admixtures.

The best (sand) will be the one that crackles when rubbed in the hand, while the one which has earth in it will not be rough enough: the sand will be suitable if, when wrapped up in a white cloth and then shaken out, the cloth is not stained and no earth is left on it.

Vitruvius, c. 30–20 BCE

The angularity or roundness of the surface is one aspect of grain shape. The other is the degree of sphericity, or conversely the degree of elongation. While this property is more an issue for coarse aggregates, there are some sands to which it may apply. Sand with a high proportion of elongate shell fragments will be difficult to work and will have a high void ratio and poor water retentivity.

> See Section 9.6 'Void ratio and its impact on mixes' and Section 14.2 'Water retentivity'

9.4 Size grading

An important property of sands is their size grading or particle size distribution (also known as granulometry). This refers not only to whether the sands have a broad range of grain sizes (e.g. coarse, medium and fine), but to the relative proportions of the different grain sizes.

A sand of only one grain size, irrespective of which size, is described as a uniform or poorly graded sand. It will not make a good mortar. A sand with a broad range of grain sizes and similar proportions of particles across the range is described as a well-graded sand, and it will make a good mortar.

The grading of a sand is the inverse of the geological term sorting, which is a measure of the uniformity of the particle size of a sediment. A well-sorted sand implies a relatively uniform grain size, and in building terms this is a poorly graded sand.

In well-graded sands, the voids (gaps) between the coarser grains are filled with medium grains, the gaps between the medium grains with fine grains, and so on with finer grain sizes. This reduces the size and proportion of voids, which is desirable because the voids need to be filled with binder. With smaller voids, less binder is needed (see Section 9.6 ' Void ratio and its impact on mixes').

Using well-graded sand also improves workability. A sand with a broad range of grain sizes including coarse grains will be more workable than a sand with a narrow range of grain sizes, even though the latter may be fine or medium sizes. This is because the grains of well-graded sand fit well together. Filling up the void spaces with smaller grains allows bigger grains to roll past each other more readily and not get caught in gaps between grains. Figure 19 shows examples of well-graded and poorly graded sands.

The size grading of sands is determined by passing them through a series of sieves of progressively finer apertures, the standard ones being 4.75, 2.36, 1.18, 0.60, 0.30, 0.15 and 0.075 mm. The last four are generally described in microns (µm): one µm is a millionth of a metre, or a thousandth of a millimetre. So, the last four apertures are 600, 300, 150 and 75 µm respectively. Table 5 shows the classification of sand sizes.

Table 5: Sand particle size classifications

Classification	Coarser than …	Finer than …
Fine gravel	2.36 mm	4.75 mm
Very coarse sand	1.18 mm	2.36 mm
Coarse sand	600 µm	1.18 mm
Medium sand	300 µm	600 µm
Fine sand	150 µm	300 µm
Very fine sand	75 µm	150 µm
Fines (silts and clays)		75 µm

The amount of sand retained on each sieve is weighed and the proportions of each size expressed as a percentage of the total. The results can be presented in different ways. The most common is a simple table. The most technical way is a cumulative size-grading plot and the most readily understood is a histogram. Figure 20 shows histograms and cumulative size-grading plots for the well-graded and poorly graded sands in Figure 19.

What to look for

The histograms in Figure 20 show that the well-graded sand has four (or five) substantial bars of similar height, whereas the poorly graded sand has only two substantial bars. In the cumulative plots, the well-graded sand has a gently sloped and straighter line, while the poorly graded sand has a steeper and more bent line.

A rule of thumb for lime-based bedding mortars is that the size of the coarsest grains should be about one third of the joint width. Pointing mortars are often made with finer-grained sands than bedding mortars.

When selecting sands, the aim is to have three and preferably four (or more) substantial bars, each greater than about 10%, on the histogram, or the straightest and least vertical line on the cumulative plot. While histograms are easier to read, cumulative plots allow better comparison between sands and against standard limits.

The description of the overall size of sands is based on the position of the central bars, using the terms in Table 5. The well-graded sand is described as medium to coarse grained and the poorly graded sand as fine to medium grained.

Figure 19: Grading of sands. The sand on the left is well graded. It has a wide range of particle sizes from very coarse through coarse, medium, fine and very fine. The sand on the right is poorly graded, with a relatively uniform (fine to medium) particle size. Each division on the scales in these photographs is 1 mm; each image is about 20 mm across.

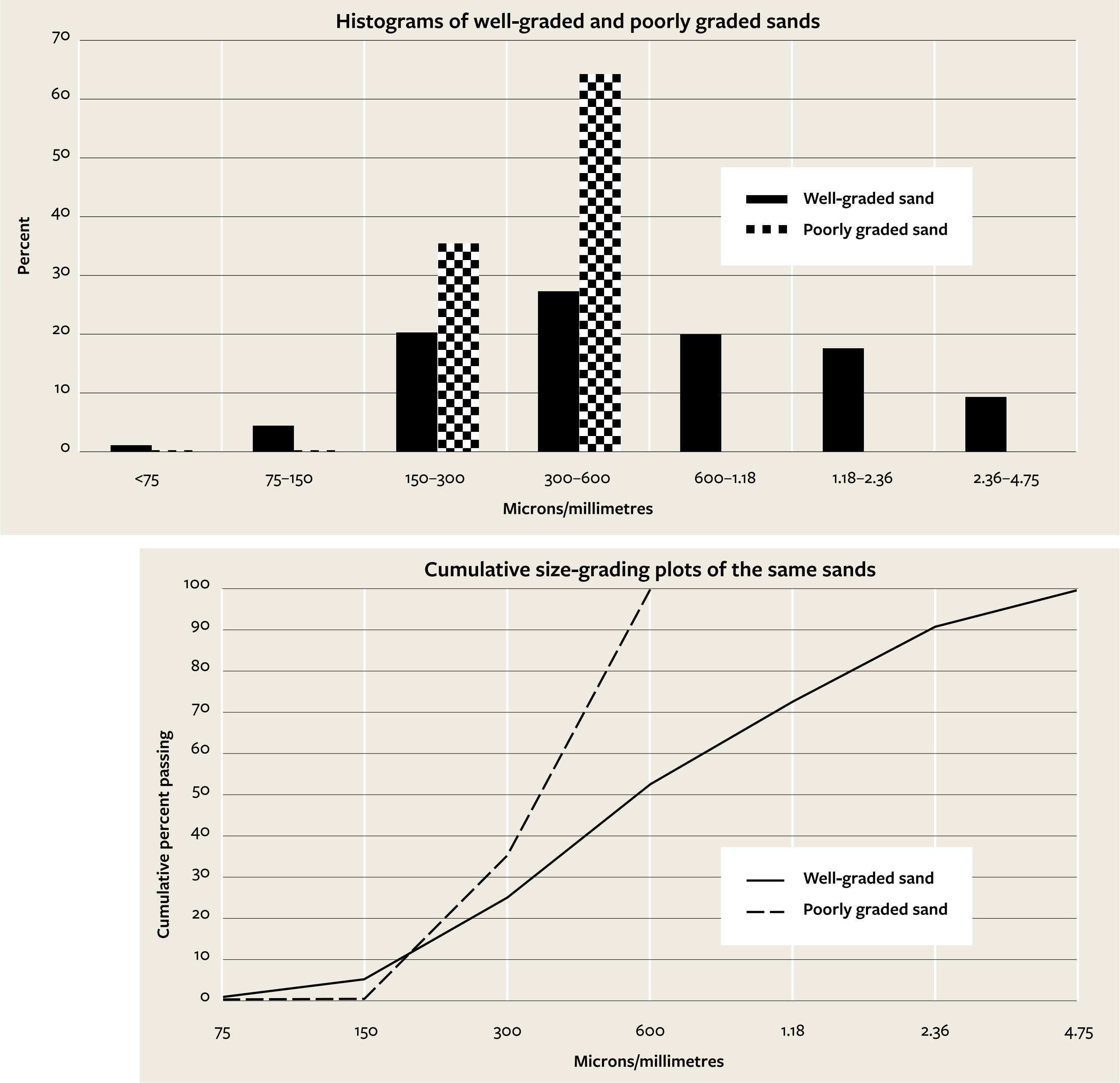


Figure 20: Histograms and cumulative plots of sand size gradings. These are the same sands as shown above in Figure 19. Note that the bars of the histograms correspond with the intervals in the cumulative plots below: the <75 μm (silt and clay) fraction at the left of the histograms represents the 'fines' material that is not shown to the left of the cumulative plots.

Size-grading limits

As there is no Australian Standard for mortar sand, Table 6 shows the size-grading limits of two standards from other countries:

- ASTM C144 – 18 *Standard specification for aggregate for masonry mortar*
- BS 1200:1976 *Specifications for building sands from natural sources: sands for mortars for bricklaying*.

Table 6: Sand size-grading limits

Sieve aperture	ASTM C144	BS 1200(S)
	% passing	% passing
4.75 mm	100	98–100
2.36 mm	95–100	90–100
1.18 mm	70–100	70–100
600 µm	40–75	40–100
300 µm	10–35	5–70
150 µm	2–15	0–15
75 µm	0–5	0–5

Note: these limits are for natural sands as distinct from manufactured sands (made from crushed rock) for which both standards permit greater proportions of fines (material less than 75 µm). BS 1200 defines two gradings: that shown here is Type S, while Type G permits finer sands and higher proportions of fines. Excessive fines can be a problem, which is explained in the next section.

Figure 21 shows cumulative plots of the grading limits of the two standards in Table 6. Pairs of lines for each standard define an envelope, the area within which complying sands will plot. Also shown are the well-graded and poorly graded sands from Figures 19 and 20.

As Figure 21 shows, the grading envelope for BS 1200(S) is relatively broad, whereas the ASTM C144 envelope is much tighter. The latter will produce well-graded, medium-to-coarse-grained sands which are appropriate for 10 mm wide mortar joints. However, it will exclude the fine-to-medium-grained sands which are needed for narrow (3 mm) joints. While the BS 1200(S) envelope allows for such finer sands, it is sufficiently wide to permit poorly graded sands, as the example from Figures 19 and 20 shows.

Sands for the base coats of plasters and renders are often coarser, or they have more coarse grains and fewer very fine grains than those used for bedding mortars. This is to avoid shrinkage cracking.

This guide proposes two new size-grading specifications, set out in Box 7 (see page 46). One is similar to ASTM C144 and suitable for normal (10 mm) joints, and the other is suitable for the narrow (3 mm) joints commonly found in ashlar masonry.

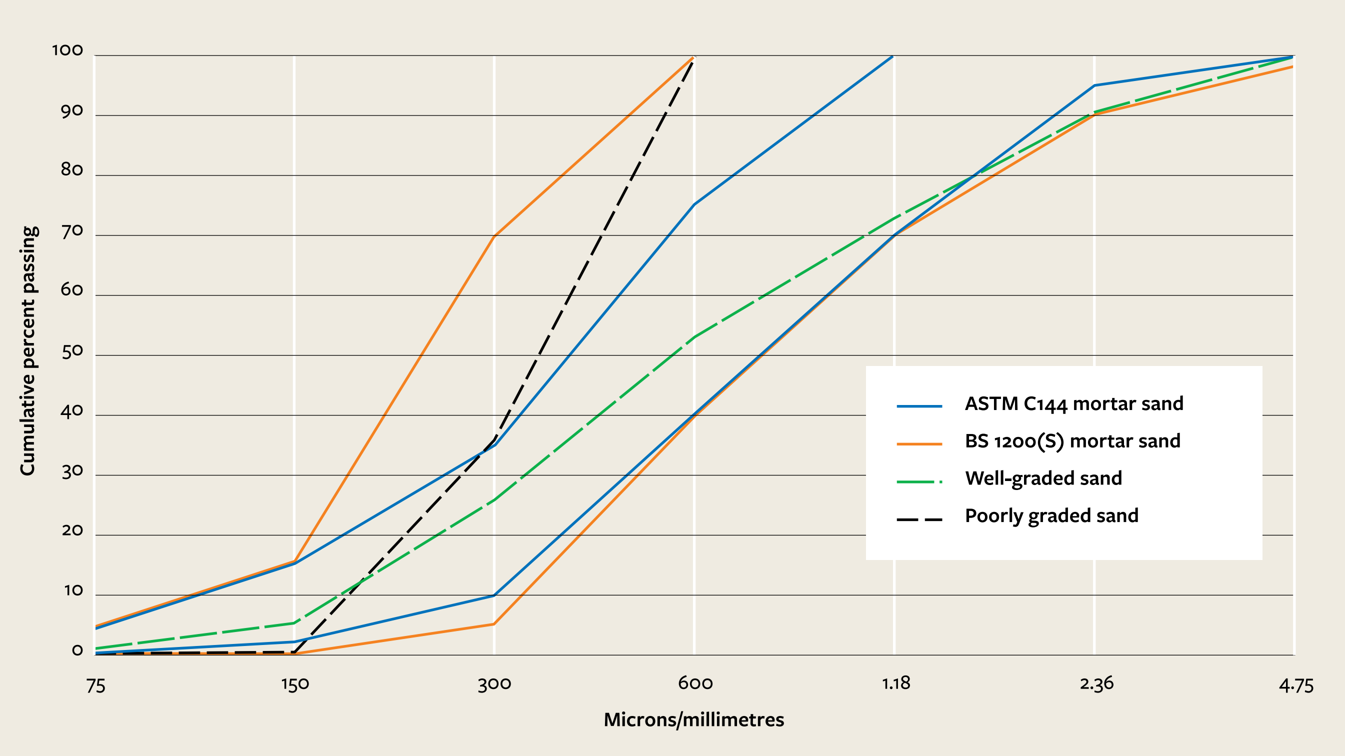


Figure 21: Standard size-grading envelopes. Cumulative plots showing size-grading limits for ASTM C144 and BS 1200(S) as pairs of solid lines. A sand meeting one of these standards will plot within the envelope defined by its pair of lines. The dashed lines show the well-graded and poorly graded sands of Figures 19 and 20. The well-graded sand is within the BS 1200(S) envelope and almost within that of ASTM C144. The poorly graded sand is within the BS 1200(S) envelope but is well outside the tighter ASTM C144 standard. Box 7 proposes new size-grading specifications for mortar sands, with two grading envelopes: one for normal, 10 mm joints and one for narrow, 3 mm joints.

9.5 Clays and silts – fines

Materials finer than 75 µm are collectively known as fines. They include coarse, medium and fine silts which grade from 75 µm down to 2 µm and clays which are less than 2 µm in particle size. Clays and fine silts can be detrimental to mortars for the following reasons:

- very high surface areas reduce strength and can cause shrinkage
- reactive (expansive) clays cause shrinkage cracking as they dry
- clays substantially reduce the bond strength of masonry
- clays reduce pore sizes, decreasing breathing capacity.

It is important to distinguish between clay minerals and clay-size particles. Clay-size particles might be of clay or another mineral (such as quartz). Similarly, silt-size particles might be of clay or another mineral. The use of the same terms to describe grain size and mineralogy often leads to confusion. In practice, many silts are quartz and most clay-size particles are indeed clay minerals. Clay minerals can naturally clump together in larger particles and in this form they can be particularly harmful, as they may survive dry-screening intact and give a misleading impression of particle size. This is why washing sands can be so important.

However, not all fines are problematic: a small proportion of medium-to-coarse silts can be beneficial, filling smaller voids and improving the workability of the mortar mix. Section 9.10 explains how adding ground limestone can improve workability.

Clay minerals are layered and consist of tiny, flat, plate-like particles that slide easily over each other, and are often greasy to touch. The structure of some clays means they swell substantially when wet and shrink as they dry. Swelling clays, which include the smectite group minerals such as montmorillonite, are the components of reactive or expansive soils which cause cracking in buildings.

Sands for lime mortars should be free of clays and fine silts.

Composition mortars can tolerate a small proportion (<5%) of fines.

Where contemporary practice would add clay to a poorly graded sand to improve its workability, ground limestone should be added instead (see Section 9.10)

Box 7: Size-grading specifications for mortar sands

Though applicable to all mortars, the size-grading specifications proposed in Table 7 are particularly intended for lime mortars, for which, clean, well-graded sands are preferred. There are two size gradings: a fine–medium sand for the narrow (3 mm) joints found in ashlar masonry and a medium–coarse sand for normal (10 mm) joints. The specifications are deliberately tight: their relatively narrow envelopes are intended produce well-graded sands and so overcome the problem that poorly graded sands can meet current standards (see Section 9.4)

The grading of sands should be determined using the procedure set out in AS 1141 and compared with these specifications. The results should be interpreted with an understanding of the aim: small variations from either envelope should not preclude the use of a well-graded sand that is otherwise acceptable.

Table 7: Proposed size-grading specifications

Sieve aperture	Fine–medium sand	Medium–coarse sand
	% passing	% passing
4.75 mm	100	100
2.36 mm	100	90–100
1.18 mm	95–100	70–100
600 µm	70–100	40–75
300 µm	35–70	10–40
150 µm	10–25	2–15
75 µm	0–5	0–5

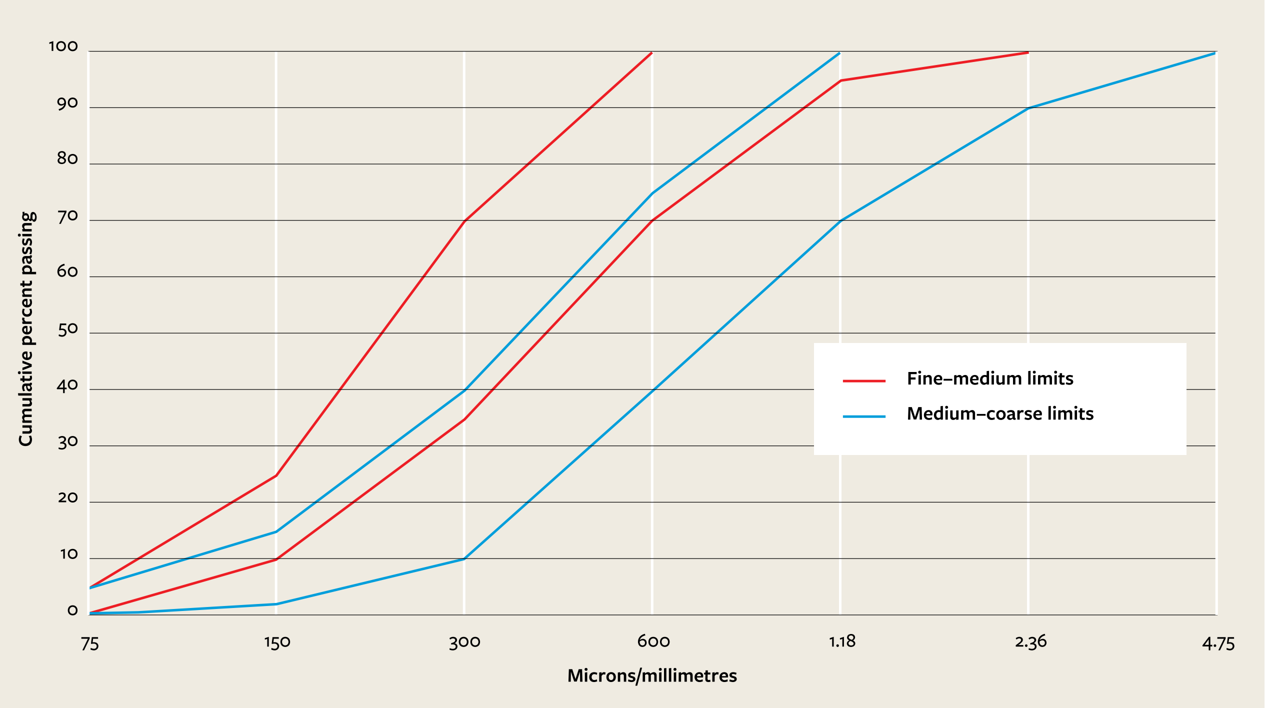


Figure 22: Proposed size-grading envelopes. Cumulative plots of proposed envelopes for fine–medium and medium–coarse sands. The plot for a particular sand should ideally lie approximately parallel to the envelope boundaries. A medium-grained sand suitable for 5–7 mm joints should plot close to the overlap between the two envelopes shown here. Sands may need to be screened to reduce the maximum particle sizes to suit particular joint widths.

Sands for building should not contain any swelling clays. Using them leads to shrinkage cracking when they dry and to long-term deterioration of mortars, plasters and renders due to stresses set up by swelling and shrinking from periodic wetting and drying.

As particles become smaller, their surface area increases, compared to a constant mass. Silt-size particles have 10 times the surface area of fine sand and 100 times that of coarse sand. Table 8 shows the specific surface area of aggregates, measured in square metres per gram.

Table 8: Specific surface area of aggregates

Material	m^2 / g
Coarse sand	0.01
Fine sand	0.1
Silt	1.0
Clay (kaolinite group)	5–100
Clay (smectite group)	700–800

As the table makes clear, the surface areas of clays are many times greater than those of silts. The different surface areas of the clays are related to their mineral structures, as are their swelling responses to water: the kaolin group are stable while the smectite group are highly reactive.

Large surface areas are a concern because all available surfaces must be fully coated with binder if a mortar is to achieve its maximum strength. Mortars made with finer-grained aggregates require higher proportions of binder in the mix than those made with coarser aggregates. When the aggregate contains a substantial amount of clays, it is not possible to coat all of their surfaces, so mortars made with them will have reduced strengths. Also, large surface areas mean more water is needed to lubricate the particles in a mix, leading to the risk of shrinkage cracking as the mortar dries.

Clays in a mortar mix significantly reduce the bond strength – the tensile strength of the bond between the mortar and masonry units. Bond strength depends on some water and binder penetrating into the surface and pores of the masonry; plate-like clay minerals prevent this happening and produce a weak layer against the bricks or stones. While the compressive strength of mortars can be increased by adding more binder, the bond strength – a key property of masonry – may not be improved.

> *This … (points) out the necessity of never using, in the place of sand, which is a durable stony body, the scrapings of roads, old mortar, and other rubbish, from ancient buildings, which are frequently made use of, as all of them consist, more or less, of muddy, soft, and minutely divided particles.*
>
> Anon (Nicholson), 1823

Laboratory research has shown that adding clays to otherwise clean sands increases the water demand of the mortar mix, resulting in an increase in the porosity of the hardened mortar. Despite this increased porosity, the drying behaviour of the mortar was impaired. Importantly, the pore size of pure lime mortars was substantially reduced by adding clay, suggesting a reduction in their breathing capacity and greater susceptibility to salt attack.

For these reasons, limits are required on the proportions of clays and fine silts in mortar sands. **This guide recommends mortar sands should have a maximum of 5% of material passing a 75 µm sieve, with no more than 1% of clay-sized particles (<2 µm) and no swelling clays. Lime mortars should ideally have no clays at all.** However, these limits should be interpreted with an understanding of the mineralogy and the size gradings. If all the <75 µm material is relatively coarse silt and composed of quartz, then more than 5% may be acceptable. More than 5% fines may also be acceptable where they consist of a mineral filler, such as ground limestone or marble (see Section 9.10).

This discussion applies to mortars made from sand and a lime or cement-and-lime binder. It does not apply to mortars that were principally earth, such as mortars used with adobe (mud brick). In these, clay is the binder and using clay to repair them is entirely appropriate.

Loamy sand will on no account be permitted even for admixture with sharp for brick mortar.

1877 specification for a South Australian school

Despite these concerns, bricklaying sands that are often rich in clay are widely used in contemporary construction. Builder's clay or fireclay are commonly added to mortar mixes, to improve workability. This is because the plate-like structure and the greasiness of clay minerals makes sand fatty and mortars buttery. As Chapter 4 'Mortars in Australia – then and now' explains, the need for such materials arose because of the difficulty of working cement, whereas in traditional practice the workability was provided by lime, and (where there was a choice) mortar sands were sharp, well graded and free of clay. **Those who change to lime mortars (particularly when using putty) must abandon the bad practice of using clay-rich sands in favour of more appropriate materials.**

9.6 Void ratio and its impact on mixes

Another important property of a building sand is its void ratio: the proportion of voids (or air) in the dry sand, expressed as a percentage of the total volume. The void ratio of sands typically ranges from about 30% to about 40%.

While it may seem unlikely, the void ratio of a fine sand can be the same or even higher than that of a coarse sand, as Figure 23 shows. Differences in void ratio arise because of variations in grain shape and surface texture and particularly because of different size gradings. As the figure shows, poorly graded (or uniform) sand will have a high void ratio (like the example on the left) whereas a well-graded sand (on the right) will have a lower void ratio.

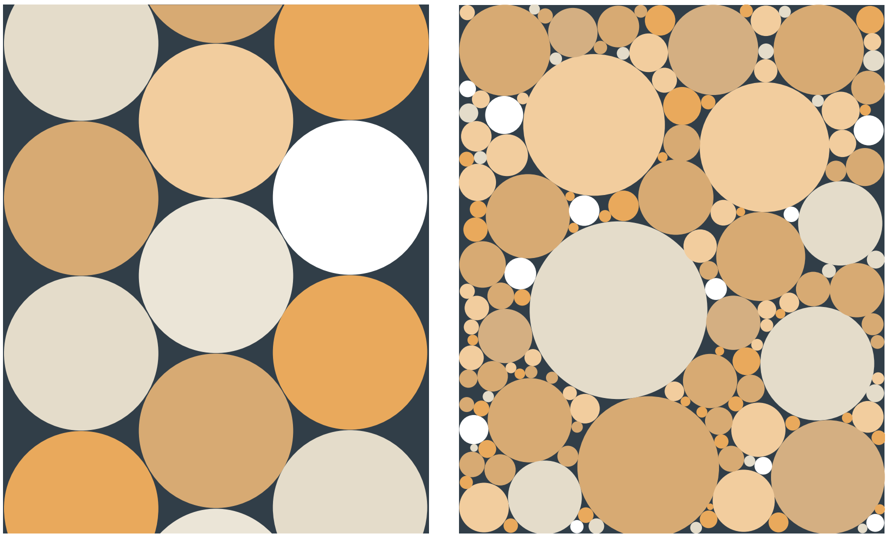


Figure 23: Impact of size grading on void ratio. On the left, provided the packing pattern remains unchanged, the proportion of voids in this uniform (poorly graded) sand will not change, irrespective of the actual size of the grains. On the right, a well-graded sand with a range of grain sizes has a lower void ratio because progressively finer grains fill the gaps between larger grains. In this illustration, the sand grains are shown as spheres to make the point; in real sands, the void ratio is also affected by the shape and surface texture of the grains (see Section 9.3).

The void ratio of a sand is an important factor that affects several key aspects of mortars: their water retentivity, workability and the mix proportions (ratio) of binder to sand.

Sands with high void ratios have poor water retentivity – their capacity to retain mixing water against the suction of the masonry is low because there are relatively large voids in the sand. A mortar made from such a 'hungry' sand will lose its workability and 'go dead' as the mixing water is drawn into the masonry. This will prevent further working and risks poor bond strength and imperfect hardening. In contrast, a mortar made from well-graded sands with smaller voids will retain mixing water and remain workable for longer, after it is applied to the masonry.

The workability of a 'hungry' sand can be improved by adding more binder or a mineral filler, or both (see Section 9.10 and Chapter 14 'Workability').

In a well-graded sand, the void ratio will be about 33%, or one-third of its volume. When making a mortar, the aim is to fill all the void space with binder in order to weatherproof the wall. This leads to mix proportions of 33 to 100, or one-part binder to three-parts sand. This is the basis for the normal (and nominal) 1:3 mix.

Box 8: Mortar sands and Australian Standards

Since the withdrawal of AS A123 – 1963 *Mortar for masonry construction* in 1995, Australian Standards have provided little guidance on the suitability of sands for mortar.

AS A123 adopted the size-grading requirements of AS A77 – 1957 *Aggregates for concrete*, but relaxed the amount passing a 75 μm sieve to allow a maximum of 10% of fines. This is the basis on which bricklaying sands have commonly been specified. Current standards have no size-grading specifications.

AS 3700:2018 *Masonry structures* requires only that 'Sand shall be free from materials deleterious to the mortar and to embedded items, and shall be chosen to produce mortar that meets the requirements of this Standard.' There is no limit on the proportion of fine material (clay and silt) that is acceptable, other than that implied by the need to meet 'the requirements of this Standard'.

AS 4773.2:2015 *Masonry in small buildings: 2. Construction* requires that 'Sand shall be free from material harmful to the mortar, grout, masonry units, reinforcement or any embedded items. Sand shall be well graded and … shall contain not more than 10% of material passing the 75 micron sieve.' And 'Fireclay shall not be used (as an additive) unless the sand is sharp and requires more workability.' The standard requires that if fireclay is added, the proposed mix shall be tested and achieve a minimum flexural strength.

This guide proposes new size-grading specifications for mortar sands. Box 7 sets out particle size distribution limits for a fine–medium sand for narrow (3 mm) joints and a medium–coarse sand for normal (10 mm) joints.

Void ratios of about 40% occur in some sands (such as dune and beach sands) which are poorly graded, with a narrow range of particle sizes. These sands require mix proportions of 40 to 100 – one-part binder to two-and-a-half-parts sand (1:2.5) – simply to fill the voids. Finer sands need higher proportions of binder (e.g. 1:2 and often as rich as 1:1.5 or even 1:1) to allow for the more uniform size grading and the progressively larger surface area of the sand.

The actual proportion of binder used in a mix may need to be different from what the void ratio indicates. With fine-grained sands it will be higher, to ensure coating of all particles; for deliberately porous (i.e. sacrificial) mixes, it will be lower.

Void ratios of about 30% and below suggest that the void space in an otherwise well-graded sand is being partly filled with an excess of fines. Such sands may need further washing and screening to make them suitable for building. Void ratios can be readily measured with simple equipment, as explained in the next section.

Another aspect of void ratios and mix proportions needs explanation. When making a 1:3 mix we begin with four parts of material – one of binder and three of sand. When combined in the mix, the total volume is only three parts, as the binder occupies the void space in the sand. If we then measure the proportions in the hardened mortar, we will get one-third (or one part) of binder and only two-thirds (or two parts) of sand: a ratio of 1:2 and not the 1:3 we started with. Understanding this apparent change in proportions from components to hardened mortars is important when visually analysing existing mortars to determine their original composition. A mortar that in cross section looks like it contains equal amounts of binder and sand is closer to a 1:2 mix than to a 1:1 mix.

In a bucket containing three parts of (well-graded) sand, there are actually two-parts sand and one-part voids. It is not possible to separate the voids from a loose sand!

9.7 Assessing sands for their suitability

Obtaining sands suitable for the repair of older buildings is made more difficult by the substantial change in the use of sands that followed the change from lime to cement. Ask a sand supplier for a mortar sand and you will commonly be offered a soft, fine-grained bricklaying sand which may contain considerable clay – in other words, a sand that is not suitable for use with lime binders. To assist in selecting sands, this section describes a series of tests, beginning with the simpler ones which anyone can do and concluding with tests done in a laboratory.

