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Short Guide

Lime Mortars in Traditional Buildings

Historic Scotland
Alba Aosmhor

National Conservation Centre
Ionad Glèidhteachais Nàiseanta

HISTORIC SCOTLAND
ALBA AOSMHOR

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1. Introduction

This short guide on lime mortars is aimed at building professionals who deal with issues relating to the maintenance and repair of traditional and historic buildings and structures. However, it will equally be of use to contractors, home owners and students with an interest in lime mortars and finishes, traditional materials and historic building maintenance strategies.

The process of preparing and using lime mortars in building work is an essential skill for all those working on traditional buildings. Traditional buildings (defined by the Scottish House Condition Survey as buildings constructed before 1919 of solid masonry) make up around 20% of the existing housing stock in Scotland and therefore the skills required to maintain such buildings should not be considered 'specialist'. The aim of this guide is to provide the reader with a background to the history and use of lime mortars in traditional building, the sourcing of raw materials, preparation of lime mortars for repairs, and how to recognise and reduce the risk of failure.

This guide provides advice on how to approach the specification of lime mortars, however it does not offer exact mixes, as these are always site specific. Where specification of lime mortar is required for conservation work, or where there is uncertainty about the correct specification to use, the reader is encouraged to employ the skills of a buildings consultant experienced in the specification, application and maintenance of lime mortars and finishes.

2. What is lime?

Fig. 1 Flush lime pointing on a wall in southern Scotland dating from approximately 1790.

Lime is the material produced from the heating or 'burning' of limestone and its subsequent 'slaking' with water. It can be combined with aggregate and water to produce a mortar or plaster, or diluted with water and used for limewashing. Lime was commonly used as the binding agent in the historic mortars of traditionally constructed buildings and structures until the beginning of the 20th century, when its use was largely superseded by Portland Cement. Lime is an extremely versatile material, used for both construction (foundation concrete, bedding, pointing and flooring mortars) and finishing (plasters, renders and limewash). To the reasonably well informed and skilled tradesperson, lime mortars are simple to prepare and use, and can be very durable and resilient if used correctly and maintained. Indeed, lime mortar can be found in very old structures (Fig. 1), in some cases over 2,000 years old, still effectively performing its function.

2.1 Production of lime

Lime is produced by burning limestone (calcium carbonate or calcite, $CaCO_3$) in a kiln at temperatures in excess of 850ºC[1] (Fig. 2). This drives off the carbon dioxide held within the lime to produce calcium oxide (CaO), a highly reactive solid known as 'quicklime' or 'lump lime'. 'Slaking' of this calcium oxide with water results in a highly exothermic reaction (a reaction that produces heat) to produce lime (calcium hydroxide ($Ca(OH)_2$)), an anhydrous (free of water) material termed slaked lime, hydrated lime or Portlandite. Quick lime or hydrated lime is mixed with aggregate and water to form a mortar; alternatively the addition of excess water during slaking results in the formation of a lime putty (Fig. 3). Calcium hydroxide in the mortar reacts with carbon dioxide (in the presence of moisture) in the atmosphere to form calcium carbonate in a reaction termed 'carbonation'. In this series of reactions, known as the lime cycle (Fig. 4), the material essentially returns to its original form, as the set lime is compositionally similar to its original limestone. Dolomites or magnesian limestones (those containing a proportion of magnesium in place of calcium), undergo a similar process to produce 'dolomitic' lime.

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Fig. 2 The historic lime kilns of Charlestown, Fife.

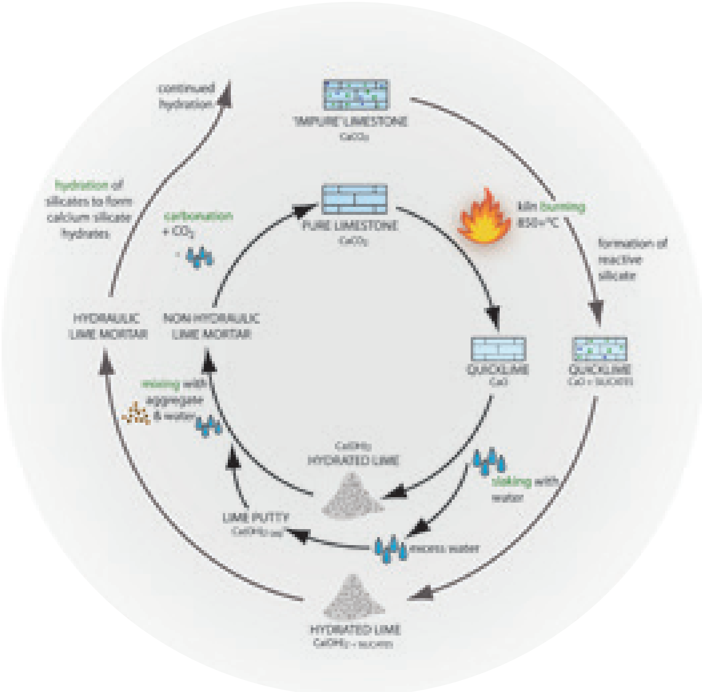
Fig. 3 Slaking quicklime to produce a lime putty.