Look for sharp, washed sands, such as concrete or plastering sands.

Looking closely

To get an accurate visual impression of a sand, it must be quite dry: damp sand grains clump together, confusing an observer by looking larger and hiding their surface texture with a layer of water.

Figure 24: Settling test. A clay layer settled on top of a fine sand after shaking in water. At 9% clay this sand is not suitable for use in mortars.

Figure 25: Establishing the void ratio of a sand. Using a measuring cylinder, 100 ml of dry sand is poured onto 100 ml of water, the difference from 200 ml is the amount of water now filling the voids. This is expressed as a percentage, in this case 36%.

To look closely, use a hand lens (loupe) of about 10x magnification (as shown in Figure 49 and explained in Section 17.3 'Visual analysis, photography, stereomicroscopy'). At this magnification it is possible to see clay coating on grains (see Figures 18 and 27) and any aggregates or clumps of grains held together by clay. The surface texture and grain shape (explained in Section 9.3) can be assessed, and it's also possible to get a first impression of the range of particle sizes (explained in Section 9.4). Close-up photographs provide a good record and, where it is possible to include a scale bar, enable a reasonably accurate description of grain sizes (see Figure 27).

Feeling a sand

Feeling a sand is a very useful test. Sharpness can be judged by rubbing a dry or slightly damp (but not wet) sand between thumb and fingers: does it crackle, or is it soft? Rubbing the sand quite hard will also show if it has a significant proportion of clay: if so, after brushing off the rest of the sand, it will leave a smooth and often greasy residue on the fingers. Rubbing will also show whether any coarse 'grains' are actually lumps of clay or clay-bound silt.

Estimating clays and fine silts

The proportion of clays and fine silts can be estimated using settling tests, based on the observation that finer particles settle more slowly in water than coarser particles.

The simplest method is to one-third fill a tall, straight-sided jar with sand, add water until it's two-thirds full and vigorously shake it for 30 seconds to separate the grains. Put it on a stable base and allow it to settle out, which may be overnight or even longer for very fine clay particles. While the boundary between silts and sands may be difficult to judge, the distinction between them and the overlying layer(s) of clay and possibly humic material will be clear, as Figure 24 shows. If the jar has a regular shape, the proportion of clay can be estimated using a tape or ruler to measure the heights of the various layers.

A more accurate version of this test uses a laboratory measuring cylinder and a 1% salt solution so that the clay settles faster. AS 1141.33 explains the method. Using a measuring cylinder allows the proportions to be easily read off.

Measuring void ratio

Use a laboratory measuring cylinder to determine the void ratio. Measure out exactly 100 ml of oven-dry sand and tip it into a temporary container (or use two cylinders). Add water to the 100 ml mark of the cylinder and pour the sand slowly onto the water. Gently tap the cylinder to settle the grains and measure the level of the water after air stops bubbling out of the sand. The reduction in height from 200 ml is the amount of water in millilitres now filling the voids. Expressed as a percentage, this is the void ratio (see Figure 25).

By doing this test first and then adding several good pinches of table salt to the cylinder and shaking it vigorously for 30 seconds, you can do the settling test for clays on the same sample.

Determining size grading

Size grading is established using sieves of the sizes identified in Section 9.4 and the procedure set out in AS 1141.11. Sieving can be undertaken dry or wet, though wet sieving is more accurate, and is required by the standard for measuring the proportion that passes through a 75 µm sieve. Dry sieving is acceptable for preliminary investigations and for routine checking that the grading of a well-washed sand is consistent with previous results.

Many producers will have had their sands laboratory tested, and will make the results available. These should indicate whether the sieving was done dry or wet, and should include the size grading according to AS 1141.11 and the proportion of (<75 µm) fines according to AS 1141.11 or AS 1141.12. By plotting the results on a cumulative size-grading chart, such as the one in Figure 22 (Box 7), comparisons can be made between different sands, as well as checking that they are within the grading envelopes.

Understanding the finer particles

These tests require a well-equipped laboratory. The <75 µm fraction saved from the sieving is analysed using X-ray diffraction (XRD), a technique explained in Section 17.6 'XRD and SEM/EDX'. This provides a semi-quantitative analysis of the minerals present in the sample, and it can distinguish between stable clays (such as kaolinite and illite) and the swelling clays of the smectite group (including montmorillonite) which should be avoided at all costs. Sometimes illites can have interlayered smectites and these, too, should be avoided (see Section 9.5).

While the settling test explained above provides an estimate of a sand's clay content, it is more accurately determined using a sedimentation technique which is also applied to the <75 µm fraction. This technique, which is detailed in AS 1141.13, determines the percentage of the sand finer than 2 µm (i.e. clay-sized).

9.8 Blending sands

One way to obtain a suitable sand is to blend material from several sources. Figure 26 shows the impact on size grading of blending a bricklaying sand which has too much fine material (11%) with a washed concrete sand that has about 1% fines. By blending two parts of the concrete sand to one part of the bricklaying sand, the mix will have about 4% fines. Usefully, the blend will have about 10% of very fine sand (75–150 µm) which will improve its workability compared with the concrete sand. This blend would be suitable for use with composition mortars, which can tolerate a proportion of fines, but should not be used with lime mortars. For lime mortars, the washed concrete sand should be used in higher proportions in the blend (e.g. 3:1 or 4:1) or preferably without blending (to avoid all clay). Alternatively, it may be appropriate to use a small proportion of mineral filler to improve workability, should the sand be very sharp (see Section 9.10).

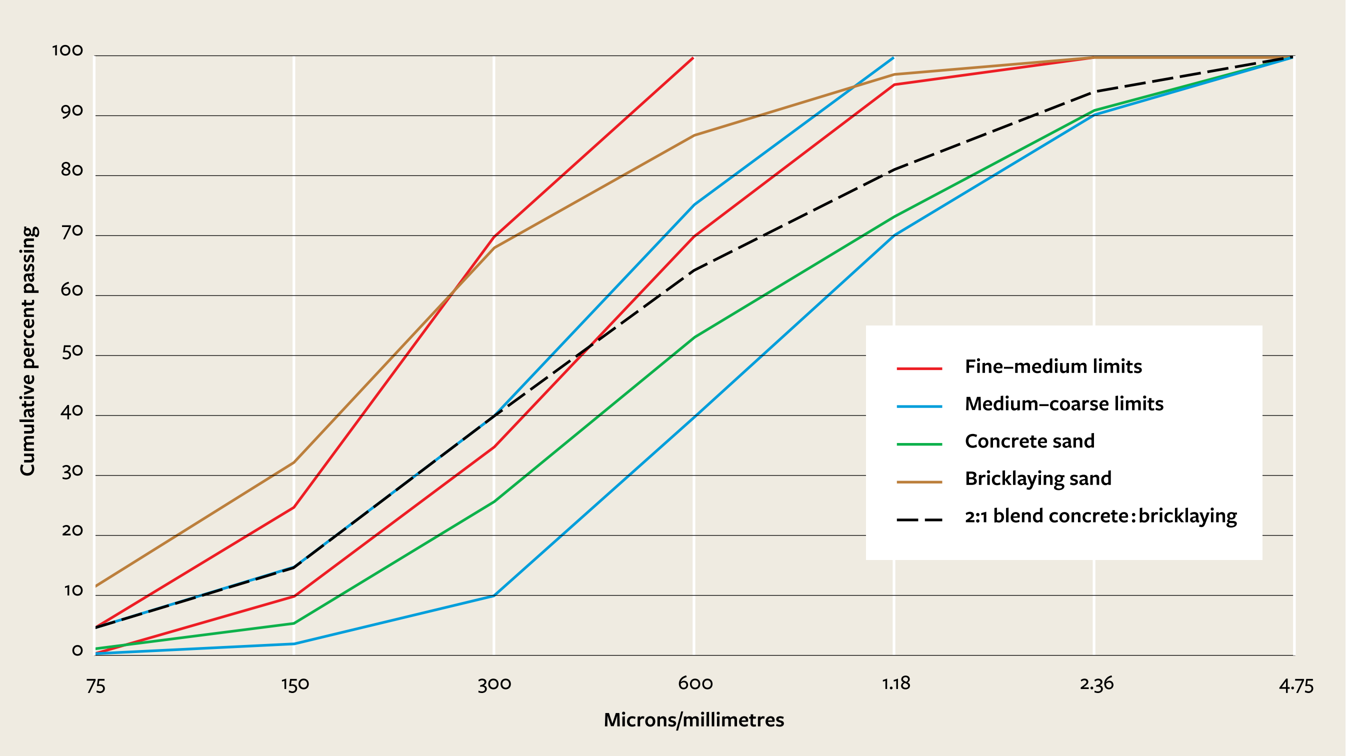


Figure 26: Blending sands. Cumulative size-grading plots of a concrete sand, a bricklaying sand and a 2:1 blend of the two. The bricklaying sand has too many fines to be used by itself, but by blending it with a cleaner sand the fines can be reduced to an amount acceptable for use with composition mortars. Fewer fines are preferred for lime mortars and so 3:1 or 4:1 sand blends would be better than 2:1. The size-grading envelopes (red and blue lines) are those proposed in Box 7 (Figure 22) for fine–medium and medium–coarse sands.

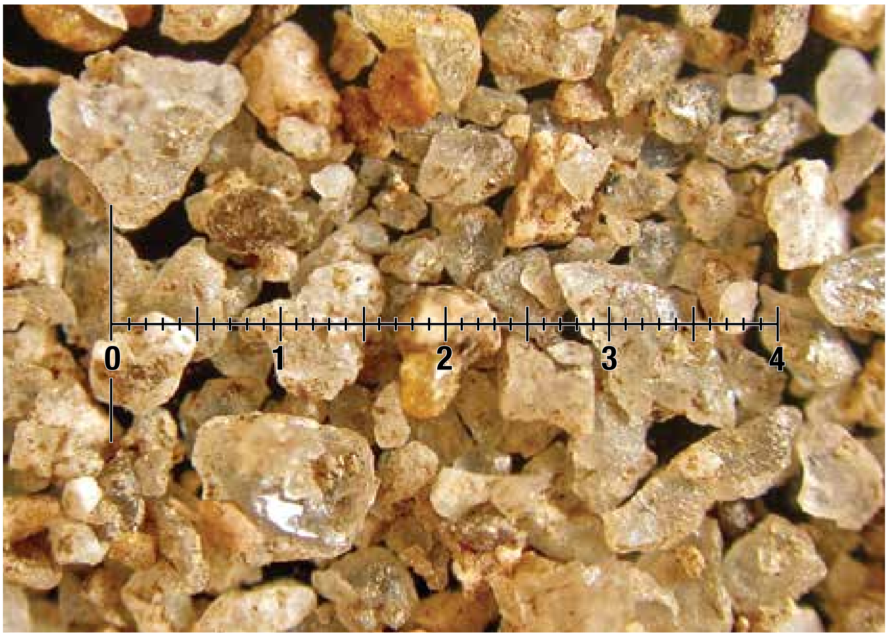


Figure 27: A sand that needs blending with a finer sand. The sharp (angular to subangular) quartz grains have noticeable, brown clay coatings on their surfaces. As well, this medium- to coarse-grained sand lacks particles smaller than about 200 μm (i.e. fine and very fine sand sizes), and so it has a high void ratio, of about 40%. Although it may initially feel workable in a mortar mix (because of the clay), in use it will prove 'hungry' as the suction of the substrate draws water from the mix. After washing to remove the clay, this sand should be blended with a small amount of a finer sand (as little as 25%) to produce a better-graded aggregate with a lower void ratio. Scale bar is in millimetres; each small division is 0.1 mm (100 μm).

Controlling the proportion of fines and improving size gradings are not the only opportunities blending can provide. Blending can be used to adjust the colour to match an original, or to improve workability by including a proportion of a more rounded sand in an otherwise angular material. A higher-quality sand that is more expensive because it has had to be transported some distance could be extended by blending it with a local, cheaper material. Figure 27 shows a sand that could be improved by blending (and washing).

9.9 Other aggregates

As well as the more common sands, a wide range of other aggregates have been used in historic mortars including:

- shell fragments, some perhaps as unburnt material from lime making
- crushed bricks, included for colour and possibly as pozzolans
- crushed stones, particularly sandstones and limestones
- charcoal and coal ashes, for colour (see Figure 32)
- coke breeze: coarser versions were used in lightweight concretes.

Some of these aggregates may have been used as cheap extenders, to make the sand go further. Coarser particles may have been included to provide structure, limiting shrinkage of otherwise very fine sands (see Figure 28).

The question arises as to when it is appropriate to use the same or similar materials when undertaking repairs, and the issues include positive and negative effects of the materials, as well as philosophical considerations relating to the extent of repair. Colour matching is discussed in Section 12.1 'Matching colours of existing mortars'.

Negative effects may arise from using coke breeze and coal ashes, due to their likely sulfate content and the tendency of coke breeze to swell with time, causing expansive cracking. Such damage is commonly seen in early, lightweight concretes that are exposed to the weather.

Figure 28: Shell fragments in an 1830s mortar. The rest of the aggregate is a very fine, silty sand with some darker gravel particles.

Porous aggregates

As well as contributing to colour and size grading, there are benefits from the use of crushed bricks and stones where those materials are themselves porous. Porous aggregates (or porous particulates) contribute in three ways:

- they assist carbonation and hydration of the binders by holding and retaining additional water during application and initial stiffening
- as the mortar dries during hardening, the additional porosity allows better penetration by carbon dioxide and hence improved (and faster) carbonation of non-hydraulic components
- the additional porosity increases the hardened mortar's breathing capacity and its resistance to salt attack.

Very porous aggregates may increase the water demand of a mortar mix.

Suitable raw materials for use as porous aggregates include older bricks with high porosities and porous stones, such as limestones comprised of fossil fragments which may themselves be porous. Both materials may have additional benefits: if low-fired, the finer fractions of brick particles may be pozzolanic (as Chapter 7 'Pozzolanic materials' explains), while the limestone, being chemically alike with lime, produces stronger mortars (as the next section explains). Further, the angular, porous surface texture of crushed limestones will ensure a more tightly interlocked structure, again producing stronger mortars.

It is important to minimise the amount of very fine dust when using crushed materials. Excessive fines will increase water demand and the risk of shrinkage (see Section 9.5 'Clays and silts – fines').

To shell or not shell?

Because of their frequently plate-like shape, shell fragments are not an ideal aggregate for mortars, though their use as a small proportion of a mix is quite acceptable. If, as in Figure 28, an old mortar has shell fragments, a question arises when repointing as to whether shells should be used in the mix to match the old joints.

For small patches, where the repair should match the surrounding original, the answer is clear: use shells to match the original texture and appearance as closely as possible.

For large areas (such as the whole elevation of a building), the decision is less obvious and will require consideration of the significance of the existing mortars (see Section 13.4 'Choosing the right mix – significance'), the availability of matching shells and alternative ways of producing a similar texture. The latter might involve using a sand containing some very coarse (fine gravel) grains to produce a similar porphyritic texture of coarse grains in a finer groundmass. The key to achieving an aged appearance similar to that of the old mortar will be in the way the joint is finished: Chapter 23 'Finishing joints' explains how tamping the surface with a stiff-bristled brush will expose the coarse grains.

Crushed shell fragments provide some carbonate chemistry to the mix, as do crushed limestones. If shells are not to be used, consideration might be given to an alternative source of carbonate, such as a mineral filler.

9.10 Mineral fillers

Adding finely ground mineral fillers (particularly limestone and marble) can benefit mortars by:

- promoting hardening of limes, when carbonate-based filler is used
- improving the size grading of otherwise poorly graded sands
- hence improving the workability of the resulting mix.

Research has confirmed what has been observed in practice: that the strength of lime mortars is greater if the aggregates are carbonate minerals (such as crushed limestone) rather than silica sands. Two- to fourfold strength increases have been reported. This is partly because of better bonding between the newly formed calcium carbonate and the carbonate aggregate: it is like bonding with like. It may also be due to the angular shape and porosity of the larger limestone particles (as the previous section explained).

Poorly graded sands often lack sufficient finer particles, particularly in the 75–150 µm range. These very fine sand-sized particles contribute workability (and colour) to a mortar mix, and their absence leads to high void ratios and poor water retentivity. These problems may be overcome by adding finely ground minerals (such as limestone or marble) with an approximate particle size range of 40–200 µm. Ultra-fine, dust-size particles (0–20 µm) should be avoided as they produce a high water demand and weaken mixes. Figure 29 shows the effect of adding one-sixth part filler to a poorly graded sand. Less filler will be required for better-graded sands.

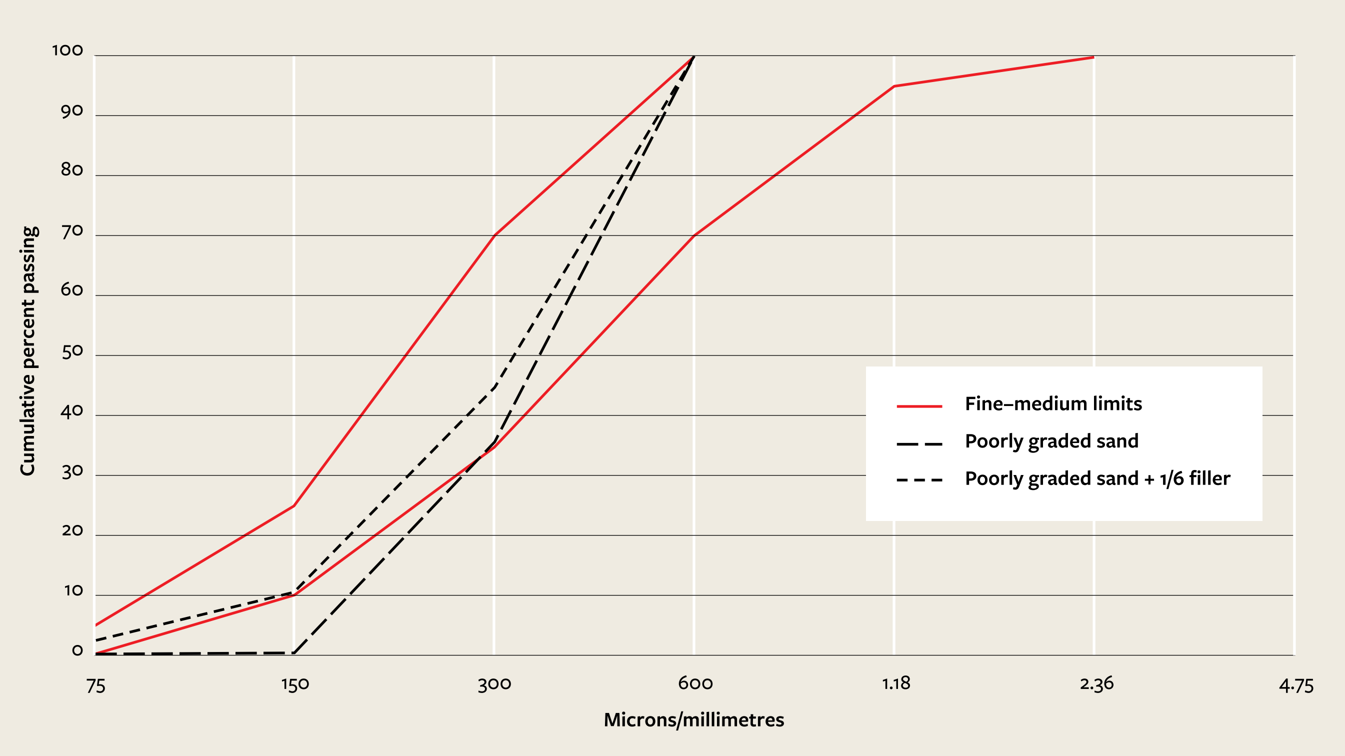


Figure 29: Adding limestone filler to improve size grading. A cumulative size-grading plot showing the effect of adding a one-sixth part of ground limestone filler to a poorly graded sand. With the filler, the sand complies with the fine–medium specification shown here and proposed in Box 7. More filler may be warranted, particularly if the aim is to make an alternative to mason's putty (see Section 16.1). Ground limestone or marble fillers should be used instead of clay or loam, which should never be used to improve the working qualities of a lime mortar.

9.11 Making do with poor sands

Some aspects of the advice in this guide may seem contradictory, and so require further comment. This guide advises that sands suitable for use with lime binders should be free of clay and have sharp surface textures and a wide range of grain sizes. Yet many early buildings, constructed of materials from nearby, have very fine, silty and often loamy sands in their mortars. How have such mortars survived? And if they are decaying, what materials should we use for their repair?

In fact, many early mortars have not survived well, and deteriorate rapidly in exposed environments. Some survive as bedding mortars only because they are protected by better-quality pointing mortars or by limewash coatings.

However, a key factor in the survival of many early mortars is the way they were made – directly from quicklime by slaking it with the sand in a process known as sand-slaking (see Section 15.1 ‘Traditional mixing’). In this process, the heat generated by the slaking quicklime cleaned the sand, and produced much better contact between sand and lime. Also, many early mixes were very rich in lime, in part making up for the poor sand. Furthermore, they commonly had large lumps of unslaked lime that effectively became part of the aggregate, providing some coarse structure to otherwise very fine-grained material (cover photo, and Figure 39 in Box 12 and Figure 42 in Box 13).

Mortars made directly from quicklime are known as quicklime mortars or hot-mixed mortars.

If the significance (i.e. heritage value) of the existing mortar warrants accurately matching it with a poor sand, then the mortar will need to be made in the traditional way, by sand-slaking quicklime, and it will need to be as rich as the original mix. **Sand-slaking is not commonly practiced in Australia, but it should be if the significance of the place justifies it.** Section 19.2 ‘Mixing’ explains how to sand-slake quicklime to make mortars.

If sand-slaking is not practicable in the particular circumstances, then lime putty should be used, but this will mean using a better-quality sand and achieving an approximate match in other ways. Blending material from several sources (see Section 9.8 ‘Blending sands’) may be a way of retaining the appearance of the original, while using a better sand. Pigments may help match the original colours, and matching the texture may be achieved by using occasional coarse, white grains of a quartz sand to replicate the lumpy look.

> See also the discussion about shells in Section 9.9 ‘Other aggregates’

Factors that may affect the approach to repairing mortars with poor sands include the significance of the existing mortars (see Section 13.4 ‘Choosing the right mix – significance’), the need to ensure compatibility with the masonry units (see Section 13.5 ‘Choosing the right mix – compatibility’) and the practical aspects covered in Part 3 of this guide. These include:

- procedures for matching previous mortars (Section 18.3)
- examples of ensuring compatibility (Section 18.4)
- matching joint profiles (Section 18.5)
- decisions about repairing small patches or larger areas (Section 18.6)
- making quicklime mortars by sand-slaking (Section 19.2).

10 Water

Water should be clean and free of organic matter, suspended particles and excessive dissolved salts. Salts are a particular concern, and bore water should be tested before use. 2,500 parts per million (0.25%) soluble salt is the maximum that should be used, but much less is preferred: blend salty with fresh water if needed. Ideally, water should be potable, or safe to drink.

There have been substantial changes in the use of water in mortars from traditional to modern practice. Traditionally, mortars were prepared with a relatively low water content, whereas in modern construction mortars are prepared relatively wet. Understanding why this change has occurred is critical for successfully repairing older buildings, and also for using traditional materials in new construction.

Few workmen are sufficiently aware of the advantage of wetting bricks before they are used; but experience has shown that works in which this practice has been followed have been much stronger than others wherein it has been neglected.

Anon (Nicholson), 1823

Traditionally, mortars were used relatively dry because the high plasticity of lime provided the necessary workability. Mortars for pointing joints were prepared even stiffer and drier than those used for laying bricks or stones. The high porosity of many traditional materials (such as low-fired bricks, some sandstones and limestones) produces considerable suction, which tends to draw water from a mortar as it is laid; too much abstraction of water and the mix will become impossible to work. Furthermore, loss of water from the mix leads to premature drying and incomplete hardening of the mortar. These problems were largely overcome by pre-wetting the masonry units before they were laid, either by dipping them in buckets of water or by throwing or spraying water over them. The water retained in the newly constructed wall provided a further benefit, namely the improved hardening of the mortar.

Unfortunately, some dated specifications still require bricks to be wetted prior to laying. Only bricks having very high water suction (the initial rate of absorption or IRA) need pre-wetting to reduce their suction, and then only in hot and windy weather with a light water spray to dampen the surface.

Think Brick Aust., 2019

In contrast, contemporary bricklaying practice is not to pre-wet the bricks and to use mixes containing a maximum amount of water consistent with good practice. This means not so much water that a brick ‘floats’ on the wet mix and fails to bond properly, or that the mix ‘falls apart’ and water leaks or bleeds out of the mortar and stains the brickwork below. This change from dryish to much-wetter mixes is partly because of the need to improve the workability of cement-based mortars, but it is mainly due to the much-lower porosities and hence suctions – the initial rate of absorption, or IRA – of modern bricks. It is essential that some water is drawn into the masonry units (whether bricks or stones) so that it pulls the binder with it and creates a good bond between the masonry units and the mortar. Consequently, the approach taken with low IRA materials like modern bricks is to encourage absorption by using dry bricks and to ensure that workability is maintained for long enough to lay the bricks by maximising the water content of the mortar.

This leads to the need to understand the suction or porosity of the masonry units, whether for use in new building, reconstruction work or when repointing joints. Also, it is important to recognise that different masonry materials in the same wall may have very different suctions.

> For more discussion of these issues see Chapter 14 ‘Workability’, Chapter 21 ‘Pre-wetting’ and Chapter 25 ‘Using lean or sacrificial mixes’.

Traditional practice should be followed when repairing traditional materials: porous masonry requires thorough pre-wetting to control suction.

11 Admixtures and additives

11.1 Plasticisers, air-entrainers, water-retainers

Traditional mortar and plaster mixes from around the globe often included local ingredients derived from animal or vegetable sources. Organic materials used in mortars have included beer; blood; egg whites; the juice and pulp of bael, fig, tamarind and other fruits; milk and milk products (such as casein and cheese); rice; sugar; urine; and vegetable oils (such as linseed oil). Some of these contributed to the properties of the hardened mortar, while others were used to modify the behaviour of the wet mix, to accelerate or retard its set and, particularly, to improve its workability and plastic properties. Today, the modern synthetic versions of such materials are known as admixtures and are divided according to their function (though some overlap).

Plasticisers (and superplasticisers) are commonly surfactants (surface active agents or detergents) and provide a lubricating action to improve the workability of mixes. By reducing the required water content by about 20%, superplasticisers can help reduce shrinkage. Unfortunately, plasticisers are widely abused by being added in excessive quantities, which produces weak mortars with poor durability. By trapping air in minute bubbles, they may also act as air-entraining agents.

Superplasticisers have an important role in grouts and in the pumping and placing of concrete.

Air-entraining agents are powerful surfactants and are added to concrete mixes to protect the hardened concrete from damage during freeze–thaw cycles in cold climates. Minute bubbles of entrained air also protect lime mortars and plasters from frost damage, and they also improve the rate of carbonation of the lime. By providing void spaces in which salts can crystallise, the judicious use of air-entrainers should help protect mortars from salt attack. Excessive use of air-entrainers will seriously reduce bond strengths, irrespective of the type of binder (cement or lime).

Water-retaining agents (water thickeners) are commonly based on methyl cellulose and are designed to resist the suction of the masonry units when the fresh mortar is placed. Retaining some of the mixing water ensures the continuing workability of the wet mix, which might otherwise ‘go dead’ and be too hard to work if the sand is poorly graded. Additionally, by slowing the drying of the mix, water-retainers improve the hardening of limes and cements.

Admixtures should never be used as substitutes for lime in composition mortars. They can be used to improve the workability, hardening and durability of mortars in which the binder is either pure lime, hydraulic lime or a composition of cement and lime. However, admixtures should not be the first port of call when seeking to improve the working characteristics of a mortar. Sacrificial mortars are an exception because of their high sand content.

> See Chapter 14 ‘Workability’

Admixtures are incorporated in very small proportions, typically a few parts in a thousand. The challenge on a building site is ensuring the correct proportioning of such small amounts, when everything else is measured in comparatively large volumes. **Admixtures must not be used at more than the recommended rates, irrespective of the type of mortar. This is particularly important with lime mortars, as they cannot afford the substantial reductions in strength which result from overdosing with admixtures.**

Some bagged cement-and-lime products contain air-entraining agents – adding more is not recommended.

11.2 Bonding agents

Various polymers have been used in modern mortars, plasters and renders as bonding agents, and to increase their strength and reduce their permeability. These materials are used as water-based emulsions or dispersions (latexes) and are added during mixing. They are also applied directly to substrates as primers to improve the adhesion of the mix. Among the more successful of these materials are the styrene acrylics and styrene butadiene rubbers (SBRs).

Product data sheets for these materials generally recommend their use in conjunction with 1:3 cement-to-sand mortars. Such mixes are not appropriate for repointing older masonry.

These materials may have some, but very limited, application in the conservation and repair of older buildings. Very limited, because they will commonly fail the compatibility test (see Section 13.5 'Choosing the right mix – compatibility') by producing mortars that are too strong for the masonry and too impermeable, restricting breathing through the joints. **They should never be used for normal repointing of porous masonry.**

These materials are likely to be required only in uncommon circumstances, and only on specialist advice. These may include situations where previous, inappropriate treatments have left masonry units with impermeable surfaces with no suction, to which conventional mortars cannot adhere.

> See Section 16.2 'Elastomeric sealants (mastics)'

Polyvinyl acetate (PVA) has been widely used as a woodworking adhesive, and also in masonry applications. However, it is not stable in the presence of moisture and it blocks pores, which prevents breathing. Although it is cheap compared to acrylics or SBRs, **PVA should never be used in the conservation or repair of valuable masonry materials.**

12 Pigments and colouring agents

Most mortars in Australia are naturally coloured: additional pigments or colouring agents have not been included in the mix. Their colour is mostly due to the finer sand particles and to the off-white of lime and white cements and the light-to-mid-greys of normal cement.

Exposure and weathering will change the appearance of a mortar with time, adding warm, yellow and reddish colours due to windblown dust and grey-to-dark-grey tones as lichens and other micro-organisms accumulate on walls which face the prevailing weather.

> See Box 12 'Changing appearances'

Pigments are added to mortars where brickwork is tuck pointed: the stopping mortar is coloured to match the bricks – commonly red but also cream and dark brown – and a narrow white (or black or red pigmented) ribbon or bead of lime and fine sand is applied over the top to give the impression of fine-jointed work (see Figure 30). Red pigments were also used to colour pointing that was ruled with an incised groove and pencilled (see Figure 31).

Pencilling is the traditional term for painting joints with a thin brush (known as a pencil). See also Box 14 'Joint profiles'.

Dark-coloured stones (such as bluestone) were often finished with a dark mortar, which contained one or a combination of coal ashes, charcoal, lampblack or coke breeze, and were ruled and pencilled (see Box 14 'Joint profiles' and Figure 57). The joints in red brickwork were sometimes pointed in a dark mortar (see Figure 32).

Figure 30: Tuck-pointed brickwork. The pale-red stopping mortar has faded from an original dark colour due to leaching out of the carbon black pigment. On completion, the stopping mortar would have been closer in tone to the surrounding bricks.

Figure 31: Pigmented mortar. The red pointing mortar, which matches the colour of the bricks, retains some of the black paint, termed pencilling, in the ruled joint. To the left, the white pointing tones-in with the sandstone on the far left.

Figure 32: 1860s blue mortar. This dark pointing mortar was made from lime and sand coloured with charcoal or ashes and a finer pigment, such as vegetable black or lampblack. The face of the brickwork was washed with a black colourwash, traces of which remain, particularly on the lower bricks. Weathering has eroded much of the pointing and exposed some of the lighter bedding mortar. Sands blackened by their use as moulding sands in foundries were also used in dark-coloured mortars.

12.1 Matching colours of existing mortars

Matching the colour of an existing mortar should first be approached by seeking to match the colour of the unweathered mortar, if necessary, by scraping off some of the surface to expose the fresh material beneath. The aim should be to match the colour of the binder and the sand.

> See Chapter 9 'Sands and other aggregates'

We are commonly faced with the problem of modern pure limes, which are made from high-grade limestone in gas-fired kilns, being much whiter than the off-white and cream colours found in traditional limes. These colours occurred because of impurities in the limestone, or because wood- or coal-fired kilns often resulted in some of the ash being incorporated into the lime. In such cases, it is appropriate to use pigments or other means to tone down the blinding white of modern, pure limes. Satisfactory toning down can be achieved with about ¹⁄₁₀₀ part (1%) pigment.

Hydraulic limes can have cream, pale buff and light grey colours. Fly ash pozzolans are also grey and will tone down a white lime. However, colour should not be the primary reason for using these materials.

Pigments should only be added to mortar mixes to match the fresh colour of traditional limes and not to match the appearance of joints that have aged with weathering. Matching an aged appearance should be achieved by applying a tamped finish (see Chapter 23 'Finishing joints') or by adding colouring (or dust) to the surface after the joint is finished.

> See Section 18.3 'Matching previous mortars'

When using pigments, the general rule should be to use as little as possible, with a maximum pigment concentration of 10% of the volume of the binder or 2% for carbon black (lampblack). These limits are necessary because the fine particle size of pigments, which are exceptionally fine for carbon black, means they have very high surface areas. Too much pigment will increase water demand and significantly reduce the bond strength of a mortar. Using smaller quantities of a stronger pigment may be preferable to larger amounts of a paler hue, even though it will be more difficult to get the proportions consistently correct.

Pigments should always be natural earths or alkali-stable synthetic oxides, such as are used with cement. Organic dyes should never be used, as they fade with time. Pigments should be considered as part of the aggregate. Importantly, a sand which already has appreciable fines may, after the inclusion of the pigment, end up having too much, and produce a weak mortar of poor durability.

> See Section 18.3 'Matching previous mortars' for advice about preparing sample biscuits for colour and texture comparisons.

Section 9.10 'Mineral fillers' discusses the use of crushed and milled limestone as a filler to improve the workability of sands that lack finer particles. Many ground limestones will be white, but if the filler is produced from coloured marble or travertine it may help reduce the whiteness of modern limes.

One way of adding a warm, dust-like hue is to paint or spray onto the new mortar a weak solution of iron sulfate (also known as copperas, or green vitriol), which was widely used in yellow colourwashes and limewashes on renders and stuccoes. The initially pale-green-coloured solution oxidises to a warm yellow on exposure. While this means adding soluble sulfate salts to the wall, the proportion will be very small and should not be a problem.

> Section 18.3 'Matching previous mortars' has advice about how to use copperas.

13 Mortar mixes

When (the lime) has been slaked, the mortar should be mixed in such a way that if quarry-sand is to be used, three parts of sand to one of lime should be poured in; if using river or sea sand, two parts of sand should be mixed with one of lime; this will be the right adjustment of the proportions of the mixture. Furthermore, if anyone using river or sea sand were to add in a third of ground-up and sifted fired brick, this will produce a mortar better mixed for use.

Vitruvius, c. 30–20 BCE

13.1 Traditional mixes

Most people involved in the conservation and repair of older buildings would be familiar with the traditional mortar mix of one part of lime to three parts of sand, a mix that has been known for thousands of years. But when we look at old mortars (and their specifications) and ask the questions, 'Which sand?', 'Which lime?' and, 'For what purpose?', we find such a wide range of mixes that things become confused. This is compounded by the substantial changes in materials and practice since World War II, which make it harder for us to comprehend how it was originally done.

Which sand?

Today, we understand the theory behind a 1:3 mix as being the amount of lime required to coat all the sand grains and to fill the void space between them, to produce a weatherproof joint. With well-graded sand, there will typically be about 33% (one-third) of voids, and so the amount of lime required is one-third of the volume of the sand. However, this only applies to well-graded sands. A poorly graded sand with a void ratio of 40% will need a mix of 1:2.5 to fill the voids. If the sand is fine grained, the mix will need to be richer still – 1:2 or 1:1.5, or even 1:1 for very fine sands (see Section 9.6 'Void ratio and its impact on mixes').

Which lime?

When planning to match a mortar, we naturally think in terms of commonly available limes – hydrated lime and lime putty. Yet in the nineteenth and early twentieth century, most mortar for brick and stonework was produced by slaking quicklime together with the sand – sand-slaking, see Section 15.1 'Traditional mixing'. The significance of this is that the mortar proportion was a ratio of quicklime to sand, not lime putty or hydrated lime to sand. The use of the term 'lime' to mean both quicklime and slaked lime has helped confuse the issue. Because quicklime expands on slaking, starting with a mix of 1:3 quicklime to sand will produce a mortar in the range 1:1.5–1:2 slaked lime to sand. Chemical analyses of many early mortars show rich mixes ranging between 1:1 and 1:3 (see Box 13 'Lime lumps' for examples of very rich mixes).

> Making sand-slaked mixes is explained in Section 19.2 'Mixing'.

Another factor is how hydraulic was the quicklime: the more hydraulic, the less it will expand on slaking, so the proportions were adjusted to account for this. This explains why one source recommended the proportions of quicklime to sand for mixes that were to be sand-slaked should be:

1:3	for fat, non-hydraulic limes
1:2.5	for feebly hydraulic limes
1:2	for moderately hydraulic limes.

What purpose?

To further complicate the picture, many specifications appropriately called for different strength mixes for different parts of buildings, and particularly for the use of richer mixtures for below the damp-proof course and for exposed elements, such as copings. Mixes ranging from 1:1 to 1:3 were specified for both lime and cement mortars.

So, while there is a sound (void ratio) basis for a modern 1:3 mix made with dense lime putty, there were many traditional mixes. The question of which mixes to use in the repair of old mortars is discussed in the following sections.

13.2 Composition mortars

1:1:6 … is fast becoming standard practice for one- and two-storey residential work and for most small to moderate-sized buildings.

Watson Sharp, 1953

After the initial enthusiasm for pure cement mortars in the late nineteenth and early twentieth centuries, the benefits of combining cement and lime in composition ('compo') mortars were recognised. They included the faster hardening and higher strengths of cement, and the workability and better water retentivity of lime. Table 9 shows typical composition mortars and their classifications according to AS 3700 *Masonry structures* and ASTM C270 *Standard specification for mortar for unit masonry*.

Table 9: Composition mortars

Mix proportions by volume			Mortar class/type		Properties
Cement	**Lime**	**Sand**	**AS 3700**	**ASTM C270**	
1	0.5	4.5	M4	S	↑ Increasing strength & brittleness Decreasing permeability & workability
1	1	6	M3	N	
1	2	9	M2	O	
1	3	12	M1	K	

Note: These mixes are for contemporary construction and are not recommended for the normal repair of porous materials. See Box 10 'Mortars and Australian Standards', particularly about the nature and proportioning of the lime component.

These mixes preserve the 1:3 ratio of binder (cement plus lime) to sand, with changing cement to lime ratios depending on the properties required. They assume well-graded sands: poorly graded sands may require richer mixes (such as 1:1:5 instead of 1:1:6 and 1:2:7–8 instead of 1:2:9).

> See Section 9.6 'Void ratio and its impact on mixes'

> See Chapter 6 'Cements' and Chapter 8 'Comparison of lime and cement binders'

Mixes like 1:2:9 and 1:3:12 have been widely specified by those seeking to replicate lime mortars, with the added advantages of some cement. There are now concerns about the suitability of such mixes for porous masonry.

This guide recommends that 1:3:12 mixes should no longer be used. Instead, mortars based on pure limes with added pozzolans, or on natural hydraulic limes should be used for circumstances where greater strengths are required than those of pure lime mortars. For a given compressive strength, a hydraulic lime mortar will have an equal or superior flexural (bending) strength and much greater elasticity and permeability than a cement-and-lime composition mortar.

Sulfate-resisting (SR) or low-heat (LH) cements should be considered instead of general purpose (GP) or blended cements (GB) where slower early hardening is acceptable (see Section 6.7 'Which cement?').

Mixes such as 1:2:9 and 1:1:6 may still have a role in repair work, such as in circumstances that need reasonably fast hardening (e.g. undersetting), or where the building or structure was constructed with a cement-based mortar and strong, dense bricks or stones. But even in these situations, alternative solutions, such as the use of natural cements or the stronger classes of natural hydraulic limes, may be more appropriate.

The lack of attention to curing that is all too common in Australia is likely, particularly during hot or windy weather, to produce weak mortars in which only a small proportion of the lime (and not all of the cement) is properly cured. In these circumstances, 1:2:9 and 1:1:6 mixes are best thought of as cement mortars containing lime as a workability aid.

> See Chapter 24 'Protection and curing'

13.3 Durability

Failures of modern, cement-based mortars and renders on porous masonry have led to research and field trials which have resulted in new understanding of the behaviour and durability of traditional limes.

Perhaps the most outstanding example comes from Sweden, where lime-rendered and limewashed walls of seventeenth- to nineteenth-century buildings were repaired in the 1950s and 1960s with cement-based renders and modern paints. The modern repairs failed in the freezing Swedish winters, whereas the traditional materials survived. A long period of research and trial and error led to the reintroduction of the traditional practice, so that today the walls are re-rendered in lime and recoated in limewash (see Figure 33).

The key understanding here is that, paradoxically, the more open and porous a mortar or render is (within reason), the more resistant it will be to the repeated cycles of freezing and thawing that are common in the harsh Swedish winters. The same goes for the paint coatings, too. Adding cement to a lime mix to increase its strength and durability was found in practice to make less-durable mixes than straight lime mortars. The reason is that the cement blocks pores (see Figure 12) which leads to water becoming trapped in smaller pores and the masonry fails as the water expands as it turns to ice. The findings of this Swedish work are also relevant to hotter climates, where salt attack is a major mechanism of masonry decay.

Figure 33: Limewashed and lime-rendered walls in Gamle Stan, Stockholm.

A project involving laboratory testing and field trials in England – the Smeaton Project – found similar results: adding small amounts of cement produces mixes that are less durable than lime mortar.

More recent laboratory work in Portugal tested a range of mixes including pure lime, lime with pozzolans, hydraulic lime and cement-and-lime compositions. This work used an accelerated weathering test, which simulates salt attack with a series of wetting and drying cycles. The results showed that pure lime mortars performed better than those with pozzolanic additives and better than hydraulic limes. While directly translating these findings to real walls is not straightforward, this work also showed that 1:3:12, 1:2:9 and even 1:1:6 composition mixes performed poorly against sulfate salts, which are particularly aggressive.

These results may seem to be at odds with durability testing of contemporary composition mortars, which shows that M4 mortars are more durable than M3, and M3 more durable than M2. Both sets of test results are valid: their different outcomes are a product of different starting points for the research, as well as different test procedures.

Poor durability is the reason for the recommendation to no longer use 1:3:12 mixes. Mortars of equivalent strength, better elasticity and greater porosity and permeability (and hence durability) can be made from pure lime with suitable pozzolans or from natural hydraulic limes.

Improved durability has been demonstrated for lime mortars containing porous particles in the aggregate (see Section 9.9 ‘Other aggregates’). Because they provide additional pore space, the porous aggregates also improve the hardening of the mortar, initially by holding water, and then by allowing more carbon dioxide to reach the carbonation front.

> See also Section 5.6 ‘Setting of lime mortars’

It’s also important to consider the durability conferred on a whole wall by using a weaker mortar that protects the masonry units (see Section 13.5).

13.4 Choosing the right mix – significance

The repair and conservation of masonry buildings and structures often involves repointing mortar joints and reconstructing walls. Decisions about the choice of materials and mixes for these works should be based on two criteria:

- the significance of the building and the existing mortars
- the compatibility of the proposed replacements.

Where the existing mortar is of cultural significance (i.e. of heritage value), its conservation should be based on the principles of the Australia ICOMOS *Burra Charter* including:

- retention of as much significant material as possible
- like-for-like replacement where needed
- preference for using traditional materials and techniques.

> See Chapter 17 'Investigation and analysis of mortars'

These principles imply matching the original materials, in terms of their nature, colour, texture, grain size and proportions. To do this well, the existing mortar needs to be closely studied and analysed to determine its make-up.

The significance of the mortar also needs to be weighed against the significance of the whole building or structure and its conservation needs.

Significance cannot be the sole factor determining the choice of materials. Some traditional materials are simply not available, or they are not available in the form they were in when used in the nineteenth and early twentieth centuries. Also, original materials may sometimes be accelerating deterioration of the fabric or unsuited to a changed physical environment. Further, where the existing mortars were made of poor materials (e.g. sand containing a lot of silt and clay), matching the existing mortar might be unwise because it could lead to the need for more frequent repairs. These factors may force us to choose alternative materials, and here the question of compatibility is critical.

13.5 Choosing the right mix – compatibility

A long term view is required – an apparent success, judged after a few years, may later prove to have failed.

New materials and the mortars made from them must be compatible with the existing mortar and with the masonry units with which they are to be used. This usually means producing a mix with porosity, permeability and strength characteristics similar to those of the original. **The key requirement for compatibility is that the new materials and mix should never damage the original bricks, stones and mortar**.

In designing a replacement mortar mix, we begin with the original materials and mix (or as close to them as possible) and then consider whether the compatibility criterion will be satisfied in the particular circumstances. This may mean modifying the original mix so that:

- it is weaker than the original
- it has appropriate porosity and permeability
- it has appropriate thermal expansion characteristics
- it is sufficiently flexible to allow for minor movements
- potential problems (such as soluble salts) can be managed
- there are no adverse side effects of the repairs.

Another way of saying this is that mortars should always be designed to suit:

- the particular masonry units or combination of masonry units
- the exposure levels of the different elements of the building
- the condition (and hence repair needs) of those elements.

Mortar types

1. Pure lime
2. Lime + pozzolan
3. Natural hydraulic lime (NHL)
4. Cement + lime
5. Sacrificial lime
6. Narrow joint

For details of these mortar types see Table 10 and Section 13.7.

Each of these points is explained below and examples of potentially suitable repointing mixes are given using the mortar types shown at left; these mortar types are explained in Table 10 and Section 13.7.

Ensuring compatibility with the masonry units

This means selecting from a range of mixes that reflect the porosities and strengths of the masonry units. For porous, weak materials (such as low-fired bricks or some limestones and sandstones), a pure lime (type 1) mortar may be appropriate, whereas for materials of moderate porosity and strength a lime + pozzolan (type 2 with less pozzolan) or a natural hydraulic lime (type 3 – NHL 2) mortar may be more suitable. For stronger materials with low porosities, lime + pozzolan (type 2) or natural hydraulic lime (type 3 – NHL 3.5) mortars should be considered. Provided they are compatible, cement + lime (type 4) mortars may be appropriate for strong, dense materials, but only where the originals were cement based and generally only for post-1920 structures.

Very hard materials (such as granites) actually require softer mortars (types 2 or 3) to allow for movement during thermal expansion and contraction. Less-elastic mortars would simply be crushed between the granite blocks. Where a building or structure is made of several types of masonry units with different porosities (e.g. bluestone with brick dressings or brick with limestone dressings), the approach to mortar selection should be based on compatibility with whichever are the more porous units. Some circumstances may warrant using different mixes for the different masonry units in the same building.

Ensuring compatibility with exposure levels

This means taking account of the different exposure levels around a building and selecting mortars appropriate to them. More exposed parts (such as chimneys and parapets) may warrant the use of lime + pozzolan (type 2) or natural hydraulic lime (type 3 – NHL 2) mixes. Stronger versions of these mixes (NHL 3.5 in the case of type 3) should be considered for very exposed elements (such as towers and spires). Thus, several different mixes may be needed in any one project.

Other exposure-level considerations include the zone below the damp-proof course, the splash zone near ground level (often the same thing) and buildings in coastal environments, particularly those facing esplanades. Each of these circumstances suggests the use of a stronger mix than normal, and this will usually be appropriate for new building work where the masonry units are also chosen to suit the higher exposure levels. However, for repair and repointing of existing buildings, a key determinant is the condition of the existing masonry (see Figure 34).

Ensuring compatibility with the existing masonry

This requires clearly understanding its present condition and the nature of any deterioration mechanisms that have been at work or that may still be at work.

Managing salt-damaged masonry is a common problem in building repair, and it often leads to the challenge faced by the chimney in Figure 34. Here, the exposure would suggest a stronger mortar than the original (which was a pure lime, type 1), but the low-fired bricks have been damaged by salt attack and will decay more rapidly if repointed with a less-permeable mortar. In the first instance, they should be repointed with a sacrificial mortar (type 5) with the aim of drawing as much salt as possible from the bricks into the mortar. Although this will mean having to revisit the work after a relatively short period, it may be that the mortar will extract most of the salt from the bricks, so the third mortar can be a little more durable.

More active methods of salt removal (such as poulticing and captive-head washing) are explained in *Salt attack and rising damp: a guide to salt damp in historic and older buildings*, another in this series of guides.

Figure 35 shows a design-detailing fault which is allowing excessive moisture to penetrate the brick buttresses, resulting in erosion of the mortar joints. An appropriate response might be to use two mortar mixes: one less permeable (e.g. types 2 or 3) to reduce water entry into the buttresses and another more permeable (types 1 or 5) to encourage rapid drying, and so localise ongoing damage to a small area on the faces and opposite sides of the buttresses.

Another aspect of compatibility is that weaker mortars can provide durability and resilience to walls. Research has shown that soft lime mortars behave plastically under triaxial compression producing a cushioning effect, which helps protect the masonry units from damage during settlement or seismic activity. This is because the stress is absorbed by compression of the pore spaces within the mortar: the mortar collapses internally rather than expanding outwards and damaging the vulnerable edges (arrises) of bricks or stones.

Figure 34: Which mortar? Because chimneys are more exposed, the initial response may be to use a stronger mortar than the original, but here the bricks are deteriorating, requiring a weaker, sacrificial mix (type 5).

13.6 Choosing the right mix – applying the criteria

The following examples illustrate how the significance and compatibility criteria guide the choice of replacement mortars.

Replacing a lime mortar in soft brickwork with a cement mortar not only fails the significance test – because it's not the same as the original – but also fails the compatibility test – because the new mortar would be incompatible with the soft bricks and with the original mortar.

Though there will always be exceptions, a replacement mortar should usually be weaker than the original, so any future failure occurs in the repair work, which protects the older fabric that may be of heritage value.

Figure 35: Water and salt damage to brickwork. Water running down the pediment coping is penetrating the buttresses and then drying out through their faces and opposite sides. This is where salt attack decay takes place, and so it will be important to replace the eroded mortar with a permeable mix to encourage rapid drying and so localise salts. A less-permeable mix finished with a denser surface to limit water entry should be used on the inside buttress faces.

Replacing a mid-twentieth century 1:3 cement-to-sand mortar with a 1:3 mortar made with Portland cement would fail the compatibility test, because modern cement is much stronger than that of the mid-twentieth-century (see Section 6.3 ‘Portland cement through time’). A replacement mortar of these proportions would be too strong, too brittle and too impermeable for most masonry units. The challenge in these circumstances is to design a cement-based mortar that is slightly weaker than the original but has appropriate porosity and other characteristics. One approach would be to use a composition mortar based on cement and lime; another would be a composition mortar using masonry cement and lime (see Section 6.5 ‘Masonry cements’). A third would be to use ground granulated blast-furnace slag (GGBFS) in combination with lime to produce a composition mortar in which the ground slag replaces Portland cement.

> See Section 6.7 ‘Which cement?’

For earlier (nineteenth and early twentieth century) cement mortars, which are weaker still, it may be appropriate to not use any cement in the replacement, but to instead use a mortar based on natural hydraulic lime: see mortar type 3 (NHL) in Table 10.

As Section 13.4 notes, original materials are sometimes contributing to decay, but those same materials may be acceptable in other circumstances. Mason’s putty (see Section 16.1) is one of these. Because it is relatively impermeable, it will not be compatible with porous sandstone or limestone, particularly where the stones are weakened by excessive water penetration. However, where the masonry units are dense materials like granite or marble, repointing with a mason’s putty may satisfy both the compatibility and significance criteria.

Reducing or omitting the linseed oil from the putty may be desirable, to limit oil penetrating into the granite or marble, which may cause staining and water repellency.

Producing a mortar with appropriate porosity and permeability may necessitate using a cleaner sand than the original (to avoid clays) or incorporating porous aggregates and/or the judicious use of air-entraining agents to increase porosity. Each of these changes from a significant original may be warranted to achieve a more compatible mix.

Selection of joint finishes is another aspect of ensuring compatibility which may sometimes require a departure from the significant original. While an original profile may have been a struck finish (see Box 14 ‘Joint profiles’), the need to ensure good breathing behaviour of the joint may suggest using a tamped finish to increase the surface area and improve the capacity to exchange air with the atmosphere (see Chapter 23 ‘Finishing joints’). There may also be good significance-related reasons to use a tamped finish, as it gives an aged appearance to the joint. If an aspect of a building’s significance is its age, then it should look old: patch repointing of mortar joints should blend in with the remainder and so may need an aged look. This in turn may happily coincide with the need for compatibility.

> See Section 18.6 ‘Small patches or larger areas?’ for a discussion of the issues with repairing small patches and large areas.

Box 9: Compatibility

These photographs illustrate a key requirement of mortars: they should always be compatible with the masonry units, even if this means more frequent repairs than we might prefer.

Though decaying, the mortar in Figure 36 is compatible with the adjacent bricks because:

- it is weaker than the bricks, and so is behaving sacrificially
- it is more permeable than the bricks, allowing drying through the joints
- its large pores accumulate salts (which are the cause of its decay)
- it has a similar thermal expansion to that of the bricks.

The mortar has failed, but because it is compatible it has protected the bricks from damage due to the rising dampness and associated salts in the masonry. Now, after a hundred years, the mortar is in need of replacement.

Figure 36: Compatible mortar.

Figure 37: Incompatible mortar.

In contrast, Figure 37 shows a sandstone wall about 10 years after repointing with a 1:1:6 composition mortar which is not compatible with the stone. The sandstone is decaying because the relatively impermeable mortar is forcing evaporation of dampness through the stones rather than the joints. As a result the stone faces are retreating due to salt attack and the mortar now sits proud of the stones, producing the shadow lines seen here.

13.7 A range of mortar mixes

Table 10 on the next page illustrates a range of mortar mixes that are appropriate for use in the repair of older buildings.

While these mixes may help develop specifications for repair, they are intended as a guide only and not as a substitute for careful investigation and analysis of the circumstances that apply to each case.

The mixes are arranged by **mortar type**, and the proportions are indicated as **nominal mixes**. The actual mixes may vary depending on the nature of the binder and the sand, and importantly on the need to ensure good workability.

> See Chapter 14 'Workability'

Where the **binder** is non-hydraulic lime, the table shows this as either quicklime or lime putty. Quicklime produces excellent sticky mixes that are richer than putty and more akin to traditional mortars. Where quicklime is not available, lime putty is preferred to hydrated lime because of its superior working characteristics, though the latter can be used if there is no practicable alternative, provided that it is fresh and that allowance is made for the different densities of these materials.

> See Section 5.3 'Lime putty and hydrated lime'

Pozzolans are measured as a percentage of the lime content, and are shown as fly ash, GGBFS or trass, in proportions appropriate to their hydraulic reactivity. Other pozzolans might be used, provided their reactivity is taken into account.

> See Chapter 7 'Pozzolanic materials'

The proportion of **sand** in a mix will depend on its properties, particularly its void ratio (see Section 9.6 'Void ratio and its impact on mixes'). The nominal mixes assume well-graded sands. Poorly graded sands, or those with finer grain sizes, will require richer mixes with less sand. Mixes richer than the nominal ones will often be required when using lime putty or hydrated lime binders.

Porous aggregates, such as crushed porous limestone, may be used in place of some of the sand to retain water and so improve curing, as well as improving the breathing characteristics of the hardened mortar.

> See Section 9.9 'Other aggregates'

Fillers, such as ground limestone or marble, may be needed to reduce the strength of a cement-based mortar (see Section 6.5 'Masonry cements'), to enhance the hardening of lime mortars, to improve the grading and hence workability of a sand (as in Section 9.10 'Mineral fillers') or to make a mortar suitable for narrow (3 mm) joint work (see Section 16.1 'Mason's putty').

Admixtures may be required to improve working and curing behaviour, particularly where poorly graded sands must be used. Air-entrainers and water-retainers are recommended for sacrificial mortars because of the need to provide additional pore space and because the higher proportion of sand reduces workability.

> See Section 11.1 'Plasticisers, air-entrainers, water-retainers'

Some **applications** for the various mixes are shown in the table. The choice of mix should be based on the significance of the existing mortar, on the exposure conditions and particularly on the need to ensure compatibility.

> See Sections 13.4 to 13.6 'Choosing the right mix'

The circumstances may warrant the use of **alternative binders and mixes** such as those shown in the table. Half the proportion of pozzolan (i.e. 5% of fly ash or GGBFS, or 10% of trass) will be appropriate for many repointing jobs. The workability of natural hydraulic lime (NHL) mortars can be improved by adding 10% of lime putty to the mix. Higher proportions of putty (e.g. 25%) are recommended for NHL mixes whenever greater permeability is needed to manage a dampness and/or salt problem. Pure lime or lime and pozzolan mixes will provide improved permeability compared to NHLs.

Table 10: Mortar mixes arranged by type

Mortar type	1. Pure lime	2. Lime + pozzolan	3. NHL	4. Cement + lime	5. Sacrificial lime	6. Narrow joint
Nominal mix	**1:3**	**1:3**	**1:2.5[1]**	**1:2:9**	**1:4**	**1:1.5**
Binder	Quicklime or putty	Quicklime or putty	NHL 2 or NHL 3.5	Cement[2] + lime	Quicklime or putty	Lime putty
Pozzolan		10% fly ash or 10% GGBFS or 20% trass[3]				± 5% fly ash or ± 5% GGBFS or 10% trass[3]
Sand	2–3 parts	2–3 parts	1.5–2.5 parts	7–9 parts	3–5 parts	1–1.5 parts
Porous aggregate	± Por. agg. replacing 0.5 part of sand	± Por. agg. replacing 0.5 part of sand	± Por. agg. replacing 0.5 part of sand	± Por. agg. replacing 0.5–1 part of sand	Por. agg. replacing 0.5–1 part of sand	
Filler	± Finely ground limestone/marble	± Finely ground limestone/marble	± Finely ground limestone/marble	± Finely ground limestone/marble		Finely ground limestone/marble up to 0.5 part
Admixtures	± Air-entrainer ± Water-retainer	± Air-entrainer ± Water-retainer	± Air-entrainer ± Water-retainer	± Air-entrainer ± Water-retainer	Air-entrainer Water-retainer	± Air-entrainer ± Water-retainer
Applications	Bedding and repointing weak bricks and stones	Bedding mortars; Repointing bricks and stones	NHL 2 pointing & bedding mortars; NHL 3.5 mortars if very exposed	Repointing of strong materials originally built with cement mortars[4]	Repointing very weak materials, and/or to control high salt levels	Repointing narrow (3 mm) joints in ashlar stonework
Alternative binders and mixes	Fresh hydrated lime, provided its density is allowed for	Less pozzolan (e.g. half the above %); NHL mixes	NHL + putty; NHL + pozzolan; Lime + pozzolan	1:1:6 for bedding stronger materials[5]; NHL mixes	Lime + 5% pozz. or NHL 2 + 25% putty for exposed locations	NHL 2 + 25% putty for exposed locations

This table should be read in conjunction with the explanation on the preceding page and the advice in the remainder of this technical guide.

1. Nominal mixes for NHLs (natural hydraulic limes) are richer than for pure limes because NHLs contain a proportion of inert material, and so have less sand-carrying capacity.
2. Section 6.7 'Which cement?' discusses the types of cement that may be appropriate for use in repairs: e.g. blended, low-heat, sulfate-resisting, or slag cements.
3. Pozzolans are measured as a percentage of the lime content, not of the total mix; their proportion depends on their hydraulic reactivity (Chapter 7 'Pozzolanic materials').
4. Cement + lime composition mortars should not be used for repointing lime mortar joints. Instead use pure lime, lime + pozzolan or natural hydraulic lime mortars.
5. Very hard materials (such as granite) require more elastic lime mortars (such as types 2 or 3), to allow for thermal movement.

± This symbol means plus or minus, or with or without the pozzolan, porous aggregate, filler or admixture, depending on the circumstances.

Box 10: Mortars and Australian Standards

Developed primarily for new buildings and addressing contemporary building practices, the current Australian Standards for masonry are AS 3700 *Masonry structures* and AS 4773 *Masonry in small buildings*. These require that cement and building lime comply with:

- AS 3972 *General purpose and blended cements*
- AS 1316 *Masonry cement*
- AS 1672.1 *Limes and limestones, Part 1: Limes for building.*

AS 3700 and AS 4773 also have material requirements for sand (see Box 8), water and admixtures.

AS 3700 classifies mortars according to their proportions by volume into four classes: M1 to M4. Durability and structural requirements are deemed to be met by mortars used in accordance with Table 11, which is extracted from AS 3700 tables 5.1 and 11.1. Note that Table 11 applies only to clay bricks and does not include mortars made from masonry cement.