This simple lime cycle is based on pure limestones producing 'air limes' (also termed 'non-hydraulic' limes). Lime production from limestones containing reactive materials (siliceous or argillaceous limestones), proceeds via a more complex cycle to produce 'natural hydraulic limes' (NHLs). Hydraulic limes set not only by carbonation, but via hydration reactions occurring between the silicate and aluminate components with water and calcium hydroxide [2]. This 'chemical' setting mechanism enables the use of hydraulic limes in wet conditions, where air limes would fail to set. Natural hydraulic limes are typically stronger and less vapour and moisture permeable than air limes.

The production of lime from limestone via this cycle is a well established and ancient technology, probably brought to Britain by the Romans. Although the lime production process has remained largely unchanged for thousands of years, on site additions and modifications to the raw material have evolved over time. Builders have experimented with different materials for different applications, often making the lime more workable, quicker setting or achieve water resistant properties. Traditional additives used to achieve these qualities included animal fats and blood, milk and volcanic ash (see section 6).

2.2 Uses of lime

The beneficial properties of lime as a binder, including its setting characteristics and permeability (detailed in section 4), make it ideal for a number of functions in construction. Lime mortars were typically used for several aspects of traditional construction including concrete foundations and floors, bedding (or building) mortar for wall construction, pointing mortar, renders, plasters and lime washes and paints. The types of limes, and mix proportions used varies depending on numerous factors including the intended function of the mortar and the substrate type (see section 7). As well as its use in the heritage and construction sector, lime is used for industrial processes such as steel fluxing and waste water treatment, and for agricultural purposes.



04 **Fig. 4** The lime cycle. The cycle is different for non-hydraulic and hydraulic limes due to differences in the composition of the original limestone.

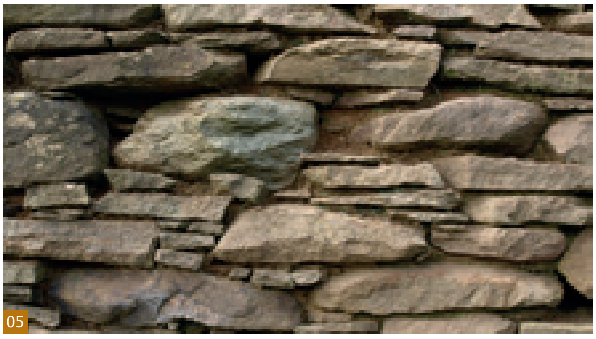


Fig. 5 Earth mortar.

Fig. 6 Clay mortar.

2.3 Other binders for construction

Historically, building materials were largely selected based on what was available locally. For centuries prior to the widespread availability of lime, binders such as earth and clay were commonly used in Scotland (Figs 5 and 6). The use of these declined as they were superseded by lime, and then cement, in modern construction.

Earth

The term 'earth' when used in reference to historic construction methods refers specifically to material containing roots and/or vegetable fibre that provide a three-dimensional mesh that binds the mortar together [3]. This type of mortar was used primarily due to its ready availability, as well as its compatibility with relatively soft sandstones.

Clay

Before lime mortar became widely available, in areas where there was no readily available source of limestone for lime production, walls were built either dry (without mortar, also termed 'drystane') or using clay or mud as a mortar. Clay mortars used in conjunction with masonry were becoming commonplace in the 15th century, replacing timber and tempered-earth construction [4]. As well as acting as a bonding agent between masonry units, clay was often used for its waterproofing properties, particularly in basements and wallheads due to their vulnerability to moisture ingress. The use of clay mortars continued well into the 19th century in some rural areas, but as lime mortar became cheaper and more readily available lime use became commonplace in building work of all types.