Table 11: AS 3700 deemed-to-conform mortar mixes

Durability grade of masonry units	Mortar class	Mix proportions by volume		
		Cement	**Lime**	**Sand**
Exposure	M4	1	0 to 0.25	3
		1	0.5	4.5
General purpose	M3	1	1	6
Protected	M2	1	2	9
	M1	1	3	12
		–	1	3

AS 3700 requires that 'Class M1 mortars shall be used only for restoration of existing buildings that have been originally constructed using this type of mortar'. Guidance provided in Appendix H of the standard says, 'Type M1 mortars (i.e. sand–lime mortars) do not possess suitable durability properties and, therefore, cannot generally be used to construct masonry in accordance with this Standard. They are permitted to be used only in masonry being constructed to restore existing buildings that were initially built using these mortars. Special approval or certification should be obtained to construct a new building using Type M1 mortars for cases where this is deemed desirable; for example, the construction of a new building as part of a reconstruction of a complex of period buildings.'

The advice that lime mortars 'do not possess suitable durability properties' is not supported by the many Australian examples that are in excellent condition after more than 150 years, nor by much older examples from around the world.

There are several other difficulties with the application of these standards to the repair of older buildings. The standards assume that a given volume of lime putty contains an approximately-equal volume of hydrated lime in dry powder form. However, as explained in Section 5.4 'Densities of lime putties and hydrated limes', a dense putty may contain 50% more lime than the same volume of hydrated lime (and may contain at least 25% more lime than a putty conforming to AS 1672.1). **Differing densities of putties and powders must be taken into account when specifying and batching mortars.**

Further, Australian Standards do not mention hydraulic limes: specifications for works that are to include natural hydraulic limes should reference EN 459 *Building lime* (see also Box 4). Binders made from lime and pozzolan are also not covered by Australian Standards.

Because of their understandable focus on new building, AS 3700 and AS 4773 don't adequately deal with traditional construction with porous materials. Such construction requires permeable mortars of low-elastic modulus (i.e. of high elasticity) that will act sacrificially and also cushion the masonry units during subsequent deformation. Lime mortars have demonstrated their suitability and durability in such construction over thousands of years.

Accordingly, while AS 3700 and AS 4773 should be used for new buildings where composition mortars are appropriate, they are not suitable for traditional lime mortar construction including maintenance and repair work.

Box 11: Mortars and the Building Code of Australia

For simple repair work, such as repointing mortar joints, the Building Code of Australia (BCA) may not be applicable, but it is important to be clear about its role as a construction standard.

Now part of the National Construction Code (NCC), the frequently updated BCA is a uniform set of performance-based technical provisions for the design and construction of buildings and other structures throughout Australia. The BCA is given legal effect by the building legislation and regulations of each state and territory, and it is generally applied to new buildings and new building work only. The application of the BCA to work on an existing building is triggered when the scale of works reaches certain thresholds that vary between states and territories. In some states and territories it may be necessary to bring an entire building into compliance due to the extent of construction work, for example, where an existing building is to be substantially extended. In general, when works to an existing building comprise only maintenance and repairs (such as repointing mortar joints), the BCA does not need to be considered.

Performance Requirements

The BCA contains mandatory Performance Requirements. Those relevant to mortars are ‘P2.1.1 Structural stability and resistance’, and ‘P2.2.2 Weatherproofing’. Broadly, P2.1.1 requires buildings or structures to perform adequately under reasonably expected actions (loads), to withstand extreme or frequently repeated actions and to avoid causing damage to other properties by resisting the actions – including dead and live loads, wind, rain, groundwater, earthquake, thermal effects, time-dependent effects and ground movement – to which the buildings or structures may reasonably be expected to be subjected. P2.2.2 requires external walls to prevent penetration of water that could cause (a) unhealthy or dangerous conditions, or loss of amenity for occupants, and (b) undue dampness or deterioration of building elements. These requirements are drawn from Volume Two of the 2019 BCA (the Housing Provisions). BP1.1 and FP1.4 in Volume One of the NCC have similar requirements.

Satisfying the Performance Requirements

There are three ways of satisfying the Performance Requirements: by a Deemed-to-Satisfy Solution, by a Performance Solution, or by a combination of both. Deemed-to-Satisfy Solutions are deemed to comply with the Performance Requirements. Volume Two of the 2019 BCA includes under Section 3 (Acceptable construction), parts 3.3.1 and 3.3.4 in which Performance Requirements P2.1.1 and P2.2.2 are satisfied by design and construction in accordance with AS 3700 *Masonry structures* or AS 4773 *Masonry in small buildings*, Parts 1 and 2.

However, as explained in Boxes 8 and 10, there are several drawbacks with these standards in relation to the use of limes and sands in mortars, and so a different approach is required.

Performance Solutions

The Performance Solution (formerly Alternative Solution) approach of the BCA should be adopted where lime mortars are specified and the nature and scale of the works requires compliance. A Performance Solution must be assessed according to one or more assessment methods which include:

(a) evidence of suitability that the use of a material or form of construction meets the relevant Performance Requirements

(b) verification by a calculation, a test, an inspection or other method that determines compliance with the relevant requirements

(c) expert judgement by someone who has the qualifications and experience to determine whether the solution complies with the requirements

(d) comparison with the Deemed-to-Satisfy Provisions.

A suitable approach is likely to be method (c) expert judgement based on (a) evidence including this technical guide (approved by panels of experts and published by the Heritage Councils or heritage agencies of the six Australian states) and the evidence of the successful performance of lime mortars in existing buildings. An appropriate expert will be someone with at least ten years of demonstrated experience in the investigation, assessment, repair and conservation of traditional masonry constructed with lime mortars.

For most cases of repointing there are no structural issues, which leaves only questions of fitness for purpose and durability. As noted in Box 10, the many Australian buildings that are in good condition after more than 150 years provide ample evidence of the fitness for purpose and durability of lime mortars. Selection and specification of materials for mortars (including binder type, sand and other aggregates, and their proportions in the mix) should be based on the advice in this guide, as should the methods of preparing, mixing, pre-wetting, applying, protecting and curing them. The importance of producing mortars compatible with the masonry units cannot be overemphasised.

14 Workability

The workability (or working properties) of a fresh mortar is a crucial factor in achieving good results in all aspects of its use, whether for laying bricks, repointing stonework or applying renders and plasters. If a tradesperson has difficulty using a mortar because it is hard to work, the job will be slower and the quality of the result may suffer. All the components of a mortar (binder, aggregate and any admixtures) contribute to its workability.

Determining whether a mortar is workable or not is to some degree subjective: different tradespeople may rate the same mortar differently.

Workability is not a single measurable property but a combination of several related properties, the key ones being plasticity and water retentivity. Both these will soon become apparent to a tradesperson.

14.1 Plasticity

The plasticity (or 'spreadability') of a mortar is judged by its response to being worked with a trowel. A laying or bedding mortar should flow well from the trowel so that the masonry units can be laid and pushed into place. For pointing, a stiffer, drier mix with the consistency of modelling clay is needed.

Consistency (the thickness or viscosity of a mortar) is related to its plasticity, but is also determined by its water content.

Factors contributing to plasticity include:

- the nature of the binder
- the shape and surface texture of the sand grains
- the size grading of the sand
- the proportion of binder to sand.

Due to their fine particle size and shape, lime putties that have been matured for at least four months are the most plastic of the binders, and these were traditionally favoured for plasters and limewashes. Then come lime putties with shorter maturing times (weeks), followed by hydrated limes, hydraulic limes and finally cements, which are the least plastic of all.

Rounded and sub-rounded sand grains will add to the plasticity of a mortar, whereas angular and sub-angular (sharp) grains will detract from its plasticity. However, the benefits of a sharp sand (see Section 9.3 'Surface texture and grain shape') are so great that other ways of improving plasticity need to be sought and rounded sand grains should not be used when sharper alternatives are available. Because of the range of particle sizes, a well-graded sand (see Section 9.4 'Size grading') will flow better than a uniform or poorly graded sand and so add to the plasticity of a mortar.

Plasticity can best be increased by ensuring that all the void spaces in the sand are filled with binder. A rich mix, with more binder than required to fill the voids, will be more plastic. A lean mix, in which there is less binder than the void ratio indicates (see Section 9.6 'Void ratio and its impact on mixes') will be more difficult to spread.

> See also Chapter 25 'Using lean or sacrificial mixes'

Workable mixes are critical to achieving good bonds between mortar and masonry units. A bedding mortar must flow readily across the unit and fully cover the joint surfaces to ensure a good bed and bond. For repointing, where stiffer mixes are used, successful bonding depends on tightly compacting the new mortar so that it is forced into the surface pores and crevices of the surrounding masonry units.

14.2 Water retentivity

The water retentivity of a mortar is judged by its response to the masonry units during application and subsequent working. Masonry units with high suction or initial rate of absorption (IRA), such as porous bricks and stones, tend to draw water out of the mortar, leaving a mix that may lose its plasticity and become stiff and difficult, and sometimes impossible, to work. Such mortars have low water retentivity and are described as 'hungry' – they 'go dead' when laid on porous masonry.

A mortar with good water retentivity will be cohesive: it will 'hang together'. A cohesive or sticky mortar will pass the 'trowel test', by sticking to an upturned trowel. This is an important aspect of its workability, for as well as being plastic, the mortar must not fall apart on being spread (or leak or bleed), leading to stains running down the masonry as water separates out from the mix and carries some binder with it.

Factors contributing to water retentivity include:

- the nature of the binder
- the size grading of the sand
- the proportion of binder to sand.

Due to their very fine particle size (and therefore large surface area), matured lime putties have a strong affinity for water and are the most water-retentive of all the binders. Hydrated limes are next, followed by the range of natural hydraulic limes and then Portland cements, which are the least water-retentive. Lime putties are so water-retentive there is a risk of shrinkage cracking as they set and dry. This can be minimised by using only well-drained, mature putties.

In a similar way but on a larger scale, fine-grained sands are more water-retentive than coarse-grained sands. Best of all are well-graded sands containing a good range of particle sizes including fine and very fine sands (see Section 9.4 'Size grading'). Worst of all are sands of a uniform grain size that lack progressively finer particles to fill the void spaces between the medium and coarser grains. In a sense, these poorly graded sands have holes in them, through which water can be drawn too readily, leading to a 'hungry' (or perhaps 'thirsty') mortar.

Poorly graded sands can often be improved by adding finely ground limestone or marble (see Section 9.10 'Mineral fillers').

Finally, there's the proportion of binder to sand: a mortar in which the binder does not fill all the void spaces in the sand will still have 'holes' in it, and so lack sufficient water retentivity. This is another reason why it's important to measure the void ratio of a sand and to adjust a mix from the nominal proportions to those that suit the particular sand (e.g. from a nominal 1:3 to 1:2.5 for a sand with a void ratio of 40%).

> See Section 9.6 'Void ratio and its impact on mixes' and Chapter 25 'Using lean or sacrificial mixes'

The required water retentivity for a particular mortar will depend on the suction of the masonry units. Porous masonry with a high suction or IRA (such as older bricks and some stones), will require a mortar with high water retentivity, so the mortar remains plastic for long enough to lay and position the masonry units. Conversely, modern bricks with relatively low IRAs will require mortars with lower retentivity, so that sufficient water (and binder) will be drawn into the bricks to ensure a good bond.

> See Chapter 10 'Water'

14.3 Achieving workability

Common practice in contemporary work with composition mortars is to achieve workability by using clay-rich bricklaying sands, by adding more water to the mix or by using admixtures, particularly air-entraining agents.

With mortars based on matured lime putty (or with sand-slaked quicklime mortars), the lime will generally contribute all the plasticity and water retentivity required, provided the sand is well graded and has a reasonable proportion of very fine, sand-size particles. However, corrections to improve workability may be required in the following circumstances:

- to account for very sharp sand
- where the sand has a high void ratio
- because of large surface areas due to a generally fine-grained sand.

Sands lacking very fine sand-size particles can be improved by adding ground limestone or marble (see Section 9.10 'Mineral fillers').

Make sure there's the right amount of lime in the mix to begin with (see Section 5.4 'Densities of lime putties and hydrated limes').

In such cases, the mix should be corrected by adding a small amount of lime putty and not by adding water. This is a key point and one that should also be applied to composition mortars. Because of its plasticity and capacity to flow into pores and crevices in the masonry units, lime contributes substantially to the strength of the bond between the mortar and the masonry. The benefits of the improved bond produced by increasing the relative proportion of lime (including fewer cracks between the mortar and the masonry, and hence more weatherproof walls) will outweigh any slight reduction in compressive strength.

> See Section 9.9 'Other aggregates', mortar type 5 (sacrificial lime) in Table 10, Section 13.7 'A range of mortar mixes' and Chapter 25 'Using lean or sacrificial mixes'

Circumstances where adding more lime may not be the right approach include the need to make deliberately sacrificial mortars to control a salt problem or to make more permeable mortars to ensure drying takes place through the joints rather than through the adjacent weak, porous masonry (see Section 13.5 'Choosing the right mix – compatibility'). These cases may warrant the use of porous aggregates (such as crushed, porous limestone).

Such cases might also justify the use of admixtures, such as air-entraining and water-retaining agents (see Section 11.1 'Plasticisers, air-entrainers, water-retainers'). Air-entraining agents contribute plasticity and cohesiveness; their tiny bubbles make the mortar spread more readily under the trowel and reduce the amount of mixing water needed. Water-retaining agents help to make up for the 'holes' in the mix, which might otherwise lead to rapid loss of water due to the suction of the masonry. Superplasticisers can be used to reduce the water content while improving the workability of mixes.

However, as Section 11.1 'Plasticisers, air-entrainers, water-retainers' notes, the overuse of admixtures must be avoided at all costs. Lime mortars need to work close to their maximum, and substantial reductions in their strength cannot be tolerated. Excessive use of air-entraining agents will seriously reduce the bond strengths of all types of mortar. Admixtures should not be used as alternatives to lime in what should be composition mortars. Instead (and where appropriate) they should be used in addition to lime. Workability should first be sought by careful selection of well-graded sands and choice of binder. Adjustments should then be made to the mix proportions to achieve the desired plasticity. Only then should admixtures be considered. Deliberately sacrificial mixes are an exception: for these admixtures will be needed to make up for the higher proportion of sand and the consequent reductions in plasticity and water retentivity.

Box 12: Changing appearances

These photographs of the joints of a mid-nineteenth-century brick stable in Tasmania show how the same lime mortar can exhibit very different appearances depending on the circumstances. The joints are about 10 mm wide.

Figure 38 shows the original, finished surface of a mortar joint in remarkably good condition: the very sticky mortar produced the ridged texture of the joint surface as the trowel was pulled away. Figure 39 shows a not-quite-so-sticky batch of mortar which left a very smooth surface, which is now weathering: the harder surface skin is being lost, exposing white lumps of lime and fine sand grains. The light reddish-brown colour of the original surfaces is largely due to the accumulation of windblown dust.

Figure 38: Original surface of a sticky mortar.

Figure 39: Beginning to lose the surface skin.

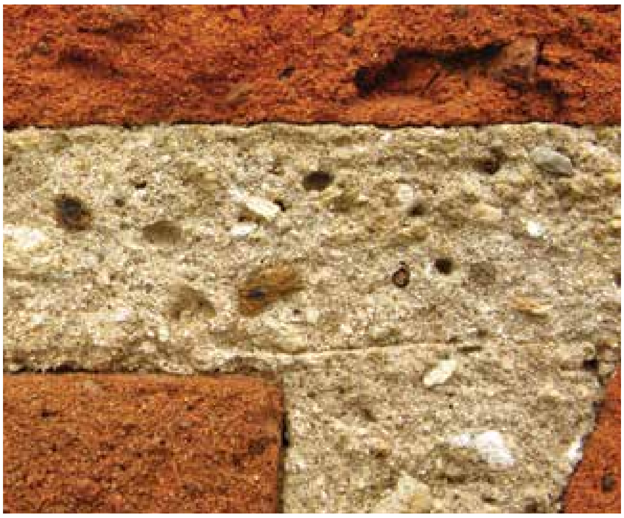


Figure 40: Internal view after abrasion.

Figure 41: Covered in lichen.

Figure 40 shows an internal view of the mortar, where abrasion has revealed the lime lumps, coarse brown grit and fine sand of which it is made. A break during construction can be seen between the perpend and the overlying bed joint. Figure 41 is on the weather side of the stable. The joint and the bricks are slightly eroded, and the mortar is almost entirely covered in a grey lichen, with only a few coarse grains showing through. The yellow lichen prefers the (silicate) chemistry of the bricks. Though slightly eroded, the joint is still in good condition and needs no repair. The rate of damage due to the lichens is low and their removal is not warranted: cleaning them off may do more damage than doing nothing.

15 Mortar mixing

When you slake the lime, take care to wet it everywhere a little, but do not over-wet it, and cover with sand every laying, or bed of lime, being about a bushel at a time as you slake it up, that so the stream, or spirit of the lime, may be kept in, and not flee away, but mix itself with the sand, which will make the mortar much stronger, than if you slake all your lime first, and throw on your sand altogether at last, as some use to do.

Moxon, 1703

15.1 Traditional mixing

In the nineteenth and early twentieth centuries, lime mortars were made directly from quicklime and sand by sand-slaking (or dry-slaking).

The term 'sand-slaking' makes it clear that quicklime was slaked with the sand, the work being undertaken on a wooden platform (or stage) which was set up for the purpose (see Figure 51). The initial slaking used a minimum of water (hence the alternate term 'dry-slaking') and produced a dry mix, which was screened (sieved) if required. Water was then added to produce a workable consistency and the mix heaped up (or banked) to mature for about a week. When required, batches of mortar were cut from the heap and 'knocked up' to make them workable and ready for use. In large projects, mortar mills were used to ensure thorough mixing.

The terms 'quicklime mortars' and 'hot-mixing' are also used. Here, 'sand-slaking' and 'hot lime mortar' are used to distinguish between those quicklime mortars that are used cold (after maturing) and those that are used while still hot.

Hot lime mortars were also made by slaking quicklime with the sand, except that the mortar was used while it was still hot, particularly for filling the cores of thick, stone walls. The steam generated by the slaking had the effect of entraining air in the mortar. By raising wall temperatures a little, hot lime mortars provided some protection against frost in colder climates.

Sand-slaking was used for pure (non-hydraulic) quicklimes and also for hydraulic quicklimes, though maturing times would be reduced with increasing hydraulicity. The heat generated by slaking initially dried the sand and ensured good contact with the lime. Even with a relatively pure lime, there may have been some slight hydraulic reaction with wood ash from the kiln. However, the benefits of sand-slaking are more likely to be due to good contact between the sand and lime, enhanced by the cleaning and slight etching of the sand grains by the hot lime. Imperfect lime burning together with sand-slaking are the most likely explanations for the lumps (knots) of lime we find in old mortars.

> See Box 13 'Lime lumps'

The lime used to be of the best kind, well burnt, and free from kernels or nodules.

The lime mortar used is to be composed of one part lime to three of sand, well mixed together and thoroughly slaked, and that for the brickwork to be passed through a fine sieve.

1904 specification for South Australian houses of brick and stone

The sand-slaked heap of mortar stiffened as it dried a little and would be knocked up just before use. Knocking up by hand involved chopping the mix with a larry or the edge of a spade or trowel, then beating it with the back of the tool. This process broke down the stiffness of the mix and created additional plasticity. Repeated beating and chopping made the mix more workable because it released water from the lime, and also because it entrained air in the mix, in the process producing a more durable mortar.

The plasterer's coarse stuff to be of mortar as above. The setting coat to be of putty and plaster.

1922 specification for an extension to a South Australian church

It is important to be clear that sand-slaking was a process used by masons laying bricks or stones, and it would not have been used for the finish coat of plasters (the set coat). Plastering lime was made from relatively pure quicklime, which was slaked separately and allowed to mature as a putty for prolonged periods. This was partly to develop finer particle sizes (and hence improved workability) and also to ensure that there were no unslaked lime particles remaining, which if they later slaked on a wall would lead to popping or pitting of the plaster surface.

Box 13: Lime lumps

Figure 42: An 1840s mortar.

Sometimes described as knots, lime inclusions or as binder-related particles, the idea of lime lumps can be grasped from these photographs. Lumps are relatively large particles of lime that can be found in most Australian lime mortars up to the middle of the twentieth century. While they appear more or less incidental to the 1920s mortar (see Figure 43), they are clearly a dominant part of the 1840s mixes (see Figure 42 and the cover photo). There are several explanations for their origin.

Sand-slaking (see Section 15.1 'Traditional mixing') is the most likely, with the lumps being underburnt or overburnt particles of lime that haven't slaked and were not screened out of the mix. Apart from the lumps, the mortars appear to be otherwise well mixed, indicating that the lumps were hard enough to survive the mixing process, which in turn tends to confirm their origin as unslaked lime particles.

Such a combination could be explained by the incorporation of hardened, leftover material from a previous batch, but if this were the case we would expect to find sand grains in some of the lumps: yet most appear to be free of sand. The same problem applies to a hardened crust that developed on a maturing mix that was not well covered. While the crust might get mixed back into the mortar and survive as lumps, we should still find sand in some of the lime particles.

Another theory is the last-minute addition of quicklime to an existing, matured mix that was too wet to use, with the aim of drying it out to a suitable consistency. This would be one explanation for the very high lime content of these mixes, which is much higher than in 'normal' mortars. Even discounting the lumps or knots, some of these mixes are very rich in lime. Note that despite the rich mixes, there's no problem with shrinkage.

Figure 43: A 1920s mortar.

Modern mortars, made with putty or powders, will not reproduce such textures, though they could be created by leaving some putty exposed to harden before combining it into a mix. Even sand-slaking will not produce substantial lumps if the quicklime is in powder form and the slaking is undertaken in a mixer.

15.2 Contemporary mixing

> ***Competition is carried on to such an extent, and we are always in such a desperate hurry, that we cannot stop to mix the mortar properly.***
>
> **Hodgson, 1907**

Sand-slaking of quicklime should still be done today (see Section 19.2 'Mixing') though its use may be limited to more important projects. Soft-burnt quicklime is preferred for its greater reactivity, and it should be slaked as soon as practicable after manufacture (i.e. freshly slaked) to retain maximum reactivity by minimising the proportion that air-slakes and carbonates, whereupon it ceases to be a binder. Rather than sand-slaking, most mortar for repairs today are likely to be mixed from lime putties and from dry powders including pure and hydraulic limes, pozzolans and cements.

The 'freshly slaked' in some old specifications, actually meant slaked while fresh rather than used straight after slaking. A period of maturing of the mix was (and still is) beneficial, even for hydraulic limes.

Making good mortars requires thorough, intimate mixing of the binder and the sand, and this is particularly important for lime binders. Damp sands have a minute layer of water bonded tightly around each grain; disrupting this water layer so that the lime can bond with the sand takes considerable force. To avoid this problem, it's best to use dry sand.

Conventional rotary cement mixers cannot deliver the force required for adequate mixing. However, they can be improved by adding dense, hard stones or large-diameter steel balls (100–150 mm) to the mixer to provide a tumbling or milling action. Lime mortars need prolonged mixing and knocking up times (of 20 minutes), compared to those commonly used for cement or composition mortars.

Better alternative mixers are roller pan mixers, forced action (screed) mixers and handheld, helical-bladed mixers. Roller pan mixers consist of a pair of steel wheels rotating around a mixing pan (see Figure 44). An important feature, not shared by all such mills, is that the height of the wheels should be adjustable so that the aggregate is not crushed during mixing. Forced action mixers have relatively small blades rotating around a vertical axis (see Figure 45). The small blades deliver a high pressure in a similar way to the stiletto heel. Purpose-made, handheld, whisk-type mixers with helical blades can also be used for mortars; their portability makes them very convenient for small batches and for knocking up on scaffolds.

Small batches can also be mixed by hand. The simplest method is to use the widened end of a mattock handle to pound the mix in a bucket or tub.

Figure 44: Roller pan mixer. Looking through the safety screen of a roller pan mixer used for mixing and knocking up mortars. The heavy wheels roll around the pan and their rolling action forces lime and sand together, overcoming the tightly bonded water layer around each sand grain. A key feature of the roller pan mixer is the height-adjustable wheels which roll over the aggregate rather than crushing it, though it can also be used to crush stones and bricks for addition to mixes as porous aggregates (see Section 9.9 'Other aggregates').

Alternatively, a larry (mason's hoe) is used to combine the lime putty and sand, a small portion at a time, in a trough. Considerable downward pressure is required to force the putty and the sand together to ensure good contact.

While mixing times should always be sufficient to ensure thorough and uniform combination of the ingredients, the advantages of prolonged mixing of lime mortars cannot be overemphasised. Longer mixing times improve the consistency and workability of the mortar. This allows the use of a lower water content, leading to less risk of shrinkage and to stronger mixes.

Figure 45: Forced action mixer. Looking down into the mixing pan of a forced action (screed) mixer in which the blades rotate about a vertical axis. The relatively small blades force the lime and sand particles together in a way not achieved with conventional rotary mixers.

15.3 Off-site preparation and maturing of mixes

There are considerable advantages to preparing mortar mixes off-site including greater accuracy of batching and improved quality control of materials. If all components are dry, they can be thoroughly blended beforehand and need only the addition of water on the site.

Lime putty and sand-slaked quicklime mortars can be premixed and stored in sealed containers to prevent them drying out and carbonating. When needed, the mix is turned out and knocked up to regain its workability, without adding water. Maturing such a mix will give improved strengths and greater porosities as well as making the mix more workable. The benefits of maturing the mix are greater than those of maturing the putty separately (see Section 5.3 'Lime putty and hydrated lime'). Shrinkage, which may increase as a result of prolonged maturation, can be avoided by using minimal water.

Any hydraulic components (such as pozzolan or cement) as well as any admixtures are added to mixes during knocking up, just before use. When adding these components, it is important to avoid clumping of dry powders onto a wet mix, for this will lead to an uneven mix that performs poorly. All dry materials should first be mixed together and then run to a slurry before adding them to the wet mix. Using the thicker liquids, drained from lime putty, as the mixing water for the slurry will aid workability.

The production of premixed lime mortars in a range of proportions and sand types should be encouraged. Premixed mortars overcome the need to mix and mature the mortar at the beginning of a job.

Premixed mortars made with immature putty may be too wet and contain insufficient lime. As explained in Section 5.4 'Densities of lime putties and hydrated limes', varying densities must always be taken into account.

> See Chapter 19 'Batching, mixing and knocking up'

16 Special jointing materials

16.1 Mason’s putty

Mason’s putty (or oil putty) is a mortar found in narrow-joint (3 mm) ashlar masonry from about the 1880s to about the 1930s. It can be thought of as a cross between lime mortar and glazing putty, and it was made by mixing lime putty, whiting (ground chalk), linseed oil and very fine sand to a putty-like consistency. The sand was often omitted in favour of more whiting. Mason’s putty was laid as a bead along each edge of the bed, a wet mortar poured into the dam created by the putty and the overlying stones laid into place. Excess putty was then trimmed off.

Mason’s putty generally has a cream colour due to the linseed oil and a characteristic crack pattern due to shrinkage (see Figure 46). The cracks allow rainwater to penetrate into the masonry while the impermeable oil limits subsequent drying.

Figure 46: Mason’s putty. It is a mixture of lime putty, whiting, linseed oil and sometimes very fine sand. It typically has a cream colour, due to the oil. Shrinkage causes a characteristic crack pattern which allows water to penetrate into the masonry. Drying is limited by the relatively impermeable oil, which forces moisture through the stones, causing the decay seen on the right.

Decisions about repointing joints with mason’s putty will depend primarily on compatibility. If the stones are dense materials (such as marble or granite) then it may be appropriate to repoint with a putty that is similar to the original. On the other hand, if the stones are porous materials (like sandstone and limestone) then it will be better to use a mortar of lime putty and very fine sand to allow the joints to breathe and so protect the stones. This is particularly important when soluble salts are present in appreciable quantities or if there is a risk of water percolating through the masonry. To limit shrinkage and improve permeability, a form of mason’s putty can be made with more sand, less whiting and without the linseed oil.

> See Mortar type 6 (narrow joint) in Table 10 in Section 13.7 ‘A range of mortar mixes’

Some proprietary mason’s putties incorporated asbestos fibres in their mix; if there’s any doubt about the presence of asbestos, the putty should be analysed before undertaking works. The same applies to lead white, which was sometimes used to whiten the putty. Appropriate health and safety precautions must be taken when raking out mason’s putty containing asbestos fibres or lead white.

> See Figure 48 and Box 16 ‘Health and safety with mortars’

16.2 Elastomeric sealants (mastics)

Elastomeric sealants (mastics), such as polysulfides, silicones and urethanes, have been used in building since the 1950s. They are commonly used as sealants between panels of relatively impermeable materials (like granite and glass) in curtain walling applications in modern buildings.

Unfortunately, sealants have been widely used for pointing and repointing joints in porous materials, such as sandstone and limestone. Elastomeric sealants are impermeable and are incompatible with porous materials because they prevent moisture from evaporating through the joints, forcing it through the adjacent masonry (see Figure 47). Further, oils bleeding from the sealant may permanently stain the masonry, while too-stiff a sealant or one that becomes stiff with age will, over time, tear apart many stones.

Penetration of water-repellent materials into the adjacent masonry can inhibit bonding of later repointing mortars.

Elastomeric sealants should never be used for normal pointing of porous masonry. They may have a role, but only in special circumstances, such as sealing movement joints to prevent water entry.

Figure 47: Inappropriate use of elastomeric sealant. Pointing the joints with an impermeable sealant has forced moisture to dry through the porous stones (rather than through the joints), resulting in salt attack decay to the sandstone. The damaged stones have been repaired with an equally impermeable patching material, forcing decay further through the sandstone.

Figure 48: Old mastic sealant. The deteriorating sealant has pulled away from the adjacent stones, allowing water to enter the structure. Weathering of the sealant has exposed fibrous material which may be asbestos. Safety precautions must be taken when removing such materials (see Box 16 'Health and safety with mortars'). The bright yellow patches are lichens.

17 Investigation and analysis of mortars

For many years, laboratory investigations of mortar have been undertaken with traditional, wet chemical analyses. While these still have a role, they are best used in combination with microscopic techniques, which are increasingly the preferred tool because of their capacity to tell so much more about the chemistry and physical structure of the mortar.

The following sections explain the wide range of techniques available and the circumstances in which they might be used. But first, it is important to be clear about the purpose of testing and about the nature of the test results. Some tests are qualitative: they identify what components are present, but not their amount. Some tests are quantitative: they identify how much of a particular material is present, while others are semi-quantitative: they produce approximate results, which can be sufficient for many purposes.

Some tests report their results in volume proportions, while others report their results on a weight basis (see note to Table 12).

17.1 Being clear about the purpose

The reasons for analysing mortars include:

- understanding heritage significance including understanding whether the mortars themselves are of historic or technological value, clarifying the construction history to understand the broader significance of the building and archival recording and documentation
- understanding decay mechanisms (such as salt attack) so they can be taken into account when designing repairs
- providing a basis for designing repair mixes for repointing or reconstructing masonry: these commonly require mortars that match the existing in colour, texture and other properties
- compliance testing of repairs or new work, to ensure they meet specifications and performance criteria.