Cement

Portland Cement is produced from limestone in a similar way to lime but is manufactured under higher temperatures and with added reactive clays. The result is a binder that sets rapidly in the presence of water and hardens to a much greater compressive strength than lime. The inventor of Portland Cement, Joseph Aspdin, allegedly claimed that the product could produce an artificial stone as good as Portland stone (the finest limestone of the time in England), hence the name. The development of Portland Cement in the early part of the 19th century marked a turning point in the history of lime mortars. The use of Portland Cement became widespread from the mid-19th century onwards, particularly for stucco work, although lime mortar continued to be used commonly for building work. Increasingly, lime mortars were 'gauged' with cement to enhance the strength and setting properties of the mortar.

Early Portland Cement was very different to modern cement, often known as Ordinary Portland Cement (OPC). The development of the material continued throughout the 19th century with ever stronger mixes being produced, so that by the 20th century cement could be used to construct architecturally and structurally adventurous buildings from concrete. OPC offers numerous benefits when used in the right context, for engineering work and work which requires a high compressive strength, low permeability, or an underwater set. Many modern architectural designs now rely on these qualities. However, cement is generally unsuitable for use on traditionally constructed buildings, particularly those built with softer and more vapour permeable (often called 'breathable') materials including lime mortar, natural stone, brick and timber, due to its high strength, lack of permeability and its tendency to crack due to its relative inflexibility.

The inappropriateness of cement mortar for repairing traditional buildings has become increasingly apparent in the last few decades. Traditional buildings to which cement mortars have been applied have begun to show signs of accelerated masonry decay due to the inherent incompatibility of the materials [5,6] (Fig. 7), primarily in terms of flexibility and vapour permeability. Unfortunately the largely indiscriminate use of cement mortars and renders over the past few decades has become so widespread that many trades are no longer familiar with the preparation and use of lime mortar and, due to the associated uncertainties and lack of confidence, can be reluctant to use it. However, in recent years an enhanced understanding of material properties and compatibility has lead to a greater appreciation of the importance of vapour permeability and flexibility in repair materials for traditional buildings. Consequently, the positive attributes of lime mortar are now widely acknowledged and its use accepted and practised for conservation work [1,6,7].

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Fig. 7 Cement mortar causing accelerated deterioration of sandstone.

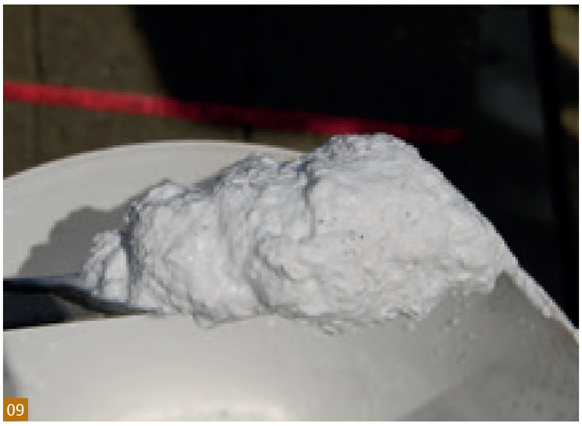

Fig. 8 Quicklime produced from burnt shells.

Fig. 9 The resulting slaked lime.

2.4 Building limes in Scotland

Historic building lime in Scotland varied in composition, a direct reflection of the country's geological diversity. Limestones are found in various forms across the country, but in many cases these sources have a complex geology and cannot be usefully exploited for producing lime. However, there are three primary regions where geologically distinct limestone is present in such quantities as to have been considered economically viable in the past: the Southern Uplands (Scottish Borders) and the Midland Valley (Central Belt); Grampian and south-west Highlands; and the north and north-west Highlands [8].

The chemical composition of the limestones in Scotland varies and as such, at various times, Scotland was producing limes of differing strengths (or hydraulicity). Mildly hydraulic limes (see section 3) were formed from the reasonably 'pure' limestones of Inverness-shire and Perthshire, as well as the Central Belt, Borders, the Lothians and Fife. Two of the more well known Scottish limes, Charlestown lime [9] and Arden lime (Central Belt) were more strongly hydraulic; Charlestown lime was favoured for wet dock and canal constructions including those of Fort George, Leith and Granton docks and Dundee docks.

Scottish lime, particularly in the Western Isles, was also produced from sea shell. When burnt in a kiln, the shells are reduced to lime (Fig. 8). The loose nature of the material allows it to burn easily and completely, so that the lime produced is not contaminated with lumps of un-burnt lime. This produced a very high quality and pure (or feebly hydraulic) lime that was particularly good for internal plaster work (Fig. 9).

At present, no Scottish lime is being produced for the construction industry. Imported materials, largely from Europe, are relied upon to carry out conservation work to the traditional and historic building stock in Scotland. The growing interest in using lime mortars in 'eco-friendly' new build construction is leading to the evolution of limes and the incorporation of additives to produce 'formulated' materials (see section 3). An understanding of traditional and modern materials is essential in ensuring compatibility with both the stone masonry and historic mortars of buildings and structures in Scotland.

3. Types of lime

Lime is the generic name given to calcium hydroxide, although there are numerous categories and sub-categories. Limes of different types may be used for different applications in building and are selected for their specific physical properties and performance characteristics. The properties of a lime mortar depend on the nature of the lime binder used to produce it, as well as the effects of any additives that are introduced to the mix (see section 6). Nomenclature for lime can be confusing, but the most common types and their various names are listed below (nomenclature relating to lime composition and properties is dictated by the European Standard BS EN 459-1:2010, Building Lime Part 1: Definitions, specifications and conformity criteria). Regardless of type, when a lime mortar is required for conservation work, its compatibility with the substrate in question should always be established prior to use (see section 4).

3.1 Air limes

Air limes, also called 'fat limes' or 'non-hydraulic limes', can be subdivided into two categories: calcium lime 'CL' and dolomitic lime 'DL' (defined by British Standard) [10] with further subdivisions relating to their specific chemical composition. These limes are natural limes formed from the burning of limestone that is considered to be 'pure', i.e. that does not contain any silicate or aluminate 'impurities'. Unlike calcium lime, which is formed from calcium limestone, dolomitic lime is formed from the burning of dolomite (magnesian limestone), a limestone in which a proportion of the calcium has been replaced by magnesium. This type of limestone requires a lower burning temperature than that of calcium limestone. Failure to account for this increases the risk of formation of overburnt quicklime, which can increase slaking and maturing times. Delayed hydration of the quicklime can result in expansion of the mortar once laid, leading to failure.

When used in a mortar, air limes set and harden only through carbonation and drying. Carbon dioxide from the air is essential for the progression of this reaction. A small amount of moisture is also required, for which the moisture in the mortar and the air is usually sufficient; air limes cannot set in wet conditions and should not be used in situations where the masonry is likely to remain permanently saturated, be exposed to extended periods of saturation, or be underwater.

Pure limestones are found widely in parts of England, particularly in the south, and in pockets throughout Scotland. Due to the very wet climate in Scotland, most modern lime work is carried out using imported natural hydraulic limes (see below), or a combination of natural hydraulic lime gauged with air lime (in which the air lime improves workability). There is a general tendency to avoid the use of air limes alone as they are not considered to set quickly enough nor to be sufficiently durable for the conditions, particularly in the north and west of Scotland. That being said, where they are used in the correct circumstances and adequate protection is provided to ensure their carbonation, air limes can prove successful and sufficiently durable even for the Scottish climate.

Air limes are available in three physical forms: quicklime, dry hydrated lime powder and aqueous lime putty.

Quicklime

Quicklime (also called lump lime) is the product of burning limestone in a kiln. Quicklime is the material that is removed from the kiln, prior to any subsequent modifications/processes that may take place to produce other forms of lime (hydrated lime, lime putty). Quicklime is a highly reactive material that should be handled with care. It should be stored in dry, airtight containers to prevent premature slaking (Fig. 10).

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Fig. 10 Quicklime.

Hydrated lime

Hydrated lime (also called bagged lime, builders' lime or dry hydrate) is an air lime which is produced by slaking quicklime with sufficient water to produce a dry powder (Fig. 11). If not stored correctly, hydrated lime can start to carbonate or 'air slake' while still in the bag, due to the presence of carbon dioxide and moisture in the air; where this has occurred the lime is said to be 'blown'. Lime in this state should not be used.

Hydrated lime should not be confused with 'hydraulic lime' (see section 3.2), which is also supplied in the form of a dry powder. Hydrated lime is often used as a 'plasticiser' in cement mortars as it improves the material's workability. The addition of hydrated lime to a cement mix does not make the resultant product a 'lime mortar', rather a cement mix gauged with lime.