It is important to be clear about the purpose and need for the proposed testing. Which one (or more) of the reasons above is driving the investigation? Does it need a battery of tests, producing precise quantitative results, or will one or two tests with semi-quantitative results be sufficient? Are the age, significance and materials of the building such that visual examination with a hand lens will be enough to design a repair mix? Visual examination with a hand lens might do if it's a simple building with a pure lime mortar made with a commonly available sand. Table 12 shows how investigative and analytical techniques might vary depending on the purpose of the testing.

17.2 Mapping and sampling the walls

If a building has a complex history with a series of stages and a range of decay mechanisms, it will be necessary to closely survey the walls to understand their history and to map the patterns of decay. While mapping alone may provide a good understanding of the decay mechanisms, laboratory tests may be warranted for confirmation and to guide repairs. If a mortar is to be tested to understand why it is decaying, then it's important to also collect samples that are not decayed, for comparison purposes.

Irrespective of the purpose, it is essential that samples (whether collected or just examined in situ) are representative of the stage of the building and the location within it. Some building elements (such as parapets and chimneys) may have different mixes because of different exposure conditions. Multiple phases of alterations and repairs can create a confusing picture, which may only be clarified by careful observation and recording. The number of samples collected should be sufficient to represent each variant that is to be tested.

The type of sample required will depend on the purpose. If the mortar is decaying due to salt attack and you need to understand the nature and amount of salts present, then powdered samples (collected as cuttings by drilling holes) can suffice. However, if the aim is a more comprehensive analysis of the mortar components and its pore structure, then intact sections of mortar 50–100 mm in length will be required. The relatively small size of many joints and the shallow depth of much original pointing makes successful sampling very difficult, particularly as samples should be disturbed as little as possible. Very fine, sharp chisels, small, craft-scale cutting wheels and oscillating-blade cutting tools may be needed (see Figure 65).

Limitations on sample size may restrict the ability to undertake particular tests.

Table 12: Investigative and analytical techniques for mortars

Technique	Purpose			
	Understanding significance	Understanding decay	Providing a basis for repair	Compliance testing
Mapping and sampling	◆◆	◆◆	◆◆	◆◆
Visual analysis, photography	◆◆	◆◆	◆◆	◆◆
Stereomicroscopy	◆◆	◆◆	◆◆	◆◆
Acid digestion & analysis of aggregates	◆◆	◆◆	◆◆	◆◆
Thin section microscopy	◆◆	◆◆	◆◆	◆◆
X-ray diffraction (XRD)	◆	◆◆	◆	◆
SEM/EDX	◆	◆	◆	◆
Wet chemical techniques		◆	◆◆	◆◆
Salt testing by TDS and/or ion chromatography or ICPOES & UV-VIS		◆◆		◆
Thermal analysis	◆	◆	◆	◆
FTIR spectroscopy	◆	◆	◆	◆
Mercury intrusion porosimetry (MIP)		◆	◆	◆

The table shows how investigative and analytical techniques for mortars may vary depending on the purpose.

◆◆ indicates techniques that are most likely to provide useful information.

◆ indicates techniques that may be useful.

This is not meant to preclude the use of any particular technique including some not explained in this guide.

Note that visual methods (visual analysis, photography and microscopy) report their results on a volume basis, while chemical methods (acid digestion, wet chemical, TDS, ion chromatography and others) report their results on a weight basis. The latter can then be converted to volumes by using densities, but assumptions on densities should always be checked.

17.3 Visual analysis, photography, stereomicroscopy

Visual analysis by an experienced person using a magnifier (hand lens or loupe in the range 6x–12x magnification) can be an effective way of investigating mortars. Some magnifiers in this range are available with built-in illumination, which can be an advantage in low light. Simple loupes (shown in Figure 49) are an alternative, as the clear plastic base allows daylight to reach the subject.

Figure 49: A simple loupe. A simple loupe of 6x–10x magnification is an ideal first tool for investigating mortars. The clear plastic base allows light onto the subject, but it does limit their use to relatively planar surfaces: mortar in a deeply eroded joint will not be in focus. Higher magnifications on fixed bases are not recommended unless they have adjustable focusing.

More powerful magnifiers in the range 15x–25x can be useful tools, particularly those that incorporate a scale bar as that enables measurement of sand grain sizes, while the magnification is sufficient to observe key features of the mortar. The benefits of magnifications higher than about 25x are offset by the unavoidably shallow depth of field – the distance between the nearest and furthest objects in focus.

Figure 27 was taken through a 25x magnifier using a moderately priced 12-megapixel compact digital camera. The sands in Figure 19 were photographed using a 20-megapixel compact digital camera. Only the central 10% of each image is shown in the figure.

Compact digital cameras with good macro capabilities can produce images that are adequate for most purposes. Close-up attachments for smart phone cameras have potential. Very high magnifications can be obtained with handheld digital microscopes connected directly to a computer. What they lack in image quality – having a shallow depth of field and often low resolution – they make up for in modest price and high magnification.

A crude scratch test has been used to try to distinguish lime mortars from mortars containing cement, the theory being that a lime mortar will be readily scratched whereas a cement-based mortar should not be. Tools range from a pocketknife or screwdriver to a car key. This test is not appropriate: there are too many variables that can affect the result. A well-made and well-cured lime mortar can be difficult to scratch, while a cement mortar will be readily scratched if it has insufficient cement, contains too much clay or was poorly cured. A more sophisticated scratch test using a specially designed tool forms a basis for classifying composition mortars in AS 3700.

Physical samples for testing should first be inspected in the laboratory using a stereomicroscope, a binocular microscope that gives a relatively low magnification view of the sample. This can provide useful information about the components, texture and pore structure of the mortar. Stereomicroscopes can magnify up to about 100 times and should be used as the first stage of more advanced microscopy (see Section 17.5).

At this stage, another test using phenolphthalein can be performed. Phenolphthalein is an indicator solution that (like litmus) changes colour depending on the acidity or alkalinity (pH) of the solution. It is colourless at acid and neutral pHs, pale pink at 9.3 and turns a strong pink above a pH of 10.0. The significance of these figures is that fresh limes (e.g. putty) have a pH of over 12, whereas carbonated lime (calcium carbonate) has a pH of 9. If adding a few drops of phenolphthalein to a lime mortar produces a strong pink colour, we know that some of the lime remains uncarbonated, making it a simple test for checking the extent of hardening of the lime. Note that the absence of a strong colour does not fully prove that carbonation is complete, because there may be thin shells of cured lime forming a relatively impermeable layer around still uncarbonated material.

pH is a measure of the acidity or alkalinity of a solution and ranges from zero – strongly acidic – through 7 – neutral – to 14 – strongly alkaline.

17.4 Acid digestion and analysis of aggregates

A common test for relatively pure lime mortars is acid digestion – dissolving a lightly ground and weighed sample in a 10% hydrochloric acid solution. Pure lime rapidly dissolves, leaving the sand, which is captured by washing the residue in a filter funnel and then dried and weighed to determine the proportion of sand in the mortar mix (and by subtraction, the weight proportion of the lime). The sand can then be examined with a hand lens or stereomicroscope for its surface texture and grain shape. If the sample is large enough, it can be screened through a series of sieves to establish its size grading. Care must be taken not to over-crush the sample before digestion or the size grading of the sand will be affected. The void ratio of the sand can also be measured.

> See Section 9.3 'Surface texture and grain shape', Section 9.4 'Size grading' and Section 9.6 'Void ratio and its impact on mixes'

A pitfall with this method is that any carbonate mineral that is part of the aggregate (such as limestone, marble or shells) will also be dissolved by the acid, leaving no trace and giving a misleading impression of the proportions of aggregate and binder in the mortar. The large lumps of lime commonly found in many early mortars (see Box 13 'Lime lumps') are also readily dissolved by acids. Such mortars are best characterised by thin-section microscopy (see Section 17.5). An experienced person should be able to identify carbonate minerals in the aggregate when examining the sample with a stereomicroscope, though finely ground limestone (included as a filler) would not be identified this way.

17.5 Thin-section (polarised light) microscopy

This is probably the most powerful tool for the scientific investigation and analysis of old mortars. Microscopic examination of thin sections of material using polarised light comes from the branch of geological science known as petrography. Most geological materials including stones used in building are translucent when ground very thin: they allow light to pass through them. All minerals have characteristic crystalline structures which refract (bend) polarised light in particular ways, enabling their accurate identification. This applies equally to mortars, plasters, renders and concretes.

Using thin-section examination, the type of aggregate and the binder can be identified, as well as the presence and nature of pozzolans. Point-counting techniques enable the semi-quantitative assessment of proportions. Importantly, thin-section examination enables the pore structure and texture – the fabric – of the material to be observed (see Figure 50). Pore sizes can be measured and assessments made of permeability. Shrinkage cracks and potential problems (such as the development of secondary minerals) can be observed. The ideal sample size is about 50 mm by 25 mm, but useful information can be obtained from smaller pieces.

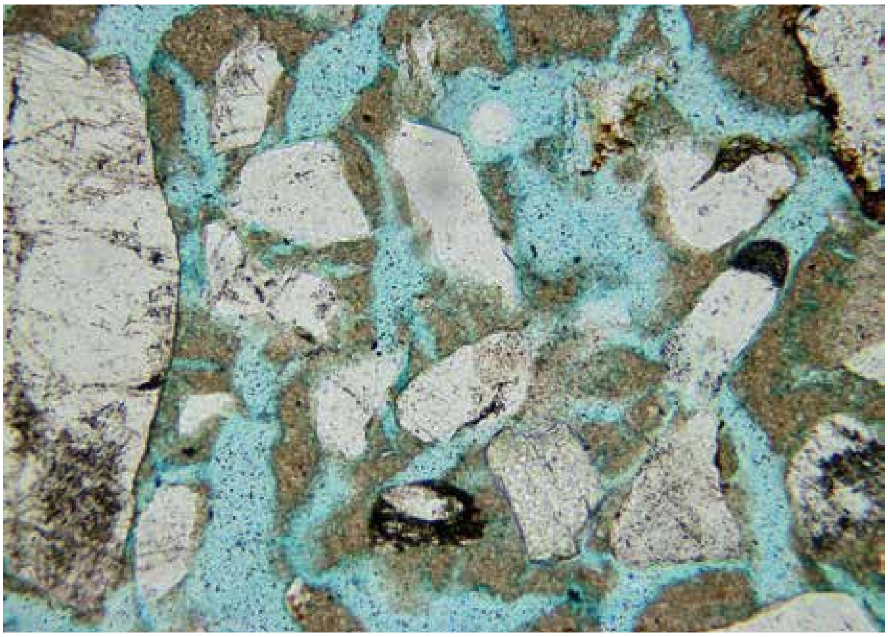


Figure 50: Thin-section photomicrograph. This is a view down a microscope looking at a thin section of a mortar made with a slaked oyster-shell lime and a quartz-rich sand. The light grey particles are quartz grains and are dominant in this view; the fine-grained brown-coloured material is the lime binder. The pale blue-coloured areas are a dyed resin that is used to encapsulate the mortar so that it can be ground thinly. The blue dye highlights the void or pore space and any cracks in the mortar, which in this sample make up approximately 20% of its volume. There are small shrinkage features and larger channel ways through the lime which make an important contribution to the permeability of the mortar. The field of view is 1 mm. A small air bubble entrapped within the resin is seen at top centre. Mix proportions for this mortar were estimated to be 1:2 lime putty to sand.

Photomicrograph and analysis: William Revie.

17.6 XRD and SEM/EDX

These acronyms are shorthand for several useful mineralogical techniques. X-ray diffraction (XRD) measures the way that different crystals refract a beam of X-rays. As each crystal is unique, the constituent minerals can be identified including any hydraulic components that may be present in a mortar. When coupled to data-processing software (such as Rietveld Refinement), the degree of hydraulicity can be assessed semi-quantitatively. Small, powdered samples are tested, and so the technique can also be used to identify the nature of a particular salt that is crystallising on masonry.

Scanning Electron Microscopes (SEMs) enable very high magnification of solid specimens, allowing close-up views of the shape and surfaces of individual particles and crystals (such as those in limes and cements). When fitted with Energy Dispersive X-ray devices (EDX, sometimes EDS), the individual elements present can be analysed. SEMs are very expensive and are mostly tools for scientific researchers, but they may be useful in resolving particularly difficult conservation questions.

17.7 Wet chemical analysis

Wet chemical analysis is a common method for analysing mortar composition, particularly in compliance testing of new work. It involves several stages of digestion in progressively stronger acids, the aim being to separate the more soluble calcium carbonate (as in Section 17.4 ‘Acid digestion’) from the less soluble silica (the hydraulic component) and that in turn from the insoluble aggregate. Assumptions about composition are then used to calculate weight proportions of lime, Portland cement and aggregate. These are converted to volumetric proportions using standard densities.

AS 2701 sets out the laboratory procedure for wet chemical analysis.

The method relies on there being no carbonate material in the aggregate and on the assumptions made about chemical composition of the components. Importantly, wet chemical analysis cannot distinguish between Portland cement and hydraulic lime. Only mineralogical techniques (such as polarised light microscopy and XRD) can make that distinction. Wet chemical analysis does have a role in fully characterising a mortar, but it should preferably be used after mineralogical techniques have first identified the constituent parts.

ASTM C1324 sets out an analytical procedure that combines wet chemical analysis with polarised light microscopy.

17.8 Testing for salts

Salt attack in association with rising or falling damp is a common cause of mortar loss from masonry. Knowing how much salt is left in a wall can be an essential step in resolving the problem, and there are several analytical techniques that can help.

There is much more information about salt attack in the technical guide *Salt attack and rising damp: a guide to salt damp in historic and older buildings*, which is published in the same series as this guide.

One is ion chromatography, in which known amounts of drill cuttings or surface scrapings are dissolved in water and analysed for the principal anions (chloride, nitrate and sulfate) and cations (sodium, potassium, magnesium and calcium) that make up the common soluble salts. The quantitative results are then recombined by an experienced person to give an impression of the likely mix of salts.

Another technique is a combination of inductively coupled plasma optical emission spectrometry (ICPOES) and ultraviolet–visible spectroscopy (UV-VIS). Like ion chromatography, these techniques measure the amounts of the principal anions and cations in a solution of the sample.

A simpler, cheaper alternative is the determination of the total soluble salt content (TSS or often TDS – total dissolved solids) by measuring the electrical conductivity of a solution of the soluble component of the mortar. Though not as accurate as ion chromatography or ICPOES & UV-VIS, TDS analyses are often adequate for our purposes. TDS analyses cannot determine which salts are present, only the total quantity.

A rule of thumb is that total soluble salt contents greater than 0.5% by weight of the mortar may warrant remedial action.

An investigation of a salt problem might include submitting samples for several tests: a few samples for ion chromatography or ICPOES & UV-VIS – to establish the type – and others for TDS – to determine the amount and extent of salt contamination.

There may be circumstances where determining which particular salt is present will help diagnose an unusual decay problem. XRD (see Section 17.6) is the appropriate tool in these cases.

17.9 Other tests

Thermal analysis studies changes in material properties with changes in temperature. Knowing the temperature at which various calcium compounds decompose, the technique can be used to determine which binders are present in mortars.

Fourier transform infrared spectroscopy (FTIR) is commonly used to analyse organic compounds (such as paints and coatings), but has application to mortars, particularly for investigating bonding agents or consolidants that may have been used in the mix.

Mercury intrusion porosimetry (MIP) is a technique in which mercury is injected into the pore structure of a material. MIP can provide quantitative data about total porosity and distribution of pore sizes, complementing observations made with polarised light microscopy.

17.10 Getting useful test results

Getting useful results from laboratory testing depends on two things:

- finding an experienced analyst
- being an informed client.

It is essential to find a materials analyst with experience in the field of historic building materials and their repair and conservation and ideally with specific experience analysing historic mortars. There will be laboratories that can do a particular test according to a standard procedure, but without experience in this specialised field they may be unable to interpret the results in a meaningful way.

The best working arrangement is to involve the analyst in the early stages of a project, so they can help select test methods and advise about appropriate sample sizes. Where possible, the analyst should also be involved in the actual sampling so they can better understand the nature of the task. Few laboratories will have the resources to undertake the wide range of analytical techniques discussed; many will subcontract out some tests to other laboratories. While there are advantages in one laboratory conducting all the tests, the most important issue is the experience of the lead analyst.

The more informed the client is, the better the outcome. Most laboratory investigations work best when you already know something about the samples, whether the information came from documentary evidence or from detailed mapping of walls and recording of decay patterns. This gives the laboratory a head start and enables it to suggest the most appropriate techniques. There's also the need for flexibility, to allow for changes to analytical techniques should there be new discoveries.

17.11 Using the test results

Test results are just that – test results. They provide a snapshot of parts of the building in its present condition. While they may help us understand what the building was built with, and why it's in its present condition, they are not a recipe for repair. Instead, they should form part of the evidence on which a repair specification is to be based. Some examples should make this clear.

A series of analyses might show the average mortar mix in a particular building was 1:2.8 lime to sand. It would be wrong to expect a repair mix to have identical proportions, for even slight variations in the types of lime and sand from the originals will mean changes to the mix; and as previously noted the currently available materials can be very different from those used originally. The repair mix should be specified as approximately 1:3 lime to sand, with the final adjustment left to the mason and based on the need to achieve workability. And that assumes there are no compatibility reasons to change the mix from the original, as the next example shows.

> See Chapter 4 'Mortars in Australia – then and now' and Section 13.1 'Traditional mixes'

Mortars in an 1880s sandstone building are found to have an early Portland cement binder in proportions 1:3 cement to sand, even though the specification called for a mix of 1:2. Neither of these mixes would be appropriate today: as explained in Section 6.3 'Portland cement through time', Portland cement has changed significantly since the 1880s and its use in those proportions would be incompatible with the masonry. The use of any cement may be inappropriate, and instead it may be best to use a lime + pozzolan or a natural hydraulic lime binder to replicate the physical properties of the original mortar.

> See Sections 13.4 to 13.6 'Choosing the right mix'

PART 3

Repointing mortar joints

This is the 'how to do it' part of the guide, and it is specifically about repointing work. The first chapter covers the decisions that need to be made – when to repoint and with what – and is followed by chapters about each stage of the process. While the guide aims to explain each stage clearly, there is no substitute for appropriate training and meaningful practical experience.

Figure 51: Medieval masons at work. Detail of an illuminated manuscript depicting the construction of a church in France, 1448. The labourer at the bottom right is knocking up some lime mortar with a larry (or mason's hoe), having cut it off as a slice from the maturing heap of banked mortar. This practice, including the kerbed, wooden platform (or stage) on which the mortar was mixed, was still in use in Australia in the late nineteenth century (see Section 15.1 'Traditional mixing'). *Chronique de Girart de Roussillon*. Codex 2549, folio 164, Austrian National Library, Vienna.

Image: New York Public Library/Science Source.

18 Repointing – key decisions

18.1 Principles of repointing

The principles of repointing can be summarised as:

- repoint only when necessary – keep original mortar where it is sound
- match previous mortars – often the original will be the most important
- ensure compatibility – which may mean different materials and mixes
- match previous profiles – which may now mean an aged appearance.

These principles are explained in the next sections and are followed by a discussion of the often difficult decisions of just how much to repoint – whether to patch a small area or to repoint a whole wall.

18.2 When to repoint?

Avoid unnecessary repointing – slightly eroded mortar joints should be left alone. A useful rule of thumb is that repointing should be undertaken once the mortar is eroded to a depth greater than the width of the joints.

Builders and tradespeople will often be surprised by the relative softness of some lime mortars compared to the cement mortars they're more familiar with. Soft mortars are not a fault. Unless the joints are deeply eroded or cracked, they should be left alone.

Figure 52 illustrates examples of repointing decisions. Repointing should definitely be undertaken if the existing mortar is eroded to the point where it risks structural failure or if it is badly cracked and letting water into the walls. Repointing should also be undertaken where a previous phase of repointing has introduced an inappropriately hard and impervious mortar, which is causing damage to the masonry units (see Box 6 'Problems with cement-based mortars' and Box 9 'Compatibility'). Each case needs to be judged on its merits. Not every case of poor previous repointing will warrant replacement: some may be best left alone if in protected areas and not causing damage.

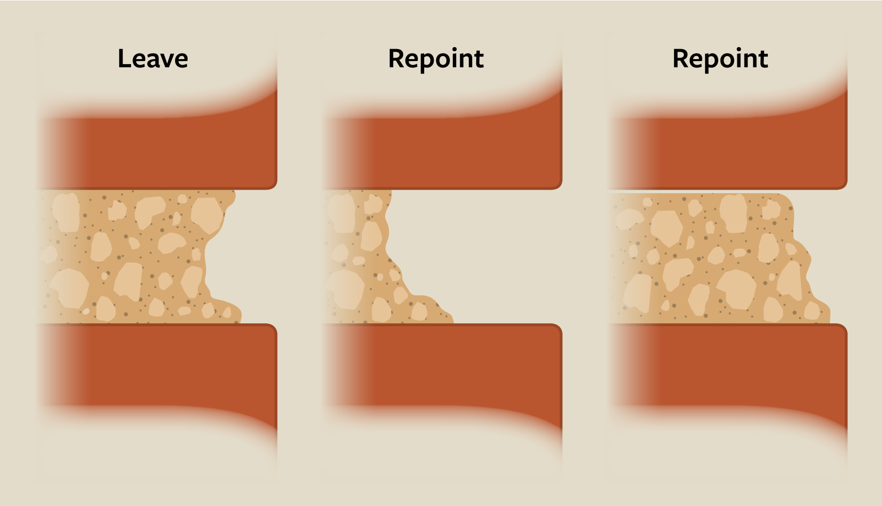


Figure 52: When to repoint. A useful rule of thumb is to repoint when the mortar is eroded to a depth greater than the joint width, as in the middle example. Cracked joints, like the example on the right, will allow water into the wall and should always be repointed.

Commonly, repointing will be required in response to mortar loss caused by dampness (such as rising or falling damp) with decay due to the action of soluble salts (see Figures 8, 54 and 75). In such situations, the source of the dampness needs to be addressed as well as replacing the lost mortar. Salt loads on the masonry may need to be reduced, and the replacement mortar may need to be made deliberately sacrificial to manage any residual salts that are deep in the wall and which will take time to reach the surface.

There is more information about salts and dampness in the technical guide *Salt attack and rising damp: a guide to salt damp in historic and older buildings*, which is another guide in this series.

18.3 Matching previous mortars

A common requirement for a repointing mortar is that it should match the original. This is particularly important for buildings of heritage value (see Section 13.4 'Choosing the right mix – significance'). The aim should be to put it back the way it was. Ideally, this means matching:

- the binder: if the original was lime, then use lime
- the sand: for colour, grain size, grain shape and grading
- the proportions of binder to sand.

> See Chapter 5 'Limes' and Chapter 9 'Sands and other aggregates'

Perfect matching is often impossible: the limes and cements available today are different from those of the nineteenth century, the original sand source may not be accessible and copying the original mix proportions may not produce a suitable mortar using today's materials. Further, as explained in the next section, the original mix may need to be modified to ensure compatibility with the surrounding masonry. Compromises will be necessary, but the aim should still be to match as closely as reasonably possible.

The general appearance of an old mortar is due to its colour, texture and the extent of weathering. Matching each of these can be quite difficult, and it is important to deal with them separately. If the masonry is also to be cleaned, repointing should be undertaken after the cleaning, so that colour matching and the extent of repairs can be better judged. Colour matching should always be to the fresh (or internal) colour of a mortar, not to that of its aged appearance, which may have a lot to do with dark-grey grime in polluted atmospheres, to windblown dust giving yellow or reddish-brown hues or to lichens and other micro-organisms adding a grey tinge.

> See Box 12 'Changing appearances'

The colour of traditional limes was often an off-white or cream, whereas modern (pure) limes are bright white and may need toning down with a small amount of pigment to match the colours of the earlier materials. This can be achieved with about 1/100 part of pigment (i.e. 1% of the lime). Suitable pigments may include raw umber and yellow: try a 75:25 mix to begin with. Many other pigments are available; always use natural earths or alkali-stable synthetic oxides (such as are used with cement). Organic dyes should never be used, as they fade with time.

> See Section 12.1 'Matching colours of existing mortars'

Sample biscuits

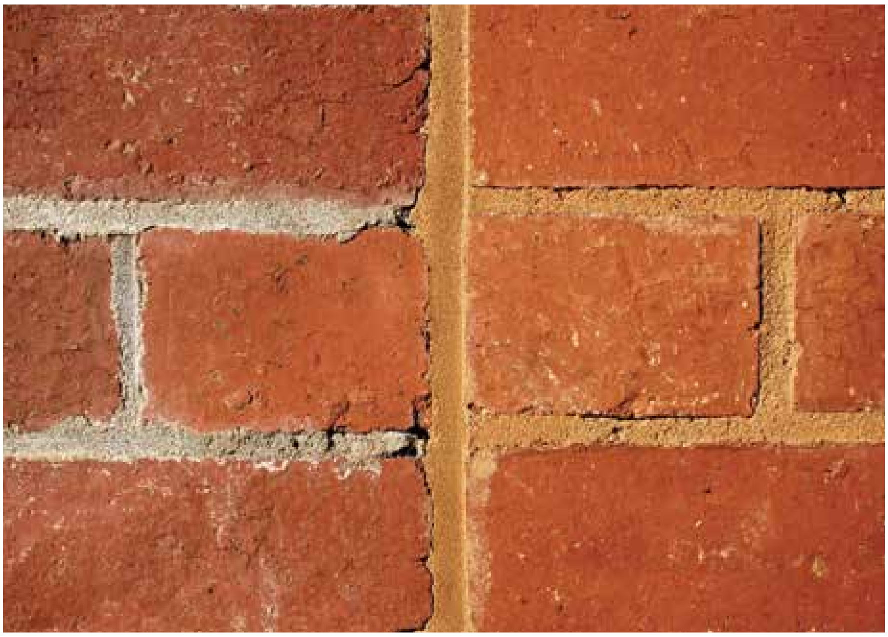
Small, biscuit-sized samples should be made for colour and texture matching. They can be easily prepared by using metal poached egg rings or slices of PVC pipe to hold the samples, which should be set on a plywood base to absorb some of the moisture from the mortar. The samples should be cured properly by keeping them damp for several days before allowing them to dry out slowly. Rapid drying of an improperly cured mix will not give accurate results.

Make three specimens of each mix:

- one as a reference and backup
- one to snap in half to see the fresh inside appearance
- one to keep as a damp sample, also snapped in half.

Only the broken faces should be used for comparison, as they show the true colour of the mortar as well as the texture imparted by the sand grains. After thorough curing, the third sample can be kept damp for the duration of the project to aid colour matching of new batches of mortar.

Figure 53: Nonmatching mortar. The new brickwork on the right uses a strong yellow sand, which does not match the original mortar on the left.



Matching an aged appearance

Attempts to match the aged appearance of older mortars have seen the common but incorrect use of strongly coloured sands, particularly yellow sands which are not at all like the original (see Figure 53). Instead, matching an aged appearance can be achieved by:

- tamping the surface to expose the colour and texture of the sand
- applying a light surface colouring, such as cold tea or copperas
- allowing the new mortar to age naturally over time.

As well as producing an aged appearance, tamping has other advantages which are explained in Chapter 23 ‘Finishing joints’. A light surface colouring can be applied several ways: a wash with cold, black tea was a common treatment. Another was green copperas (iron sulfate) which was traditionally used in yellow colourwashes and limewashes on renders and stuccoes. It is readily available today as a garden fertiliser (sulfate of iron) which can be used to tone down bright mortars as follows:

> See Section 12.1 ‘Matching colours of existing mortars’

- dissolve the pale-green or grey crystals in hot water at a rate of 0.5% (5 g/L)
- brush or spray on a very light coating
- wait for an hour for it to fully colour up before deciding whether further coats are needed
- don’t overdo it – less is usually more in these cases.

Multiple thin coats are best, as gaps and overlaps can be dealt with. Spraying risks run-downs and colour streaks where there are uneven absorbencies, such as with glazed headers in brickwork.

The colouring action of copperas will be strongest with fresh mortar and weaken as the mortar ages. Colouring should be applied (after tamping) during the first week of curing (see Section 24.2 ‘Curing procedure’).

Soft earth mortars are liable to rapidly erode if sprayed with water during raking out and pre-wetting. After raking out, consolidate with multiple light sprays of limewater.

Many early buildings, particularly those with thick stone walls, were constructed with relatively weak bedding mortars, often of earth in which clay was the principal binder. These walls were protected with a more durable pointing of lime and sand. Today, we may be faced with the loss of the pointing and the subsequent rapid erosion of the weaker bedding mortar. Given the risk of shrinkage of earth mortars, the appropriate response may be deep repointing (in stages) with an earth mortar, stabilised with quicklime. The wall is then pointed to match the original.

Occasionally, a building may be more important for a later period, perhaps when it was extended substantially and the original pointing style and other details were changed to match that of the new. If this is the case, it would be wrong to return the existing pointing back to its original state. Decisions about which is more significant should be made as part of the Australia ICOMOS *Burra Charter* process.

18.4 Ensuring compatibility

While our initial aim is to match an original mortar, a key requirement is that the new mortar should not damage the existing masonry: instead, it should be compatible with it. This means that we may need to change the components and mix proportions, as the following examples show.

> See Section 13.5 'Choosing the right mix – compatibility'

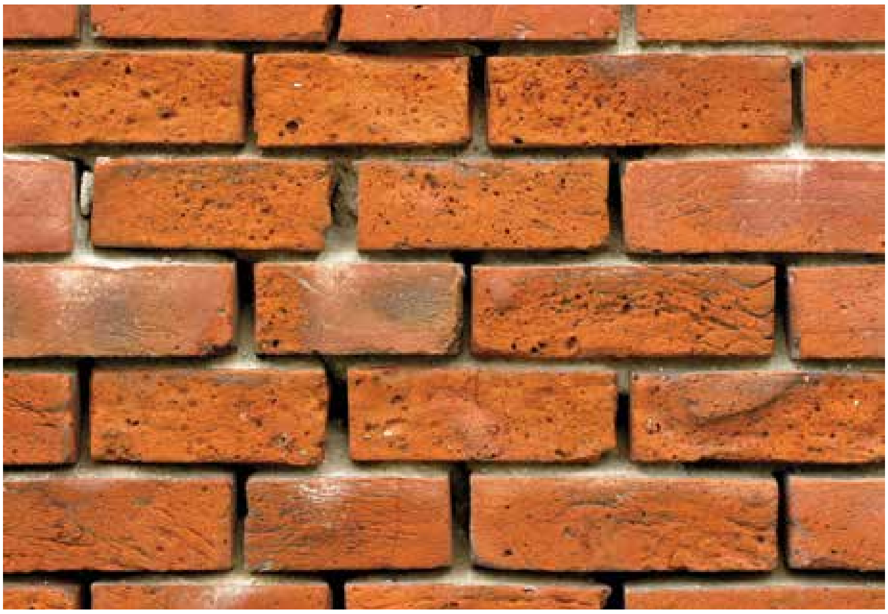


Figure 54: Salt attack decay of mortar and low-fired bricks. A 1:3 pure lime mortar might not be permeable enough for these bricks, so instead we should consider a sacrificial mix containing crushed limestone (to add porosity) and possibly admixtures to entrain air and retain water during the initial stiffening. Depending on the void ratio of the sand, the proportions of lime putty to sand might be around 1:3.5. A weaker mix may be appropriate for a more protected location (e.g. a cellar). The condition of the bricks suggests that other works may be needed, including removal of salts, though the sacrificial mortar will contribute to this by encouraging the wall to dry out through the joints rather than through the bricks. See Mortar type 5 (sacrificial lime) in Table 10 in Section 13.7 'A range of mortar mixes'; see also Chapter 25 'Using lean or sacrificial mixes'.

Cement-based mortars: When repairing cement-based mortars, we must recognise that modern cement is much stronger than that used in older buildings (see Section 6.3 'Portland cement through time') and so we may need to design a mix containing much less Portland cement than before, and replace the rest with lime. Alternatively, we may replace it entirely, and instead use ground slag (GGBFS) in composition with lime, or use one of the stronger natural hydraulic limes (NHLs). These alternatives provide improved workability and greater elasticity and permeability.

> See Mortar type 3 (NHL) and type 4 (cement + lime) in Table 10 in Section 13.7 'A range of mortar mixes'

Mason's putty: Water penetration through porous stonework may have weathered the masonry to such an extent that repointing the joints with a relatively impermeable mason's putty would increase the rate of decay. This is because it would force all the drying of the wall to occur through the stone, rather than through the joints. In this situation, an appropriate repair mortar would omit the linseed oil and some of the whiting from the mason's putty, while adding some fine sand, all with the aim of achieving a permeable (breathable) mix.

> See Section 16.1 Mason's putty, Mortar type 6 (Narrow joint) in Table 10 in Section 13.7 'A range of mortar mixes'

18.5 Matching joint profiles

In principle, the profile of the new pointing should match the original, or the more significant if it's not original. Determining what the original was can be difficult, especially where there has been subsequent repointing. Clues to the original may remain on a building, hidden behind downpipes or tucked away in protected areas, such as high-up under overhangs or verandahs. Careful, close examination is required. Sometimes, the answer can be found on neighbouring buildings constructed at the same time and in a similar style. Where there is no evidence of the original profile, a plain, flush finish should be used, so as not to invent a more elaborate detail that the building may never have had. Figure 56 in Box 14 shows some of the joint profiles commonly found on Australian buildings.

The question can arise: should an aged or weathered appearance be matched, or should the original profile be reproduced? To some extent, the answer will be related to the scale of the repairs: if it's just a small patch, it should be matched to the surrounding, aged appearance; if it's a complete elevation, there is an opportunity to put the original form back. Here, the significance of the building should guide decisions. If the form is important, then reproducing the original profile will be desirable. If age is a key component of its significance, a time-worn appearance (or at least a not-new appearance) may be appropriate.

> See Section 18.6 'Small patches or large areas?'

In turn, the picture is complicated by the need to ensure compatibility. This may mean having an open-textured (worn) look to the joint surfaces, to gain maximum surface area and permeability to enhance the drying behaviour of the wall. Tamping joints to improve their drying behaviour (and curing) is explained in Section 23 'Finishing joints'.

> See Section 18.4 'Ensuring compatibility' and Section 13.5 'Choosing the right mix – compatibility'

Where the weather has eroded the arrises (edges) of stones to a more rounded profile, there is a case for slightly recessing the joints, as shown in Figure 55. This way, the width of the joint is maintained as it was intended, whereas finishing it to the original wall line would show very wide joints and substantially change the appearance of the wall. But don't overdo it: the recessing should be slight.

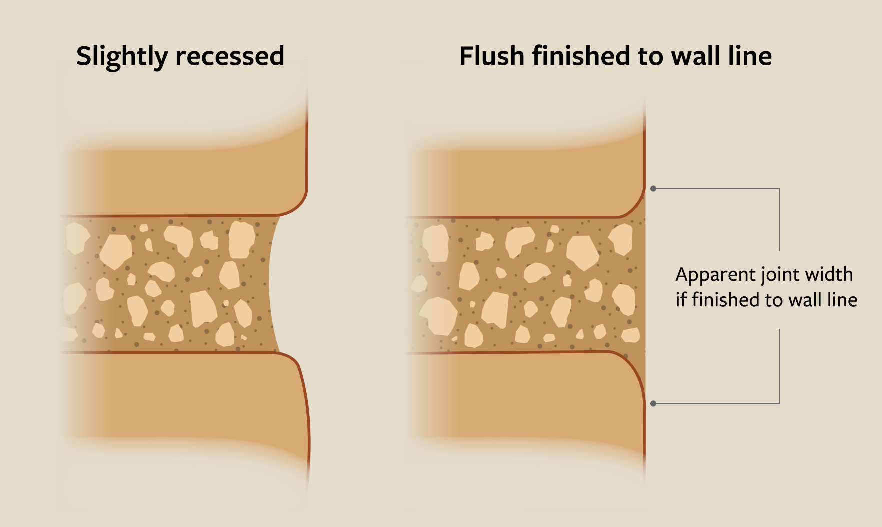


Figure 55: Slightly recessing a joint. At left, the joint is slightly recessed to allow for the rounded arrises. Finishing the joint flush in line with the wall face (at right) will produce apparent joint widths much larger than intended, dramatically changing the appearance of the wall. Also, the feathered edges of the joints will fail, allowing water to enter the masonry.

18.6 Small patches or larger areas?

How extensive should the repointing be? The issue here is the visual effect of the repointing. If not done very carefully, a series of small patches across a wall may be rather unsightly. For the sake of a uniform appearance, it may be better to repoint a larger area, perhaps a complete wall. Here we may need to compromise between the heritage ideal of only doing as much as necessary and the client's response to what may be a less-than-ideal visual result.

Accurate matching of existing joints is not always easy: it requires skill, patience and sometimes many trials of mixes and finishing techniques. Because of the time required, some suggest that the cost of a series of patches could be greater than the cost of repointing a complete wall. However, apparent cost differences may diminish when the full costs of the job, including thorough curing, are taken into account.

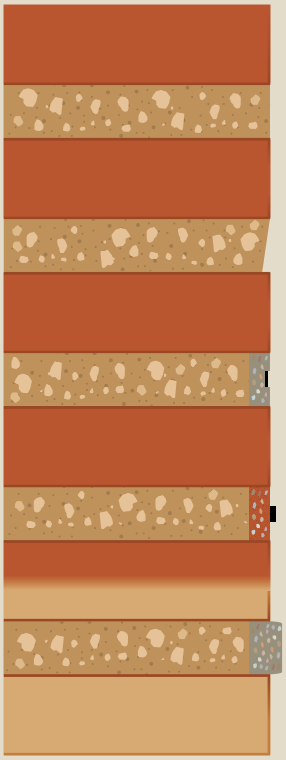
> See Chapter 24 'Protection and curing'

Where there is considerable heritage value in the existing mortars, careful patching will be the appropriate aim and any extra cost well justified. Where there is less significance in the existing joints, it may be acceptable to repoint larger areas but still with the aim of matching the colour, texture and profile of the joints in the rest of the building.

Where the job is a total repoint, it is good practice to leave a representative area – say a square metre – of the original pointing, in a discreet location.

Box 14: Joint profiles

Traditional profiles



Flush
Commonly seen on side and rear walls.
See Figures 38 and 59.

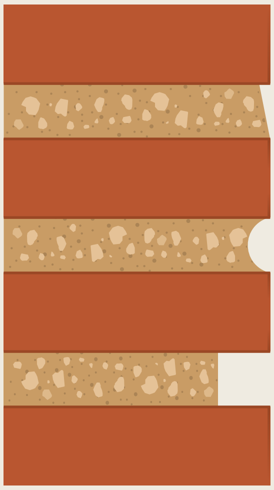
Struck (or overhand struck)
A very common profile.

Ruled
Pointing mortar ruled with a narrow tool while soft, then pencilled (painted) white or black. See Figures 31 and 57.

Tuck pointed
Stopping mortar coloured to match the brick and tuck pointed with white or black ribbon. See Figure 30.

Ribbon
Used on stone rather than brick.

Modern profiles



Weather-struck

Ironed

Recessed

Figure 56: Common Australian joint profiles.

These are some of the more common Australian joint profiles. The first five are traditional profiles, while the last three are from the second half of the twentieth century. While the weather-struck profile may be more sound (in terms of water shedding) than overhand struck, it is not a traditional Australian profile and should not be applied to older buildings. Neither should the ironed nor recessed joint profiles. The recessed profile is not suitable for use with porous brick or stone, as it will promote water entry. Where bedding mortars were pointed (or stopped in the case of tuck pointing), the depth of the pointing or stopping was typically only 2–6 mm. When repointing, joints should be raked out to a depth of at least 2.5 times the joint width (i.e. 25 mm for 10 mm joints) to ensure good bonding with the masonry units (see Chapter 20 ‘Raking and cutting out joints’).

Extending the area to be repointed to meet architectural details (such as string courses and sill lines and to re-entrant angles) may be an appropriate way of minimising the visual impact of the repairs. Keep in mind that the new repairs will weather-in and become less apparent with time.

Several examples of matching existing (aged) joints need discussion in this context. Carbon or vegetable blacks have often been leached out of pointing or stopping mortars: this has left what once may have been a very dark colour faded to a mid-grey (see Figure 57) or a pale-red (see Figure 30). Patch repointing would mean matching the faded colour, whereas for a whole wall or building reinstating the original, darker colour may be the correct approach.

White or black pencilling may have eroded from the ruled joints across much of a wall face, only a section of which needs repointing. Finishing the repaired joints by ruling the lines but not pencilling (painting) them, and then tamping to produce an aged appearance, may be the right response.

> See Chapter 23 ‘Finishing joints’

Figure 57: Matching an aged mortar. Loss of the joint surface (due to abrasion) exposes how the pointing mortar has been darkened with charcoal, coal ashes, coke breeze or lampblack (or a combination of these) to tone-in with the darker bluestone. Leaching of the finest particles (lampblack) has produced a faded grey colour at the surface, which is also coloured by red, windblown dust. Off-white bedding mortar is exposed at the extreme left. Patch repointing would mean matching the faded grey and then adding a little red dust!

Box 15: Respecting traditional practice

Traditional practice commonly saw the use of more highly finished front walls, with a simpler finish used on side and rear walls. This practice should be respected when undertaking repairs: don't change the pointing styles to make them 'better' – match what was there originally.

Figures 58 (left) and 59 (right): Traditional practice.

Figures 58, 59 and 60 are examples of traditional practice. Figure 58 shows South Australian bluestone that has been squared for the front walls, with smaller pieces used as rubble in the side walls. The pointing follows the same hierarchy: ruled and pencilled on the front walls, with a plain, flush finish on the side walls. Similar detailing is seen around Australia on walls of sandstone, limestone and bluestone. Figures 59 and 60 show flush-finished lime pointing to rubble bluestone on the side wall of a house. This original pointing is almost 150 years old and is in good condition, though it is beginning to retreat from the stones and will eventually require replacement. Figure 60 shows a closer view, with lime lumps and large quartz grains in the mortar, and small pinning stones, which compact and tighten the joint (see Chapter 22 'Repointing').

Figure 60: Flushed up pointing.

Figure 61: What not to do.

Figure 61, on the other hand, shows what not to do when repointing – the joints have been recessed to emphasise the stones in a way that was never intended. As well as not respecting the traditional aesthetic, the less permeable cement mortar will limit drying of the wall through the joints, and so will promote decay of the stones (see Section 13.5 'Choosing the right mix – compatibility').

19 Batching, mixing and knocking up

19.1 Batching

Traditional practice involved the use of bottomless, wooden gauge boxes for each component of the mix.

Accurate batching (or gauging) of mortars is essential to achieving good, repeatable results. Mortars should never be shovel-batched: the inevitable bulking up of dry powders will produce mixes very different from those specified. Mortars should always be batched by volume using containers of known measures kept expressly for the purpose.

Some argue for batching by weight, but this is impractical in many situations. Nevertheless, the correct amount of dry powders (such as hydrated and hydraulic limes) should initially be determined by weighing out the required amounts, using the compacted density data supplied by the manufacturer. Subsequent measures can then be based on repeating the same volume, but care is still required to avoid further bulking up during measuring. Tap the sides of measuring containers to minimise bulking of powders and sands.

Bagged products should ideally be used by the whole bag: it has a known weight and therefore volume, based on its compacted density. Cutting bags in half is an option for smaller batches – but measure it, don't guess it.

Drain lime putties of limewater and creamy slurry and use only stiff putty that will stand like feta cheese. See also 'Managing the water content of mixes' later in this chapter.

Batching needs to account for the different amounts of lime present in putties and dry hydrates. As explained in Section 5.4 'Densities of lime putties and hydrated limes', lime putty should have a density of at least 1,350 g/L (when each litre will contain about 600 grams of lime). To achieve this, Australian putties should be allowed to settle and then be carefully drained to remove the liquid material – clear limewater and creamy slurry – from the top. The liquid shouldn't be discarded: the creamy slurry can be used in knocking up, should the mix be too stiff, and also for mixing dry materials (such as pozzolans and pigments) to a slurry before adding them to the mortar mix. Clear limewater can be used to promote curing and to consolidate weak brick, mortar and plaster. Many applications are required: 30–50 may be needed when using limewater as a consolidant.

Figure 62: Fresh and matured lime putties. At the front, the freshly slaked putty has the consistency of thick cream. To the rear right, the mature putty is more like feta cheese and will stand without slumping. For repointing work, putties should be matured for at least four months. Despite the stiff, dryish look of the mature putty, there's enough water in it to make a workable repointing mortar when it is mixed with dry sand. No water should be added to the mix, the exception being when dry materials (such as pozzolans or pigments) are to be included. These should be added as a slurry, made with the liquid material drained from the putty.

Photo: Paul McGahan.

The densities of hydrated limes range from 350–640 g/L: that is, from about half to the same amount of lime per litre as in a dense putty. This has to be taken into account when batching: to make a mortar equivalent to a 1:3 mortar made with a dense putty may require a mix as rich as 1:2 hydrated lime to sand.

One way to avoid having to adjust for the differences in density is to first prepare the hydrated lime as a putty by adding it slowly to a bucket that is one-third filled with water, and continually whisking it until it reaches the consistency of whipped cream. Allow the putty to settle out to a stiff, cheese-like consistency and then drain it before use. This approach has the additional advantage of maximising the workability of the hydrated lime. Note, this is soaking, not slaking: soaked, hydrated limes will never achieve the same densities as directly slaked lime putty.

Because of their finer particle size and greater reactivity and workability, directly slaked lime putties are preferred over the use of hydrated lime. If availability or other circumstances dictate the use of hydrated lime, it must be fresh material to avoid it having gone off in the bag.

> See Section 5.3 'Lime putty and hydrated lime'

When all the materials are dry (such as a hydraulic lime and sand mortar or a composition mortar of cement, hydrated lime and sand), they should be thoroughly mixed together dry before adding any mixing water. Where some of the binder is wet (like putty) the dry components should be run to a slurry before mixing them together with the putty. Thus, in a composition mix of lime putty and cement (or lime putty and hydraulic lime), the cement (or hydraulic lime) should be run to a slurry before mixing it with the putty. This is to ensure thorough mixing of the components: adding dry powders to a lime putty will result in the dry particles 'patching', or clumping, producing an uneven mix. To minimise dust, dry mixing requires a forced action mixer (see Section 15.2 'Contemporary mixing' and Section 19.2).

The workability of hydraulic lime and composition mortars can be improved by using the slurry drained from lime putties as the mixing water.

The same principle applies to any fillers, pigments, pozzolans and admixtures, such as air-entraining or water-retaining agents. If they are dry powders, they should be mixed directly with other dry ingredients, but if lime putty (or a sand-slaked quicklime mortar) is used they should be added in slurry form. If there's more than one dry component, they should be thoroughly mixed together before adding them to the wet mix. This will improve their dispersal and ensure a more uniform mix. **Accurate proportioning of pigments, pozzolans and admixtures is an essential aspect of making good mortars**.

Dry rather than damp sand is preferred for three reasons. Dry sand ensures better contact with the lime, because of the absence of a layer of water on the sand grains (see Section 15.2 'Contemporary mixing'). Relatively stiff, dryish mixes are needed for repointing work, and even slightly damp sand can be too wet when mixed with lime putty. Further, using dry sand avoids any concern about the bulking that occurs with damp sand.

Bulking of sand

Damp sand occupies a greater volume than dry sand. This is not because of the additional volume of the water: add enough water to fully saturate the sand and it will collapse back to the dry volume. The increase in volume, or bulking, is due to forces related to surface tension which hold small amounts of water tightly between the sand grains, so that it acts as a temporary (and weak) adhesive or binder. The amount of bulking will vary with the type of sand, as well as with the water content. Typically, damp sands show an increase of 10–30% over the dry volume. Well-graded sand will bulk up less than a poorly graded sand. **Whenever there's no choice but to use damp sand the amount of bulking must be measured, and the mix proportions adjusted accordingly: otherwise mixes will have too little sand**.

19.2 Mixing

Beat all your mortar with a beater three or four times over before you use it, for thereby you break all the knots of lime that go through the sieve, and incorporate the sand and lime well together, and the air which the beater forces into the mortar at every stroke, conduces very much to the strength thereof.

If I might advise anyone that is minded to build well, or use strong mortar for repairs, I would have them beat the mortar well, let it lie 2 or 3 days, and then beat it well again when 'tis to be used.

Moxon, 1703

Ideally, mortars should be mixed in a forced action (screed) mixer (see Figure 45), a roller pan mixer (see Figure 44) or with a handheld mixer. Normal rotary cement mixers are not capable of delivering the pressure required to force the binder and sand together and to displace water layers on the sand grains (see Section 15.2 'Contemporary mixing'). Handheld mixers should be purpose-made; normal drills will burn out quickly. Using a handheld mixer can be made easier by whisking up the lime putty before adding the sand.

Hand methods of mixing include pounding and chopping lime putty into the sand with a mason's hoe (larry) in a suitable trough, or for small amounts with the end of a mattock handle in a flexible tub. Pounding the relatively dry mix will seem like a lost cause, but eventually there comes a magic moment when it all goes sticky and hangs together. Simply turning over the ingredients with a shovel will not produce satisfactory mortars. Considerable force is required: traditional practice was to beat the mix with a piece of timber or the back of a spade.

Where practicable, lime mortars should be premixed and matured for as long as possible in sealed containers. They will not go off, provided there is no hydraulic component (such as hydraulic lime or pozzolan) in the mix.

Even when off-site premixing is not practicable, there are definite workability gains to be made by short-term maturing of lime mortars before use. Pure lime mortars can be stored indefinitely, while the lower classes of hydraulic limes can be stored for a day after mixing. Keep stored mortars cool and covered or sealed to prevent them drying out.

> See Section 15.3 'Off-site preparation and maturing of mixes'

Making quicklime mortars by sand-slaking

Rather than slaking quicklime to a putty and later adding sand, mortars were traditionally made by slaking quicklime with the sand in the process known as sand-slaking (see Section 15.1 'Traditional mixing'). This method, which has been found to produce excellent sticky mortars with good working properties, should be used whenever the significance (heritage value) of the building warrants it. It is the only practical way of producing mortars with the lumpy lime appearance found in older buildings (see Box 13 'Lime lumps').

Those working with quicklime (and any limes) must understand the risks involved and must be able to describe and apply the necessary safety precautions (see Box 16 'Health and safety with mortars').

A sheet of thick plywood can be used as the slaking platform (see Figure 63) and should be wetted down to avoid charring from the heat of the slake. The quicklime is placed within a ring formed in the sand, and water is added using a watering can with a sprinkler head to spread it evenly. Sand is immediately drawn over the quicklime using a mason's hoe (larry). The heap will crack open as the slaking quicklime expands and will need attention to keep the lime covered. The heat energy released by the quicklime is absorbed by the sand, making the process safer than slaking it separately.

An alternative to sand-slaking on a platform is to do it in a forced action mixer (see Figure 45). The sand and quicklime are first turned in the mixer and then water is added through a hose fitted with a 'shower' trigger nozzle while turning the mix. This method requires quicklime that has been crushed to a small particle size.

The quantities used in a recent series of slakes are presented here as a guide to what to expect. Twenty litres of quicklime (a mix of rock and powder) were added to 60 litres of dry, well-graded sand. This amount was found to be convenient for a standard size sheet of plywood. Thirty-five litres of water were slowly added to ensure that the water was absorbed by the quicklime and did not simply run off the board.

Figure 63: Sand-slaking quicklime. The hard lumps of quicklime (rocklime) have slaked to a white powder, seen here breaking out through the sand. The plywood board is a reduced-scale version of a traditional sand-slaking platform or stage.

> *The (lime) concrete is to be made upon a timber platform, 12 ft square, with a 9" curb on three sides. The same to be left for mixing the mortar upon throughout the contract … All the mortar is to be made with fresh burnt lime and clean sharp beach sand, mixed one part lime to two and a half parts sand thoroughly beaten up before being put on the scaffold for use by the masons.*
>
> 1877 specification for a South Australian school

After cooling, the slakes were covered overnight to keep out any rain. The next day they were found to be still damp in parts, suggesting that the amount of water was about right for this particular quicklime and the dry sand. Less water should be added if the sand is damp. An advantage of this technique (unlike using lime putty) is that you can start with damp sand, as the quicklime will dry it (but you must allow for bulking).

The aim should be to add the full amount of water needed for the slake in the one go, while avoiding adding too much. This will maximise the energy released from the quicklime and so dry and clean up the sand, improving the contact between sand and lime. Adding some of the water at the beginning and then more later will result in the second addition cooling the slake and reducing the heat available to the sand.

The mixes were then put through a forced action mixer (see Figure 45) and a small amount of water (generally less than a litre) was added to produce stiff, dryish mortars. Each slake produced about 70 litres of mortar – a result of the expansion of the quicklime on slaking – making the effective mix proportions close to 1:2.

The mixes were stored in 15-litre pails for later use. On opening after an extended period of maturing, the mixes had expanded in the pails and were very stiff – some quicklime had continued to slake during maturing – and a little more water was needed to make them workable.

Managing the water content of mixes

In contrast to laying bricks or stones, many mortar-repair tasks, including repointing or deep packing of joints or cracks, need relatively stiff mixes. Consequently, it's better to start with mixes that are too dry, rather than mixes that are too wet. As noted above, sand-slaked quicklime mortars can initially be made very stiff and dry and then wetted up if more workability is needed.

If a quicklime mortar is accidentally made too wet, it can be corrected by adding more quicklime – and dry sand in the right proportions, but not water – while turning the mix in a forced action mixer. Add only a small amount of quicklime (a handful) at a time and wait until it has fully slaked and taken up the water from the rest of the mix before deciding whether to add more. This may take 10 minutes or more – fortunately, you can't overmix a lime mortar.

For mortars made with lime putty, the options for drying out a wet mix include spreading it out on a sheet of plywood and allowing the wood to absorb some of the moisture; some will also evaporate. Because lime hardens slowly, it's a very forgiving material: it won't go off in the few hours needed to dry the mix to a better consistency.

Repeatedly pouring off the water that accumulates on top of the putty will help.

However, the main ways to achieve stiff mixes with lime putties are to use dry sand and as dense a putty as possible. While prolonged maturation and gentle vibration in the back of the ute will help settle putties stored in drums or pails, they still may not produce putty that is sufficiently dense.

In colder climates, lime putty is matured in woven bulker bags through which excess water can slowly drain, but this is not practicable in the hotter and drier Australian climate. One option may be to drain putties by standing them in a tightly woven sieve or bag of dense shade cloth suspended in a sturdy bin with a tight-fitting lid to slow air getting to the lime.

An alternative to draining putties is to thicken them by adding hydrated lime powder, a small amount at a time, while whisking the putty with a drill mixer in a flexi-tub. To retain most of the workability advantages of the putty, limit the hydrated lime to 10–15% of the total.

When putty mixes are too stiff, they should be made workable by adding more putty and not by adding water. In a recent example, a fine sand was initially assessed as needing a 1:2 putty to sand mix, but this balled up in the mixer and produced solid marbles until more putty was added, bringing the mix proportions closer to 1:1.5 and yielding a workable mix. This example highlights the need to allow the tradesperson to adjust a mix on-site to make it workable: insisting on a rigidly specified mix will not achieve good results.

19.3 Knocking up

The beating of mortar is of the utmost consequence to its durability, and it would appear that the effect produced by it, is owing to something more than a mere mechanical mixture.

Nicholson, 1850

Lime mortar should … (be) well knocked up and left in large heaps fully ten days before use.

Haddon, 1908

Turn out a well-matured lime mortar onto a board and it will be stiff and apparently unworkable. However, by thorough reworking or knocking up for at least 10 minutes (using the same techniques as mixing) the workability will be greater than before. Don't add water, add force. If after thorough knocking up a lime mortar intended for repointing is still too stiff to use, its workability can be improved by adding a small amount of lime putty, but not water.

Workability of a lime mortar intended for laying masonry can be corrected by adding a small quantity of lime slurry drained from the putty. Where adding more water is undesirable (e.g. to limit shrinkage) the use of superplasticisers or air-entrainers may be warranted, see Chapter 11 'Admixtures and additives' and Chapter 14 'Workability'.

Admixtures and pozzolans are added to mixes during knocking up and should be thoroughly incorporated into the mix. All dry, powdered materials should be added in slurry form (see Section 19.1).

As distinct from reworking or knocking up, retempering is the bad practice of trying to rejuvenate a mix that has already started to harden, by adding more water and remixing it to the desired consistency. The resulting mortar will be weaker than intended, as some of the chemical bonds that have started to form will be broken. Retempering is a problem more commonly associated with cement and composition mortars that have shorter pot lives. Water may be added to mixes that are drying out too fast in warm weather, but only within the time limits specified for the particular binder.

Box 16: Health and safety with mortars

Since 2012, Australian work health and safety regulations have been aligned with the United Nations' Globally Harmonised System (GHS) of classification and labelling of chemicals. Under this system, limes, cements and some pozzolans are classified as hazardous.

What are the hazards?

The hazards related to using mortars and their materials are due to:

- the caustic (highly alkaline) nature of limes and cements
- dusts from limes, cements and pozzolans, which as well as being caustic may contain respirable silica
- the heat produced by slaking reactive quicklimes (see Section 5.2 'Non-hydraulic (pure) limes and the lime cycle')
- dusts and particles produced during raking and cutting out existing mortars
- the potential for sealants and mason's putties to contain asbestos (see Chapter 16 'Special jointing materials')
- the potential for mason's putties to contain lead white (see Chapter 16).

What are the associated risks?

The risks associated with these hazards are:

- serious eye damage (and potentially blindness) from lime and cement particles, putties and limewashes
- irritation and chemical burns to the skin from caustic materials
- irritation and caustic burns from inhaling dusts, particularly quicklime
- burns from hot quicklime, which may be both physical (heat) and chemical (caustic)
- inhalation of respirable silica, with the consequent risk of silicosis
- inhalation of asbestos fibres, with the consequent risks of asbestosis and mesothelioma
- ingestion of lead white, with the consequent risk of lead poisoning.

What precautions should be taken?

Worksites should provide eyewash stations and readily accessible first aid kits that include eyewashes and cotton buds.

Workers should wear and carry:

- eye protection (close-fitting goggles that exclude dusts and splashes from putties and limewashes)
- an individual eyewash, based on complexing agents (e.g. Diphoterine®)
- dust masks, wherever and whenever dust might be created
- waterproof gloves (long-sleeved, chemical-resistant gloves if slaking quicklime)
- protective clothing (full-length clothing to minimise exposed areas of skin)
- barrier cream (for exposed skin).

All workers should be aware of the potential for sealants to contain asbestos fibres and for mason's putties to contain asbestos and/or lead white. If there is any doubt as to whether these materials are present, the mortars or sealant should be analysed before undertaking any works. Should they be discovered, their removal should be managed in accordance with the following model codes of practice published by Safe Work Australia (www.swa.gov.au):

- *How to manage and control asbestos in the workplace* (2020)
- *How to safely remove asbestos* (2020)
- *Managing risks of hazardous chemicals in the workplace* (2020).

What first aid should be provided?

Eyes: should dust or splashes from limes, cements, mortars or limewashes lodge in the eyes, immediate action is required. Quickly flush the eyes with an eyewash or with tap water or other clean water if an eyewash is not available. Continue flushing while seeking urgent medical attention. If needed, use cotton buds with great care to remove particles. Keep flushing.

Nose and throat: should dust from limes or cements be inhaled, continuously flush the nose and throat with clean water for at least 20 minutes, taking care to avoid breathing in the water.

Swallowing: should limes or cements be swallowed, thoroughly wash out the mouth with water, drink large amounts of water and do not induce vomiting. Seek medical attention.

Skin: should spills of limes or cements and all types of mortar contact the skin, wash them off as soon as possible. Replace lost natural oils with skin cream.

20 Raking and cutting out joints

Always work from the top down when raking out and repointing.

Good preparation is one of the key aspects of successful repointing: the failure of work is often due to inadequate raking out of joints.

Although much original pointing was quite shallow – often only a few millimetres in depth – repointing needs to be much deeper to be successful. This is because the original pointing was applied when the wall was green – when the bedding mortar and masonry were still damp – and the dampness helped the pointing harden properly and bond well. Today when we repoint, we do so in much drier walls and so need a greater mass of new material. This is partly to introduce and retain more water and particularly to ensure sufficient contact area for a good bond to the adjacent masonry.

Narrow 3 mm joints in ashlar stonework should be raked out to at least 20 mm.

Joints should be raked out to a depth that is at least 2.5 times their width. This rule of thumb means that a normal 10 mm bed joint in brickwork should be raked out to at least 25 mm. Wider joints generally don't need to be raked out more than about 30 mm, though there are circumstances where greater depths will be necessary. These may include rubble stonework where small pinning stones have been inserted into the joints (see Figures 60 and 72). Raking out will loosen them and so they will need to be carefully removed and put aside until the repointing stage (see Chapter 22 'Repointing'). Where dampness and salt attack have decayed the mortar, the raking depth may need to be much greater, partly to remove decayed material and also to remove as much salt as possible (see Chapter 26 'Deep repointing').

Tungsten-tipped 'score and snap' tools for cutting cement fibreboard are ideal for removing lime mortars.

The term 'raking out' derives from traditional practice when pointing new work: the still-soft bedding mortars were readily raked out with simple tools. Softer mortars may still be raked out today, using chisels that are dragged along the joints or skates (rakers) which have wheels that run over the face of the bricks and adjustable raking heads to control the depth.

However, it is often necessary to cut out much harder mortars, particularly previous repointing with hard cement, and for that work we often need mechanical tools as well as sharp, tungsten-tipped chisels. There have been arguments about the use of mechanical tools, such as angle grinders and disc cutters: their high torque can make them hard to control and they can kick or run off, damaging adjacent bricks (see Figure 64). This can widen joints and leave bricks above and below perpends with unsightly slots cut in them. This has led to some people wanting to ban the use of machines and to limit all work to hand tools.

Figure 64: Grinder damage. This shows damage to bricks from using angle grinders to cut out old mortar. Overruns and widening of joints often occur because of oversized blades and because the torque produced by rotating tools makes them difficult to control. Oscillating-blade tools (see Figure 65) are preferred for removing old lime mortar.

Figure 65: Oscillating-blade tools. These enable removal of moderately hard mortars while maintaining good control, reducing the risk of overruns. They are also much safer to use than rotating tools and produce less dust.

Fortunately, this problem has been partly overcome by the development of oscillating-blade tools (such as the mortar saws or multi-tools shown in Figure 65). These are much more controllable and can be used with greater accuracy. Also, they produce less dust and are much safer to use than angle grinders and disc cutters. They can cut deeply into joints, enabling ready removal of bricks from a wall.

> See Box 16 'Health and safety with mortars'

Given the advantages of oscillating-blade tools, angle grinders should not be used for cutting out mortar joints that are not excessively hard (i.e. lime mortars). However, hard, cement-based mortars can be difficult to remove and for these it is appropriate to use disc cutters and small handcraft-scale cutting wheels.

Hard mortars should be removed in two stages. First cut a narrow slot along the centre of the joint with a small-diameter diamond disc or cutting wheel. Then use a sharp, tungsten-tipped mason's chisel to remove the mortar from the brick or stone. By always working into the free space in the centre of the joint, hard mortar can often be removed without significant damage to the masonry units and without disrupting the bond of the remainder of the joint.

This latter point is critical: heavy hammering with plugging chisels will damage arrises (edges) and bounce hard stones and bricks around in the wall, breaking the bond of the nearby joints and destroying the wall's structural integrity and weatherproofing.

For cutting out mortars by hand, there are mason's quirks or carving chisels which have blades wider than their shanks (throats) so they won't wedge the joints and damage the arrises of the bricks or stones. Provided they are kept sharp, small stonemasonry chisels with tungsten tips are useful for removing hard mortars from masonry units (see Figure 66). All tools require skilled, patient hands for good results.

Very narrow joints present particular challenges, but they should never be widened to make them easier to clean out and repoint. Instead, use hacksaw or reciprocating saw blades, masonry saws or old, wood saws that have been cut off near the handle to leave a short but deep blade.

Joints should be cut out square and attention paid to thoroughly cleaning the surfaces of the masonry units on both sides of the joint, as absorbent surfaces are essential for ensuring a good bond with the new mortar.

Figure 66: Mason’s chisels. On the left is an inappropriate, modern, plugging chisel alongside some tungsten-tipped stonemasonry chisels and quirks used for cutting out joints by hand. Note the narrow throats which help prevent the chisels becoming wedged in the joints, thus avoiding damage to the edges (arrises) of the bricks or stones.

Thoroughly clean out the debris with a vacuum cleaner, followed by a low-pressure water spray, which can double as the first stage of pre-wetting (see the next Chapter). Capture as much mortar dust as possible before wetting the walls. Fine white powders that get stuck in the pores of masonry units can be difficult to remove and may remain visually intrusive.

21 Pre-wetting

If you lay bricks in hot dry weather, and it be (a) piece of work that you would have very strong, dip every brick you lay, all over in a pail of water, which will make the wall much stronger than if the bricks were laid dry.

Moxon, 1703

Pre-wetting is an essential step in the repointing process. Thorough pre-wetting is needed to control the background suction of the masonry and to prevent premature drying and consequent failure of the new mortar.

For most old walls, it will be necessary to wet them the day before repointing and then several times on the day. The last wetting should be just before placing the new mortar. Wall surfaces should be damp, but not glistening with surface water.

Older walls are generally more porous than modern ones: their bricks, stones and existing mortar may have porosities exceeding 20% and sometimes 30%. Applying a new mortar (or plaster) to these materials when dry would result in the mixing water being rapidly drawn out of the wet mortar by the suction of the adjacent masonry. The new mortar will 'go dead' and be impossible to work, as it will now be too dry. Rapid drying also means that the mortar won't harden properly and will fail prematurely.

Traditional practice with porous materials like older bricks and some sandstones and limestones was to dip them in water or hose them down before laying them, so as to reduce or 'kill' their suction. In contrast, modern bricks have much lower porosities: their initial rates of absorption (IRA) are low and contemporary practice is to avoid pre-wetting during construction (see Chapter 10 'Water'). Some suction is essential so that some of the binder is drawn into the masonry units to form a good bond.

All bricks to be well wetted with fresh water immediately before being used.

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Very porous materials should be soaked the evening before repointing and then several times on the day. The walls should be thoroughly wet but not glistening with surface water, as that may mean too little suction and the risk of leaking and smearing mortar across the face of the bricks or stones. Research suggests that to be effective in controlling suction, the last phase of pre-wetting needs to be applied (and the water allowed to soak in) immediately before applying the mortar (or plaster).

All bricks should be charged with moisture before use. In dry weather bricks should be hosed or dipped in water, otherwise the dry nature of the brick will quickly absorb the moisture from the mortar and nullify its adhesive properties.

Haddon, 1908

The common use of splash brushes (stock brushes) will deliver only a small fraction of the water required for most old walls. Instead, use a hose fitted with a fine spray nozzle or a garden sprayer with a good-capacity tank. A sprayer is particularly useful for the last phase of pre-wetting if the nozzle can be placed within the joint. This avoids wetting the face of the masonry, while adding water to the back of the joint, where it is needed most.

A sprayer will also be useful where walls consist of materials of very different porosities, e.g. granite blocks in lime mortar. Little or no pre-wetting is required for the granite, but the mortar at the back of the joint will need plenty. Similarly, walls of different masonry units, such as a bluestone wall with brick dressings, will need careful control of pre-wetting to ensure that the more-porous bricks get sufficient water while the less-porous bluestone gets enough, but not too much, dampening.

Pre-wetting is also needed when reconstructing walls. When bricks and stones are being reused or recycled from salvaged materials, it's essential to remove dust and mortar residues from their surfaces.

Building up a store of water in the wall has an additional purpose: that of providing a moist environment to improve the hardening or curing of the lime binder (see Chapter 24 'Protection and curing').

22 Repointing

The key messages about filling joints during repointing are:

- use a stiff, dryish yet still-workable mortar
- compact the mortar tightly into the joints
- use tools that fit snugly into the joints
- always fill any deep voids, working in stages
- fill inaccessible voids with grout
- never use backing rods, as they prevent joints from breathing
- if needed, use masking tape to keep the faces of narrow joints clean.

Repointing needs stiffer, drier mortars than those used for laying bricks and stones. Though stiff and with the consistency of modelling clay, the mortar should still be quite plastic and easy to work. A mix that is too wet will ooze out around the trowel or jointing tool and will not be compacted tightly into the joint. A wet mix also risks staining the face of the masonry, whereas crumbs from a dryish mix will not.

> Section 19.2 ‘Mixing’ explains how to deal with a mix that is too wet.

It should be apparent by now that the key ingredient of stiff, dryish yet plastic and workable mortar is lime, which ideally should be used as a sand-slaked quicklime mortar or in dense putty form for all repointing work. Where the nature of the work calls for the use of a natural hydraulic lime (NHL), the mix can be made more workable by adding 10% of putty. Further, the workability of an NHL (or composition) mortar can be improved by using the slurry drained from lime putty as the mixing water.

> See Chapter 14 ‘Workability’ and Section 19 ‘Batching, mixing and knocking up’

Due to its relatively low water content, pointing mortar must be compacted tightly into the joints to achieve a good bond with the masonry units on either side and with the bedding mortar at the back. This means having the right tools: caulking or finger trowels, as well as traditional pointing keys or jointing irons that fit snugly into the joints (see Figures 67, 68 and 69). Tools with blades of different widths will be needed to deal with the varying joint widths in a single building. Caulking trowels are made with blades about 150 mm long, but for perpends in brickwork they should be cut down to lengths of about 70 mm. The shorter the length, the greater the force that can be delivered to compact the mortar.

> Figure 6 also shows a range of jointing tools.

Plasterer’s small tools may be useful for repointing rubble stonework, where the joints are often wider. Triangular pointing trowels are not appropriate for this stage of repointing: they won’t fit into the joints and they can’t deliver the force required to ensure they are fully packed. Furthermore, their use can produce mortar smears over the surface.

Provided the correct tools are used, a stiff, dryish mortar can be placed into a joint without risk of staining the surface. This is because any crumbs or spills that sit on the surface won’t be pushed into it, and their dryness will mean that little or no lime will be transferred into the surface. For very narrow joints, masking the stones with tape on either side of the joint can help placing the mortar without staining the masonry. The problem of the masking tape not sticking to damp stonework may be overcome by thorough pre-wetting the day before, masking up the joints on the day then wetting again using sprayers with small nozzles that fit within the joints (see the previous Chapter).

There is no in-principle objection to using a caulking gun to inject mortars into joints. However, achieving the consistency required to enable the mortar to be pumped will generally mean using softer sands and wetter mixes than are appropriate for lime mortars. The injected mortar must still be tightly compacted using a caulking trowel, and this will mean waiting until some of the water is absorbed by the masonry.

The addition of polymer modifiers to allow a mortar to be pumped through a caulking gun will block pores and is not acceptable.

Deeply eroded joints will need to be filled in several stages, building up no more than 30 mm of mortar at a time and allowing at least three days for the previous stage to begin hardening. Pre-wet before each stage. Inaccessible, deep voids in thick walls may need to be grouted as part of the repairs. If so, this should be undertaken before the final stage of repointing.

Backing rods, of compressible foam that are inserted into joints, have become commonplace in construction and have an important role in the application of elastomeric sealants between granite and glass in modern buildings. Unfortunately, some people have used them to minimise the amount of repointing work required in traditional masonry. This is bad practice as it leaves potentially damaging voids behind the rods, reduces the adhesion of the pointing mortar and prevents the proper drying of the walls through the joints. **Backing rods should never be used when repointing traditionally constructed porous masonry.**

Traditional masonry, whether brick or stone, relies on the mortar joints being more permeable than the masonry units so that walls dry ('breathe') through the joints (see Figure 8).

Rubble stonework often has pinning stones in the wider joints (see Figures 60 and 72). These are small pieces of stone pushed into the mortar to compact it and reduce shrinkage. They will be loosened during the raking-out process, and should be removed, saved and reinstated during repointing. They should never be left out: it would be a mistake to think that they are not needed. The joints should be nearly filled flush and then the pinning stones pushed and tapped lightly into place in the still-damp mortar.

Maintaining the character of the wall requires reinstating any pinning stones.

Figure 67: Filling a bed joint. An 8 mm trowel is used to place a small amount of mortar at the back of the raked-out joint; this is repeated until the joint is filled. The mortar is tightly compacted into the joint and also back into the last-filled section. This means working from right to left for a right-hander and left to right for a left-hander.

Figure 68: Filling a narrow perpend. Using a 4 mm wide trowel to place a thin wedge of mortar into a narrow joint. Careful placement with this technique removes the need to mask the face of the bricks with adhesive tape.

Figure 69: Using a trowel as a hawk. Speeding up delivery of mortar to a bed joint by using a gauging trowel as a hawk. Provided the underside of the trowel is kept clean, there need be no mortar stains on the face of the brickwork. A plastering trowel can be used in the same way.

23 Finishing joints

The process of finishing the joints is as important as using the right mix and compacting it tightly into the back of the raked-out joints. Finishing gives the work its character and can also affect its durability. When repointing old walls, we may need to use techniques, such as tamping with stiff brushes, which are not used in contemporary work. Finishing involves:

- matching a previous joint profile
- compacting (but not overworking) the surface
- keeping new work damp with fine water sprays
- scraping off any excess mortar
- possibly tamping with a stiff-bristled brush
- more spraying to maintain damp conditions.

Joints should be slightly overfilled with the pointing mortar and then left to stiffen a little. Dampen the new work with a fine water spray as soon as possible after pointing. Provided the mix has been made to a stiff, dryish consistency, there will be no risk of lime washing down the face of the work unless excessive water pressure is used. If lime does run down the face, it's generally a sign the mix was too wet to begin with.

Reference panels of each pointing style should be established at the beginning of the project and used as a basis for accepting or rejecting work (see Chapter 27 'Specifying repointing').

After allowing the mortar to stiffen a little, apply the correct profile to the joint (see Section 18.5 'Matching joint profiles'). Here the use of a pointing trowel to apply flush and struck finishes is entirely appropriate. As Box 15 explains, it's important to respect traditional practice and not attempt to 'improve' walls by applying joint profiles they never had. This particularly applies to side and rear elevations, which were often finished with plain, flushed-up joints.

Compaction is an important part of finishing the joints, closing up the surface and reducing the risk of shrinkage cracking. However, overworking with the trowel should be avoided. Overworking brings too much binder to the surface and forms a smooth skin (laitance) which will slow hardening by reducing the permeability (or breathing capacity) of the surface. The smooth skin can be broken up by working over the joints with wooden tools (see Figure 6), which will raise the sand grains.

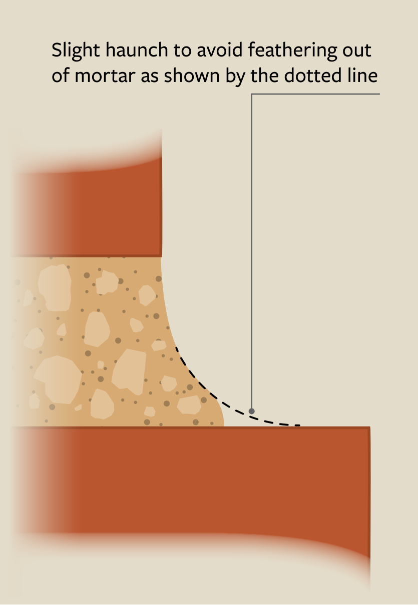

Figure 70: Avoiding feathered edges. To avoid feathering, finish the tail of a joint with a slight haunch, which can be shaped by tamping with a bundle of bristles.

Lightly scrape off any excess mortar with the side of a trowel or small tool. Use the small tool to trim mortar from holes in the face of the masonry units to avoid the appearance of variable joint widths, while ensuring that the finished profile won't encourage water penetration into the joint.

Never finish a joint with mortar thinly feathered out over the masonry units. Not only is it unsightly, it won't last as it won't harden well. The edges will open up and let water into the joint. Instead, where some water shedding is required (such as on string courses), finish the joint with a slight haunch as shown in Figure 70.

Keep the new mortar well dampened. As it begins to harden, the amount of water sprayed on each time can be increased, but take care not to disrupt the surface with excessive water or pressure.

23.1 Tamping

Tamping is the process of using a stiff-bristled brush (such as the churn brush in Figure 71) to strike the new mortar with the ends of the bristles. This is not a brushing or sweeping action, but a direct tamping of the surface: each bristle, acting like a stiletto heel, delivers considerable force. As a result, the mortar is compacted, reducing the risk of shrinkage cracking. Lime is removed from the top of some sand grains, exposing their colour and texture. Also, the surface area is increased, which together with the removal of the surface skin (laitance) will improve hardening and the breathing capacity of the joint.

Tamping produces an aged appearance (see Figures 71 and 72). It can be light or heavy, to suit the degree of ageing required when matching existing joints. While tamping has many benefits, it is not appropriate in all circumstances and the decision to tamp must be made in a considered way (see Chapter 18 'Repointing – key decisions'). Tamping is appropriate where small areas are being repointed to match existing joints that are slightly eroded. It is also appropriate in very old masonry where no evidence remains of the original joint finish. Clearly, tamping will not work on raised joint profiles, such as ribbon pointing and tuck pointing: tamping these would simply destroy them. Trials and reference panels should be used to resolve and agree on the extent of tamping (see Chapter 27 'Specifying repointing').

Joints are ready for tamping once the mortar has stiffened to the point where it is just possible to push a fingernail into them: this is sometimes described as 'leather hard'. This may take several days (or even a week) for pure lime mortars in cool, damp conditions, or just a few hours for stronger, hydraulic limes in warm weather. Timing is critical: too soon, when the mortar is too wet, and the brush will dimple the surface, pick up lime and spread it over the face of the masonry; too late, and the mortar will have hardened too much for tamping to be effective.

A variety of stiff-bristled brushes and similar tools can be used for tamping. These include the traditional churn brush (see Figure 71), cut-down sections of stiff brooms and small bundles of plastic bristles bound together. The latter can be used to shape the joint and cut away feathered edges (see Figure 70). Spray the new work with a fine water mist as soon as tamping is complete.

One method of producing an aged appearance that has unfortunately become prevalent on new building work is to cut off the top of an uncompacted joint with the edge of a trowel, let it dry and then clean it up with acid and a pressure wash. This can open up the joint, exposing a loosely bound mortar with poor durability, irrespective of the type of binder used. Using acid to clean up mortar spills may be warranted in some special circumstances, but it simply isn't needed if the quality of the repointing work is up to standard.

Figure 71: Tamping the joints. Tamping with a stiff-bristled brush (such as this churn brush) produces an aged appearance.

Figure 72: Tamped joints in rubble stonework. The tamped joints have a weathered or aged appearance with exposed sand grains. Without tamping, the colour would be that of the binder and finer sand grains. Also note the small pinning stones pushed into the mortar during repointing (see Chapter 22).

24 Protection and curing

All mortars including those based on cement, hydraulic lime and pure lime need attention to their curing if they are to perform as intended.

There is an erroneous perception among many in the industry that cement doesn't need curing, and this is often extended to composition mixes of cement and lime (compo). The result is that many mortars are not properly hardened and will have low durability.

> Section 13.2 'Composition mortars'

Very rapid drying may bring fines to the surface of the joint, producing a distinct skin (or crust) with reduced permeability, limiting further hardening.

Rapid drying of any mortar will lead to early failure. In the case of cement and any hydraulic component in limes, this is because they harden by reacting with water. Insufficient water will lead to the formation of weak shells (like eggshells) of hardened material surrounding uncured cement or lime, which may react only very slowly or not at all. A similar situation applies to the non-hydraulic component in limes, but here the reason is that water must be present for carbon dioxide to react with the lime.

> Section 5.6 'Setting of lime mortars'

Newly repointed lime mortars that fail within 12 months of placement, exposing friable mortar beneath a thin surface skin, are generally a sign of poor curing, though their failure may also be due to the presence of salts in the masonry.

Limes harden much more slowly than cements and depend more on good curing conditions being maintained. This applies equally to pure limes and hydraulic limes. It is wrong to think that using pozzolans or natural hydraulic limes negates or reduces the need for good curing.

Good curing practice includes:

- protecting work from adverse weather (wind, rain, heat and frost)
- tight enclosure of scaffolds, with misting systems in warm weather
- staging works around a building, to avoid hot sun on new work
- keeping new mortars quite damp for a week (wetting)
- a second week of 'dry' (but damp) curing
- a third week of thorough wetting
- a fourth week of damp 'drying'

> Cyclic wetting and drying improves hardening, see Section 5.6 'Setting of lime mortars'

24.1 Protecting work

New work should be protected from adverse weather conditions from the pre-wetting stage until at least four weeks after repointing. Scaffolds should be tightly enclosed to prevent direct rain strike and rapid drying due to wind. Hot-weather work (over 30°C) should be avoided, but as this is not always practicable, measures (such as intermittent mist-spraying systems) may be needed to maintain humidity. Specifiers should identify the need for such systems in tender documents whenever alternatives are impractical.

Cover all your walls in the summer-time to keep them from drying too hastily, for the mortar doth not cement so strongly to the bricks when it dries hastily, as when slowly.

Be sure to cover them well in the winter-time, to preserve them from rain, snow and frost, which last is a great enemy to all kinds of mortar, especially to that which hath taken wet just before the frost.

Moxon, 1703

In cold weather, work should stop when the temperature risks going below 5°C. This is because hydration ceases and the expansive force of frost will damage new mortar that is still wet and not yet sufficiently hardened. Providing heated scaffolds or enclosures around the work site is an alternative to having to stop work in cold conditions.

For ground-level projects where scaffolding is not required, the new work should be protected with removalists' blankets or carpet hung on simple frames that can be laid close to (but not directly against) the wall. Hessian sheeting is often used, but unless there are many layers which are protected by an outer layer of plastic, the hessian will dry too rapidly to provide effective curing conditions. Frames should be easily pulled back to allow the wall to be sprayed. Other methods of keeping new work damp include using timer-controlled soaker hoses on top of copings and some means of dispersing the water, such as sheets of geofabric.

Where possible, work should be staged around a building to avoid hot sun. Repointing may be best done in the late afternoon, allowing the cool of the evening to provide better curing conditions when rapid drying is less likely. **It's important to continue providing protection overnight and particularly on weekends. Repointing late on a Friday with no attention paid to curing until the Monday morning is not acceptable.**

To avoid the work involved in protection and curing being overlooked or underestimated, the cost should be a separate item on the tender form. This will enable it to be assessed separately when tenders are evaluated.

> See Chapter 27 'Specifying repointing'

24.2 Curing procedure

1. Wetting

Keep mortars quite damp for a week after placing them. Use fine water sprays many times a day and keep blanket or carpet covers damp at all times. Maintain a minimum relative humidity (RH) against the walls of 90%. During this period any hydration reactions are occurring, and the water in the mix is absorbing carbon dioxide for later combination with lime.

Adding water is necessary to make up for that lost to the suction of the adjacent masonry and to evaporation.

2. 'Drying'

Provide a week of protected 'drying'. Rather than totally dry, the aim is to maintain 60–70% RH against the walls. Providing protection against wind and rain may be all that is required in cool, humid weather. However, in the warmer and drier months, extra moisture will be needed, ideally supplied by timer-controlled misting systems. In addition, walls should be lightly sprayed daily: this should be done around midday and again later in the day when the walls are 'breathing in'.

Smartphone weather apps can be used to monitor local humidities and adjust timing of additional spraying.

3. Further wetting

Wet the walls again for a week. Rather than maintaining continuous dampness, this week-long period can be undertaken as a series of thorough wetting events, three or more times a day, with the background humidity being maintained at 60–70% RH as before.

4. Further 'drying'

Maintain the same conditions as in stage 2 for a further week.

This four-week curing period should be the minimum for most projects. Any proposal for a shorter period must be substantiated with evidence (such as climate data) and not just assumed.

Curing may need to be extended during cold weather to offset slower hydraulic reactions.

Improved results can be achieved by further cycles of wetting and drying, which should be considered for projects where the climate will not assist the curing process. These include exposed locations such as chimneys, towers and spires, coastal environments where strong winds will dry mortars too quickly, and most other sites during hot, dry weather.

If not proceeding with further cycles of wetting and drying, at least wet the walls thoroughly several times as enclosures and scaffolding are being removed.

25 Using lean or sacrificial mixes

Lean mixes are those where the proportion of binder is less than the normal mix, as determined by the properties of the sand, such as void ratio, grain shape and size. For example, 1:3.5 or 1:4 are lean mixes compared to a normal 1:3; or 1:3 would be a lean mix when a normal mix is 1:2 because of a fine-grained sand and a high void ratio. By contrast, a rich mix has a greater proportion of binder than a normal mix. Sacrificial mixes are made deliberately lean to reduce their strength and increase their permeability, the latter to promote good breathing through the mortar joints.

With normal mixes, the aim is to completely fill the voids in the sand with binder. Additionally, fine-grained sands require extra binder to ensure complete coating of all particles (see Chapter 9, in particular Section 9.6 ‘Void ratio and its impact on mixes’).

When lean mixes (whether deliberate or unintentional) are used on porous bricks or stones, the mortar will stiffen rapidly and ‘go dead’ (i.e. be difficult to work). This stiffening is not due to any chemical reaction but to the loss of the mixing water due to the suction of the masonry and the poor water retentivity of the lean mix (see Section 14.2 ‘Water retentivity’). Where a particularly permeable (i.e. sacrificial) mix was not intended, the mix should be corrected by adding more binder up to at least the proportions suggested by the void ratio of the sand. This will make the mortar workable for a much longer period after being placed on or in the porous masonry. The richer mortar will stiffen and harden more slowly, but it will if properly cured produce a stronger mortar.

Thorough pre-wetting is essential to minimising the suction of porous masonry.

Delaying the stiffening will mean that any tamping will have to be delayed by up to several days, depending on the change of proportions and the weather conditions. However, this may be beneficial if working on a large area where there is a need to complete all the repointing before tamping.

> See Chapter 23 ‘Finishing joints’

Where the circumstances call for a deliberately lean sacrificial mortar, ways of improving its workability include using air-entraining and water-retaining agents. Air-entraining agents will improve the plasticity (‘spreadability’) of the mix. Water-retainers (water thickeners) will slow the rate at which a porous substrate will draw water from the mix, prolonging the working time after it has been applied.

> See Chapter 14 ‘Workability’ and Section 11.1 ‘Plasticisers, air-entrainers, water-retainers’

It is essential that admixtures such as air-entraining and water-retaining agents are not overused as they can severely reduce bond strengths.

When using lime putty as the binder, it’s important to use only stiff material that has been drained of excess water: only then will it contain sufficient lime to make a sound mortar. A putty that is too wet will produce a lean mix which may initially feel workable, but when applied to a porous substrate will stiffen rapidly as the water is lost.

> See Section 5.4 ‘Densities of lime putties and hydrated limes’, Section 14.2 ‘Water retentivity’, Section 19.1 ‘Batching’ and Section 19.2 ‘Mixing’

Avoiding problems with unintentionally lean mixes requires:

- measuring the void ratio of the sand to determine mix proportions
- adjusting mix proportions to account for finer-grained sands
- draining lime putties and only using stiff material
- taking account of bulking when using dry, powdered materials.

> See Section 5.4 ‘Densities of lime putties and hydrated limes’ and Chapter 19 ‘Batching, mixing and knocking up’

All lean mixes require particular attention to pre-wetting and curing: rapid drying on porous substrates risks premature failure as hardening reactions (carbonation and hydration) cease due to lack of water.

26 Deep repointing

There will be occasions where mortar loss has exceeded the 20–30 mm depths commonly associated with repointing. These might be caused by:

- salt attack and rising damp (salt damp) at the base of walls (see Figure 75)
- falling or penetrating damp that has dissolved lime and flushed mortar out of joints and out of the cores of thick walls (see Figure 76)
- the burrowing action of lizards and ants, wasps and other insects.

Repairing walls in these situations will commonly need deep repointing, also known as deep packing.

Grouting may also be required, but it is outside the scope of this guide.

There are other circumstances when deep repointing may be required to weatherproof a wall as well as to regain its structural integrity. A defect that often produces leaky walls is the lack of mortar across the full depth of perpend or cross joints. Poor construction practice often saw only 20–30 mm of mortar near the face of the brick, with voids behind. Even when filled, cross joints are more vulnerable to erosion because they were often not tightly compacted: the weight of the masonry units compacts the bed joints, but extra effort is required to fully compact the perpends.

Another not-so-obvious problem sometimes occurs in composite solid walls where a stone facing has a backing of brickwork. This is particularly the case in buildings of the 1920s to 1960s, when cement mortars were used. Brick growth may produce a slight expansion in the brickwork, sufficient to relieve much of the vertical load from the stones and leave hairline cracks at every second horizontal joint (see Figure 73). Deep repointing of the whole building may be required. Brick growth may not be apparent in walls made with elastic lime mortars, because they can accommodate the expansion.

The task with deeply raked joints is to place and tightly pack mortar into the back of the joints. This is done with tools including steel tampers (see Figure 74) and pieces of wood. Because of their weight, steel tampers can provide considerable force, and care is required to avoid breaking the remaining bond with the adjacent masonry.

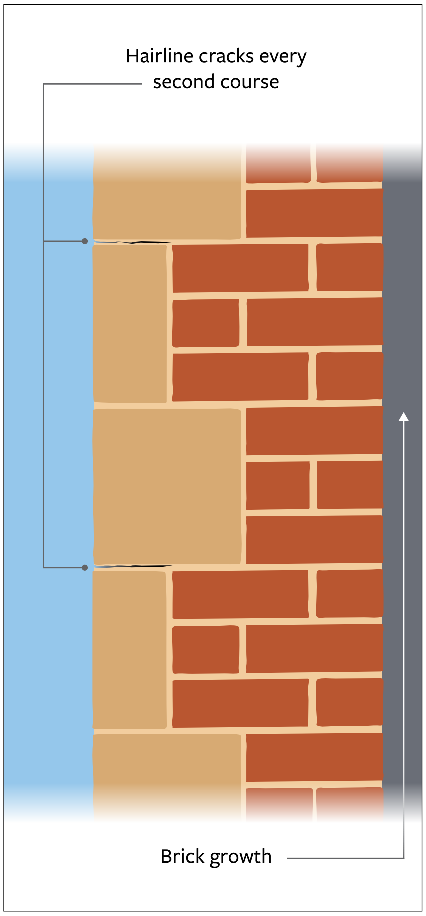

Figure 73: Brick growth. In this sectional view of a composite wall, brick growth has lifted the stones, producing a hairline crack at every second bed joint.

Figure 74: Steel tamping or deep-packing tools. While the aim is tightly compacted mortar, tamping with these heavy, purpose-made tools needs to be done with care, as too much force will break the bond of the remaining joint. Other packing devices include pieces of wood or plywood for narrow joints. Mortars must be relatively dry and stiff if they are to take up the load of overlying masonry and weatherproof the wall. The outer part of the joint is finished in the way described in the previous chapters.

Deep joints should be filled in layers of no more than 30 mm at a time, and at least three days allowed for initial hardening of lime mortars before applying more. Pre-wet between layers and provide protection and good curing conditions (see Chapter 24 'Protection and curing'). Because of the slow carbonation of lime in deep joints, it may be appropriate to include a pozzolan (or use a natural hydraulic lime) in the mortar. This will depend on compatibility with the masonry units.

> See Section 13.5 'Choosing the right mix – compatibility' and Section 18.4 'Ensuring compatibility'

Where salt attack and rising damp (salt damp) has eroded so much mortar that bricks or stones are barely supported (see Figure 75), the repair technique known as undersetting may be required. Undersetting involves the progressive removal of sections of masonry from the base of the wall and their reconstruction with salt-free materials, together with the insertion of a new damp-proof course. This is explained in more detail in the technical guide *Salt attack and rising damp: a guide to salt damp in historic and older buildings*, which is published in the same series as this guide.

When undersetting an old wall with a cement-and-lime composition mix, always repoint the joints in a lime mortar, to minimise thermal expansion stresses on the surfaces of the bricks or stones.

Figure 75: Mortar loss due to salt damp. Salt attack and rising damp has deeply eroded the lime mortar joints at the base of the wall. Deep packing will be needed for the first stages of repointing to fill the joints in this solid wall. Had the wall been of cavity construction, the extent of mortar loss may have been too great to enable successful repointing, and undersetting of the outer leaf may have been required.

Figure 76: Mortar loss due to dissolution. An 1830s sandstone retaining wall in which water percolating through the joints has dissolved much of the lime, with some of it redeposited at the face of the joints, as seen here. The dental probe on the right was inserted 40 mm into the joint without meeting resistance. Raking out and deep packing of the joints will be required to partially reinstate the wall's structural integrity. Similar work is likely to be required on the other (buried) side of the wall.

27 Specifying repointing

Specifications for repointing should be appropriate to the scale and importance of the job. Small, domestic-scale repointing may warrant only a brief statement of the materials and mixes to be used and the various work methods to be employed, including how the new work is to be protected and properly cured. Larger projects and work on places of heritage significance should have comprehensive specifications for a range of works across the site. Such specifications should deal with the following aspects of repointing.

1. Materials

- the materials to be used, such as lime, sand, pozzolan and pigment
- the properties of the materials, such as age and density of lime putty; class of NHL; size grading, fines content and surface texture of sand
- additional materials, such as crushed porous limestone, fillers and admixtures
- the alternatives that are acceptable, and in what circumstances
- preferred suppliers and quality control procedures.

2. Mixes and batching

- what mix proportions are to be used, for what part of the site
- whether additional mixes are to be prepared for the trials (see '10. Trials, samples, reference panels' following)
- whether full bags are to be used for dry ingredients
- initial weighing to ensure correct quantities when dry batching
- whether sands are to be dry or, if damp, the procedure to be used to account for bulking
- the use of separate containers specifically for batching
- special requirements (e.g. a record or logging system) to manage the use of admixtures, to ensure they are used in the correct amounts
- whether batching is to be done wet or dry and the procedures for the addition of dry materials (e.g. admixtures or pigments) to a wet mix.

3. Mixing and knocking up

- whether premixing and maturing is required and for what period
- what mixing equipment is to be used and for how long
- if hand mixing, the method(s) to be employed
- requirements for on-site storage of prepared mixes
- acceptable knocking up or reworking procedures
- procedures for adding hydraulic components and admixtures
- flexibility (within limits) for the operator to adjust the mix for workability
- controls on retempering of mixes containing cement.

4. Raking and cutting out old mortar

- the depth to which joints are to be raked or cut out
- tools to be used and not used
- the shape and cleanliness of raked- or cut-out joints
- flushing-out of debris from joints and prevention of fine-particle stains.

5. Pre-wetting

- requirements for pre-wetting walls to control suction
- acceptable methods of pre-wetting
- frequency and timing of pre-wetting.

6. Repointing

- tools to be used for placing and compacting mortar
- the method to be used, building up in layers for deeper repointing
- use of any tape for masking the surface of the masonry.

7. Finishing the joints

- joint profile(s) to be matched
- the method of finishing joints
- the degree of tamping and tools to be used
- any prohibition of the use of acid for cleaning up
- any provision for the use of acid in specially approved circumstances.

8. Protection and curing

- protection methods and the period of protection from adverse weather
- unacceptable weather conditions for repointing and curing
- recording of temperature and humidity during works and curing
- a week-long period of wetting (very damp) curing after placement
- a week-long period of damp drying during which protection is to remain and relative humidity maintained within acceptable limits
- whether additional spraying will be required during damp drying
- requirements for subsequent week-long cycles of wetting and drying
- separate listing of costs of protection and curing on tender forms.

9. Site practices

- storage of materials (off the ground, kept dry and protected)
- general site management (e.g. dust control)
- protection of the building and occupants.

10. Trials, samples, reference panels

- sample biscuits of different mixes and aggregates
- schedule of trials, mixes and workability
- reference panels or sample areas, to be retained during job
- at least one sample for each style of pointing
- testing if required of properties such as density and entrained air
- acceptance of trial samples as minimum standards to be met
- retention of a section of existing/original mortar as evidence.

11. Compliance

- frequency and role of site inspections
- what tests will be used to assess compliance
- responsibility for testing
- test procedures and approved laboratories
- how non-compliant works are to be dealt with (e.g. replacement of all repointing since the previous inspection)
- certification of compliance.

12. Training

- induction and training requirements for contractors
- minimum proportion of trained workers to be maintained on-site throughout the duration of the works.

28 Conclusion

The last three decades have seen extensive international laboratory research and field trials on most aspects of traditional mortars including work on lime putties, sand-slaked quicklime mixes, natural hydraulic limes and pozzolans. Chapter 30 'Further reading' includes some of the key historical sources, technical guides, research papers and conference proceedings that document our continually evolving understanding of the field.

Among the principal insights are that:

- traditional masonry walls need to breathe and to do so through permeable mortars
- Portland cement blocks pores and restricts the breathing of mortars, plasters and renders
- the availability of suitable pozzolans and natural hydraulic limes removes the need to use any cement when repairing lime mortars
- sands should be clean, sharp and well graded: this is not new, but it is often not contemporary practice
- using clayey sands (or worse, adding clay) to improve workability is bad practice: it significantly reduces bond strength, durability and the breathing capacity of mortars
- plasticising, air-entraining and water-retaining admixtures can improve the working characteristics and durability of some lime mortars
- porous particles in the aggregate can help retain water during placement and improve carbonation and breathing characteristics
- partly because of like bonding to like, crushed limestone aggregates produce stronger mortars than those made from crushed sandstones
- using ground limestone or marble fillers can improve size grading of some sands and promote hardening of lime mortars
- prolonged maturation of lime putties improves workability, while maturing mortar mixes improves their workability and strength
- good practice with non-hydraulic limes (including putties and sand-slaked quicklime mixes) can make excellent, durable materials
- porous masonry must be thoroughly pre-wetted and mortars well cured if they are to perform as intended.

As well as the heritage principle of replacing like with like, there are good performance reasons why lime mortars should be used to repair older buildings. These relate to their compatibility with the adjacent masonry and the need for walls to work as systems and not just as piles of stones or bricks.

There is still much to learn about traditional lime practice and about the properties of the available materials. There is even more to be done passing on what is known to those who use it. The need for training extends across the industry, from specifiers to estimators, project managers, builders, contractors and tradespeople. Making the substantial changes that are needed will require a new level of understanding and engagement from all those involved in the process. Relearning and maintaining traditional trade skills will be a key challenge in the face of the incessant tide of modern practice with its quick-fix approach, which is so damaging to traditionally constructed buildings.

29 Glossary

admixture	A substance, not including aggregate, binder or pozzolan, added to a mortar mix to modify its properties. For example see *air-entraining agent*.
aggregate	Hard, inert, granular material used as a filler in mortars and concrete: coarse aggregate = gravel; fine aggregate = sand. It includes natural sand, sand produced by further crushing of coarse aggregate, crushed brick and stone, and ground mineral filler.
agricultural lime	Ground limestone used to sweeten acidic soils. It has no binding power and cannot be used for mortars, except as a filler.
air-entraining agent	Admixture for mortars to improve their durability, workability and the rate of carbonation of lime mortars by increasing porosity. Air-entrainers can be used to partly overcome poor size grading of some sands, particularly those with insufficient very fine sand-sized particles.
air lime	Non-hydraulic or pure lime. A lime that hardens by reacting with carbon dioxide in the air (carbonation). See also *water lime*.
air-slaking	Slaking of quicklime due to the absorption of moisture from humid air. It is accompanied by some carbonation and hence loss of binding power.
alkali-stable pigment	Pigment that is stable in the alkaline conditions found in lime and cement mortars and concretes.
alumina	Aluminium oxide: Al_2O_3. In this context, it is generally found in combination with silica as aluminosilicates in clays and in pozzolans.
aluminosilicates	Silicate minerals containing alumina, as in many clay minerals.
amorphous silica	A glassy, non-crystalline form of silica that can be a reactive pozzolan.
argillaceous	Rocks or sediments consisting of or containing clay.
artificial cement	Cement (e.g. Portland cement) made from several raw materials that are blended together. An old term, contrasting with natural cement.
arris	An edge produced by the meeting of two surfaces on a brick or stone.
ashlar masonry	Stone masonry dressed to fine tolerances and regular shapes and laid with narrow (nominal 3 mm) mortar joints.
autogenous healing	The capacity of lime mortars to self-heal across small cracks, as a result of dissolution and recrystallisation of some calcium carbonate binder.
batching	Proportioning the constituent materials for a mortar mix.
bedding mortar	Mortar used for laying masonry units (such as bricks, blocks, stones and terracotta). See also *pointing mortar*.
bed joint	A horizontal joint on which masonry units are bedded in mortar.
binder	Materials, such as limes and cements, used in powder, paste or putty form, which harden to hold the aggregate particles together and bind to the masonry units.
blended cement	A composite cement containing Portland cement and pozzolanic additions, such as fly ash or GGBFS.
blue mortar	Dark-coloured pointing mortar made from lime and sand (or used foundry sand) charcoal, ashes and pigments (such as lampblack).
breathability	See *breathing (of walls)*, *permeability* and *vapour permeability*.
breathing (of walls)	The exchange of air and water vapour between permeable masonry materials and the atmosphere, due to changes in temperature and air pressure.

brick growth	The long-term, permanent expansion of some clay bricks due to the absorption of moisture onto and into clay minerals in the bricks. It may lead to cracking of masonry with hard mortars.
bricklaying sand	Sand that is commonly fine grained and often contains clay, which is used because it improves workability of cement mortars. 'Brickies sand'.
builder's lime	See *hydrated lime*.
burning (limestone)	The calcining of limestone in a kiln to make quicklime. The word burning, though commonly used, is technically incorrect because limestone does not burn.
calcining	Heating, firing or roasting at high temperatures.
calcium carbonate	The chemical name for the mineral calcite, $CaCO_3$, which is commonly found in nature as limestone, marble, chalk, coral or seashells.
calcium hydroxide	The chemical name for slaked or hydrated lime: $Ca(OH)_2$. Commonly described as lime, it is the product of slaking quicklime with water.
calcium lime	Limes consisting mainly of calcium oxide or calcium hydroxide. EN 459 uses the designation CL. See also *dolomitic lime* and *high-calcium lime*.
calcium oxide	The chemical name for quicklime: CaO.
carbonates	Minerals, such as calcite and dolomite, which contain carbon and oxygen and other elements, such as calcium and magnesium.
carbonation	The hardening of calcium hydroxide (lime) by the absorption of carbon dioxide from the air (in the presence of water) to form calcium carbonate. The term is used in the concrete industry for the formation of calcium carbonate by carbonation of free lime in cement paste, and also for the alteration of silicate minerals to carbonate minerals.
cement	A binder that consists only of hydraulic materials, unlike hydraulic limes. Cement can be natural or artificial, the latter including Portland cement. Cements harden by reacting with water (hydration).
Cementation Index	An index for classifying hydraulic limes and cements, based on the proportions and hydraulicity of their chemical components.
clinker (cement)	The hard, stony, fused product of calcining cement raw materials, which is then finely ground to make it reactive.
coarse stuff	Lime and (generally coarse) sand mixed together as a mortar for masonry, or as a material for the first coats of plaster. See also *fine stuff*.
cohesive (mortar)	A cohesive mortar will adhere to itself, or 'hang together', and not separate into its constituent parts while it is being placed.
coke breeze	Waste product from coal gas ovens used in lightweight concretes and building blocks. Cinders and charcoal were used similarly.
compatible (mortar)	A compatible mortar will have physical properties (such as strength, elasticity, porosity and permeability) that are appropriate for the adjacent masonry. Its compressive strength should be lower, while elasticity, porosity and permeability should be higher than those of the adjacent masonry units.
composition mortar	A mortar in which the binder is a composition of cement and lime: 'compo'.
consistency	The thickness or viscosity of a fresh mortar, due to the nature of its constituents (such as lime, cement and sand) and its water content.
copperas	Green, ferrous iron sulfate (green vitriol) used as a colouring agent in limewash and colourwash. It turns yellow-orange as it oxidises on exposure to air.
curing	The process of ensuring (by maintaining appropriate moisture and temperature conditions) the chemical hardening of a binder (such as lime or cement) to form a solid material.

cutting out	Removing mortar from the face of a joint that is too hard to be raked out and must be cut out with sharp chisels and/or mechanical tools.
damp-proof course (DPC)	A layer of impervious material (e.g. polyethylene) built into a wall to prevent the upward migration of water. Also called a dampcourse. Remedial damp-proofing may include chemical DPCs.
deep packing	Packing mortar into deeply eroded joints by tamping with purpose-made tools.
desalination	The removal of salt, in this case from masonry materials.
dolomitic lime	Lime made from a magnesian limestone or dolomite. In addition to calcium hydroxide, it contains a significant proportion of magnesium hydroxide: $Mg(OH)_2$. EN 459 uses the designation DL.
dry-slaking	Slaking quicklime in sand with a minimum of water. See also *sand-slaking*.
durability	The ability of materials to withstand the action of the weather over an extended period. Durability is not necessarily related to strength.
efflorescence	The crystallisation of white, powdery salts on the surface of masonry.
elastomeric sealant	Elastic polymers (commonly known as mastics): viscous liquids that cure to become an elastic, sealing compound. They are widely used in modern construction.
extreme dryness	As dry as a lime-burner's boot.
fat lime	Pure, non-hydraulic lime, which is also called high-calcium lime and pure lime. See also *lean lime*.
fines	The portion of aggregate that passes through a 75 µm sieve. Fines consist of clays and silts.
fine stuff	Lime and fine sand mixed together, generally for the final (setting) coat of lime plasters. Also known as 'setting stuff'. See also *coarse stuff*.
fly ash	Fine, glassy ash, a by-product from burning pulverised coal. Highly siliceous, it is a reactive pozzolan and used in blended cements.
formulated lime	A term used in EN 459 for a hydraulic lime mainly consisting of air lime and/or natural hydraulic lime with added hydraulic and/or pozzolanic material. EN 459 uses the designation FL.
gauging	Measuring mortar materials in the correct proportions, traditionally by using gauge boxes. See also *batching*. Also, adding cement or pozzolan to a pre-mixed lime mortar, hence the term 'gauged with cement'.
'go dead'	When a mortar loses its plasticity and becomes difficult to work.
granulometry	Particle or grain size distribution. See also *size grading of sand*.
ground granulated blast-furnace slag (GGBFS)	Glassy, siliceous slag is a by-product of smelting ores in blast furnaces. When finely ground, it is a reactive pozzolan and is used in blended cements. It is also written as GGBS and as ground slag. See also *latent hydraulic cement*.
ground slag	Short form of ground granulated blast-furnace slag.
hard-burnt quicklime	Quicklime produced by burning at higher temperatures than needed. It slakes slowly and is less reactive than soft-burnt quicklime.
hardening	The chemical hardening of a binder (such as lime or cement) to form a solid material. It follows stiffening. See also *setting*.
high-calcium lime	Pure lime. Quicklime or hydrated lime containing at least 80% available lime as CaO or $Ca(OH)_2$ respectively. EN 459 uses the designation CL 90.
hot lime mortar	Mortar made by slaking quicklime in conjunction with the sand, which is then used while still hot or warm. See also *hot-mixing* and *sand-slaking*.
hot-mixing	Making mortar by slaking quicklime with the sand, resulting in a hot mix. The terms sand-slaking and hot lime mortar distinguish between those mortars that are used cold after a period of maturing and those that are used while still hot or warm from the slaking process.

hydrated lime	Calcium hydroxide: $Ca(OH)_2$. The result of combining quicklime with water to produce either a wet hydrate (putty) or a dry hydrate (powder). The term is normally used for the dry powder form. It is also known as builder's lime. See also *hydration*.
hydration	A reaction resulting in combination with water. It applies to quicklime, which reacts to become hydrated lime, and to hydraulic limes and cements which harden by reacting with water to form hydrates.
hydraulic cement	A binder that hardens by reacting with the mixing water. Portland cement is the main hydraulic cement used in modern construction.
Hydraulic Index	An index for classifying hydraulic limes and cements, based on the proportions of their chemical components. See also *Cementation Index*.
hydraulic lime	A lime that hardens partly by reacting with water (hydration), and so can harden underwater. Hydraulic limes contain silicates (and aluminates), which harden by hydration and calcium hydroxide, which hardens by carbonation. See also *natural hydraulic lime*.
hydraulicity	The degree of hydraulic reaction (i.e. with water) of a lime or cement.
hydrophobic	Materials that are water repellent.
hygroscopic	Materials (such as salts) that absorb moisture from the air.
initial rate of absorption (IRA)	A measure of the suction of porous masonry units.
jointing	The process of laying masonry and finishing the mortar joints in one operation with a single bedding mortar. See also *pointing*.
knocking up	Making a stored (matured) lime mortar workable by repeated beating and chopping – in traditional practice – or by further mixing in an appropriate mechanical mixer. It is also called reworking.
laitance	A milky skin of binder and fines that is brought to the surface of a mortar joint by the action of trowelling. Overworking thickens the laitance and reduces the permeability of the joint surface.
latent hydraulic cement	Materials (such as GGBFS and some high-lime fly ashes) that have a slow hydraulic set but which require an activator (such as lime) to produce a hydraulic reaction sufficient to make satisfactory binders.
larry	A mason's hoe, used for mixing mortars.
lean lime	Non-hydraulic lime containing appreciable inert impurities. Lean limes are not common today, as most non-hydraulic limes are relatively pure. See also *fat lime*.
lean mix	A mortar mix in which the proportion of binder is less than normal. See also *rich mix*.
lime	Confusingly, a term used for quicklime (calcium oxide), for slaked or hydrated lime (calcium hydroxide) and for hydraulic limes. References to lime in most nineteenth- and early-twentieth-century specifications mean quicklime. The term is also loosely used for other calcium compounds.
lime cycle	The three stages of burning, slaking and hardening of lime that form a complete cycle, which begins and ends with calcium carbonate.
lime putty	A putty of calcium hydroxide, $Ca(OH)_2$, made by slaking quicklime in water and allowing it to settle out until it is stiff enough to retain its shape without slumping. It can also be made by soaking dry hydrated lime.
lime slurry	Midway between lime putty and milk of lime, lime slurry has the consistency of cream and will flow like a viscous liquid.
limestone	A sedimentary rock consisting mainly of calcium carbonate: $CaCO_3$. It is the principal raw material of lime and cement binders.

limewash	A coating material produced by thinning lime putty with water to a thin, milk-like consistency. It may include additives and pigments.
limewater	A solution of lime in water, the clear liquid above a settled lime putty. It is used as a consolidant for weak bricks, limestone, mortar and plaster.
loamy sand	A soft sand containing clay, silt and humic (soil) material.
low-alkali cement	Portland cement that contains low proportions of the alkalis, sodium and potassium, in order to avoid alkali-silica reactions with aggregates.
masonry	Clay bricks, concrete bricks or blocks, stone and terracotta (the masonry units) laid in mortar to form walls or other structures.
masonry cement	Cementitious material for use in mortars for masonry construction, containing Portland cement with fillers and plasticisers or air-entraining agents to improve workability.
mason's putty	An Australian term for a putty-like mortar made with lime putty, whiting, linseed oil and very fine sand (which is sometimes omitted). It is used in narrow-jointed ashlar masonry. It is also known as oil putty.
mastic	Waterproof, flexible sealant used in building applications. See also *elastomeric sealant*.
matrix	The fine material in a mortar, including the binder and any pozzolan.
maturing	The ageing of lime putty, leading to finer particle sizes and greater workability. Like wine, you need to start with good material. It also applies to lime mortars which improve with maturing before use.
milk of lime	Lime putty thinned with water to a milk-like consistency. See also *limewash*.
mineralogy	The scientific study of minerals.
mortar	Any material that in wet, paste form can be used to lay masonry or make plasters and renders, and which then stiffens and hardens. It applies to clay-bound materials as well as those bound with limes or cement. Mortars generally consist of binder and aggregate.
mud	Colloquial term for mortar.
natural cement	Hydraulic cement made from a single, natural, raw material, commonly an argillaceous limestone. It hardens rapidly due to its calcium aluminate components. It is also known as Roman cement.
natural hydraulic lime (NHL)	Hydraulic lime made by calcining impure limestone that naturally contains silica or aluminosilicates in suitable proportions, without any additions. EN 459 uses the designation NHL.
non-hydraulic lime	Relatively pure limes including lime putty and hydrated lime that harden by reacting with carbon dioxide in the air (carbonation) rather than with water. Air lime, fat lime and high-calcium lime are alternative terms for pure or non-hydraulic lime.
pencilling (brickwork)	The use of a thin paintbrush, known as a pencil, to paint the ruled line (or other surface) of a joint in white or black to contrast with the jointing or pointing mortar.
permeability	The property of a porous material that allows gas (such as water vapour) and liquids (such as water) to pass through it. Permeable materials breathe; impermeable materials don't.
perpend	A perpendicular, vertical or cross joint in masonry, often shortened to 'perp'. See also *bed joint*.
pinning stones	Small pieces of stone that are 'pinned' into wide joints in rubble stonework to compact the mortar and reduce shrinkage.
plaster	A mortar applied to walls and ceilings in a plastic state and which later hardens. External plasters are commonly known as renders.
plaster setting coat	The thin, finishing coat of internal plasters. It was made of lime putty and fine sand (fine stuff or setting stuff) in early buildings and later of mixtures of lime putty and plaster of Paris (gypsum plaster).

plasticiser	An admixture for mortars and concretes, used to improve workability and to reduce the required water content. Superplasticisers are used to promote flow in grouts and in pumped concrete.
plasticity	The 'spreadability' of a fresh mortar while being worked with a trowel. Plasticity is determined by the nature and proportion of the constituents (binder, aggregate and any admixture). Plasticity is a key element of workability.
pointing	Finishing a mortar joint by raking out some of the bedding mortar and inserting a separate pointing mortar. See also *jointing*.
pointing mortar	Mortar used to finish joints by pointing. It may differ from the bedding mortar in its materials, mix proportions, colour and durability.
poorly graded sand	A sand that has a uniform grain size or a narrow range of grain sizes. See also *well-graded sand* and *size grading of sand*.
porosity	The void (or pore) space in a material, expressed as a percentage.
porous aggregates	Crushed porous bricks or stones added to mortars in place of some of the sand to increase their porosity. They are also known as porous particulates.
Portland cement	A hydraulic cement produced by calcining a blend of raw materials including limestone and clay or weathered shale. The resulting clinker is ground with gypsum to prevent rapid hardening.
pozzolan	Fine-grained, glassy materials containing reactive silica and often alumina that have no binding power of their own but combine with pure lime to make binders that are similar to hydraulic limes.
pozzuolana	Volcanic ash, pumice and related material from Pozzuoli, Italy. It was used by the Romans in their mortars and concretes, hence the origin of the term pozzolan.
pre-wetting	Wetting walls prior to repointing to control, or 'kill', their suction, so that mortars do not dry out prematurely.
pure lime	Lime made from relatively pure limestone, resulting in a non-hydraulic, high-calcium lime. Pure limes are also known as fat limes or air limes.
putty	See *lime putty* and *mason's putty*.
quicklime	Calcium oxide, CaO, produced by calcining (burning) limestone, marble, chalk, coral or shells. It is also known as rock lime or lump lime.
quicklime mortar	Mortar made directly from quicklime by sand-slaking (hot-mixing).
raking out	Removing mortar from the surface of a joint, using a raker or other tools, to enable pointing or repointing. See also *cutting out*.
render	A mortar applied to external walls in a plastic state that hardens as it dries. The term is also used for the first coat of plasters on masonry. See also *stucco*.
repointing	Replacing the outer part of a mortar joint in masonry, which may have been originally jointed or pointed.
retempering	The bad practice of adding water and remixing to again make workable a cement or composition mortar that is beginning to harden.
reworking	Making a matured lime mortar workable again by a period of further mixing. It is also called knocking up.
rich mix	A mortar mix in which the proportion of binder is greater than normal. See also *lean mix*.
rising damp	The upward migration of water in masonry due to capillary suction. It is often the medium for transporting soluble salts into walls.
Roman cement	The trade name of a nineteenth-century English natural cement with a distinctive brown colour, which was used in Australia. The term Roman cement is now used more widely to mean natural cement.

sacrificial mortar	A mortar designed to fail in preference to the adjacent masonry, and so protect it. A sacrificial mortar will be significantly more porous and permeable, and of lower strength than the masonry units.
salt attack	The progressive decay of masonry materials due to cyclic crystallisation or hydration of soluble salts within the pores of the material.
salt damp	A term originating in South Australia that neatly combines the two discrete phenomena of salt attack and rising damp.
sand-carrying capacity	The amount of sand that a binder can carry in a mix. A pure (fat) lime will carry up to three parts of well-graded sand. Because of the presence of some inert material, a natural hydraulic lime will carry up to about two and a half parts of the same sand.
sand-slaking	Slaking of quicklime in conjunction with the sand to produce a mortar, which is then matured before use. It is also known as dry-slaking, when a minimum of water (sufficient only to slake the quicklime) is used initially. See also *hot-mixing*.
setting	The stiffening and hardening of a mortar, plaster or render to form a solid mass.
sharp sand	Sand that is angular and so feels sharp when rubbed in the hand.
silica	Silicon dioxide: SiO_2. When it is crystalline, it is the mineral quartz which is found in many sands. When it is amorphous, it is a potentially reactive pozzolan.
silica fume	A reactive form of amorphous silica used as a pozzolan in concretes.
silicates	Minerals which contain silicon, oxygen and other elements, such as aluminium, calcium, iron, magnesium and sodium.
siliceous	Rocks or sediments consisting of or containing silica.
size grading of sand	The distribution of particle sizes (grain sizes) in a sand. It is also known as granulometry. See also *sorting of sands, poorly graded sand* and *well-graded san*d.
slag cement	Cement based on GGBFS. It may also contain Portland cement.
slaked lime (putty)	Lime putty or hydrated lime, both of which have been produced by slaking quicklime, though the term is commonly limited to lime putty.
slaking	Like a thirst, quicklime is slaked (or slacked) by adding water. The product of slaking quicklime is slaked or hydrated lime.
slurry	A thin mixture of solid material in water. Mortar mixes intended for grouting are made into slurries by the addition of plasticisers.
soaking	Making a form of lime putty by mixing hydrated lime powder with water and leaving it to stand and settle out. This is not slaking.
soft-burnt quicklime	Quicklime produced by burning (calcining) the raw material at relatively low temperatures, ideally 900–950°C. If pure, it will be very reactive when slaked. See also *hard-burnt quicklime*.
soft sand	Sand that feels soft in the hand because it is fine grained and loam rich (clay, silt and organics). It is not the direct opposite of a sharp sand.
sorting of sands	A term used by geologists to describe the maturity of a sediment in a stream. Well-sorted sand will have relatively uniform grain sizes whereas poorly sorted sand will have a broad range of grain sizes. Sorting and grading are inversely related: a well-graded sand is poorly sorted, and a poorly graded sand is well sorted.
specific surface area	The total surface area of all the particles of a material (such as sand), measured for a standard quantity (such as a gram weight).
stiffening	The initial setting of a mortar as a result of the loss of water by suction into the masonry and by evaporation. Stiffening is followed by hardening.
stopping	A tuck-pointing term for the coloured mortar applied to the face of the bedding mortar joints, before adding the tuck ribbon or bead.

stucco	An external lime- or cement-based rendered surface, commonly to imitate stone. It is often self-coloured or colour-washed. See also *render*.
subflorescence	The crystallisation of salts within the pores of masonry. It is sometimes referred to as crypto-efflorescence, meaning hidden. See also *efflorescence* and *salt attack*.
suction	The negative force exerted by the capillarity of porous materials. It draws water into walls and helps plaster and mortar adhere. Suction is a function of porosity, pore size and distribution. See also *initial rate of absorption*.
superplasticiser	See *plasticiser*.
supplementary cementitious material (SCM)	Binder additives that include pozzolans and latent hydraulic cements. When added to Portland cement they make blended cements. When added to pure lime they make binders similar to hydraulic limes.
tamping	Finishing a semi-hardened mortar joint by tamping the face with the ends of the bristles of a stiff-bristled brush.
trass	Light-coloured, compacted volcanic ash (tuff) that is ground and used as a pozzolan. It was formerly called tarras.
tuck pointing	Finishing a mortar joint with a narrow ribbon or bead of light- or dark-coloured mortar that contrasts with the stopping, which is usually coloured to match the bricks or stones. This creates the illusion of finely jointed, high-quality brickwork or stonework.
undersetting	A treatment for salt damp in which sections of the base of a wall are progressively removed and rebuilt, often using new materials and incorporating a damp-proof course.
uniform sand	A sand with a single grain size, or a narrow range of grain sizes, making it poorly graded.
unit (of masonry)	Bricks, stones or blocks that are laid in mortar to form masonry.
vapour permeability	The rate of passage of vapour (e.g. air and water vapour) through a permeable material. It is loosely described as breathability.
voids	Empty spaces; the gaps between the grains of a dry sand that make it porous.
void ratio	The proportion of voids in a dry sand (the porosity) expressed as a percentage of the total volume.
water lime	An historic term for hydraulic lime; a lime that was suitable for building works in water, such as canals or harbours. See also *air lime*.
water-retainer	A water-retaining agent or water thickener; an admixture that improves the water retentivity of a fresh mortar.
water retentivity	A property of binders, aggregates and mixed mortars that is a measure of how well they retain their mixing water against the suction of the masonry to which they are applied. See also *workability*.
weathering	1. The action of the weather and pollutants over time, producing an aged appearance and ultimately causing decay. 2. A surface (such as a coping or sill) that is sloped to promote water run-off (hence a weather-struck joint profile).
well-graded sand	A sand that has a broad range of grain sizes in roughly similar proportions. See also *poorly graded sand* and *size grading of sand*.
whiting	Ground chalk or limestone used in glazing putty and as a filler in many industries. It is a component of mason's putty.
workability	The relative ease with which a fresh mortar can be spread and worked. It is related to its plasticity, water retentivity and consistency.

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AS 2701:2001 (R2015). *Methods of sampling and testing mortar for masonry construction*.

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30.5 Audiovisual training materials

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30.6 Internet links

A PDF version of this document, and links to related documents, can be found on the following internet sites:

Heritage New South Wales
www.heritage.nsw.gov.au

Heritage South Australia
www.environment.sa.gov.au/topics/heritage

Heritage Tasmania
https://heritage.tas.gov.au

Heritage Victoria
www.heritage.vic.gov.au

Queensland Department of Environment and Science
www.qld.gov.au/environment/land/heritage

WA Department of Planning, Lands and Heritage – Historic Heritage
https://www.dplh.wa.gov.au/information-and-services/historic-heritage

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