Lime putty

Lime putty (also called fat lime or slaked lime, Fig. 12) is produced by slaking quicklime in an excess of water. Lime putty is fully slaked and typically allowed to 'fatten up' for at least 48 hours prior to use in a lime mortar. The maturation or 'fattening up' of putty results in the formation of increasingly finer lime particles over time [11]. It is this process that makes putty the most soft, permeable, flexible and malleable of all the types of lime. Putty is often considered to be a superior product to dry hydrate limes. The practice of producing a lime putty by slaking dry hydrate with an excess of water is not recommended. This results in the formation of a material with inferior characteristics to lime putty formed from quicklime.

Historically, mortars used in building work would have been prepared either as hot lime mixes (see section 8.4), or as lime putty mixes. Bagged hydrated lime (as a powder) is a more recent product, used primarily as a plasticiser in gauged cement mortars.

Fig. 11 Hydrated lime.

Fig. 12 Lime putty.

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3.2 Hydrated limes with hydraulic properties

Hydrated limes with hydraulic properties are typically referred to as 'hydraulic limes'. However the current European Standard [10] subdivides the category of 'lime with hydraulic properties' to differentiate between those that are natural and those which contain additives. Sub-categories include 'natural hydraulic limes', 'hydraulic limes' and 'formulated limes'. The properties of limes falling within these three sub-categories can vary considerably. An understanding of these terms is therefore essential in avoiding the specification of inappropriate materials for conservation work.

Natural hydraulic lime

Natural hydraulic lime (NHL), sometimes referred to as 'water lime', is produced from limestone that contains a proportion of reactive minerals [2,12]. Once burnt in the kiln, these minerals allow the lime to set in the presence of water; they are said to have a 'chemical set'. Some degree of set is still attributable to carbonation, the proportion of which is dependent on the quantity of reactive minerals present in the source limestone, the temperature within the kiln and the burning time. As hydraulic limes will set or 'cure' even in wet conditions, they can be used for the construction and repair of bridges, harbours and foundations. That being said, carbonation still plays an important role in the setting of NHLs, and where they fail to carbonate, they will not perform adequately and are more vulnerable to frost damage. The composition and properties of natural hydraulic limes can vary quite widely, but for manufacturing and commercial purposes they are classified according to their compressive strength and are assigned to one of three categories: NHL 2, NHL 3.5 or NHL 5 (Table 1).

The strength of lime binders can vary considerably from one type of lime to another due to the natural variations in the limestones from which they are formed. In theory, an NHL 2 from one manufacturer can be stronger than an NHL 3.5 from another manufacturer. This unpredictability needs to be carefully considered when specifying lime binders (see section 7) as simply specifying 'NHL 2' for example could result in the formation of numerous mortars of differing physical properties depending on the binder selected, some of which might be unsuitable for particular applications.

Classification	Compressive Strength at 28 days (MPa)	Traditional Terminology*
NHL 2	≥ 2 to ≤ 7	Feebly hydraulic
NHL 3.5	≥ 3.5 to ≤ 10	Moderately hydraulic
NHL 5	≥ 5 to ≤ 15	Eminently hydraulic

Table 1 Classification of NHL binders based on compressive strength of laboratory manufactured samples at 28 days. Values from BS EN 459-1:2010.

*Traditional terminology only loosely relates to modern classification. In reality, modern limes are generally much stronger than those produced historically.

It is important to note that the NHL classification system is indicative only. This standard classification system is intended to ensure consistent manufacture of lime and, although it can provide a guide, should not solely be relied upon for specification purposes. Values relate to the average compressive strength of laboratory specimens prepared and cured for 28 days under a strict regime. The ultimate strength of a lime mortar on site can vary drastically; mortar performance varies with lime type, mix proportions, site conditions and site practices. Strength of natural hydraulic lime mortars continues to increase over time for a number of years. Strongly hydraulic mortars should be used with care as the final strength of the mortar might significantly exceed the perceived strength based on the early stage values.

Natural hydraulic lime binders are typically sold in bags as a dry hydrate and are produced by mixing quicklime with just enough water to convert the calcium oxide to calcium hydroxide, but not enough to initiate the chemical set of the silicate components. Natural hydraulic lime is suitable for use on copings, chimneys and exposed elements as well as for bedding and pointing mortars, and for rendering and harling. Despite their perceived high strength relative to air lime, most natural hydraulic limes have good water vapour permeability and the ability to accommodate movement. However, both vapour permeability and flexibility do typically decrease as compressive strength increases [13]. Natural hydraulic lime should not be confused with hydrated 'builders' lime', which is in fact an air lime.

Hydraulic limes

The term 'hydraulic lime' (HL) (without the prefix 'natural') refers to a hydraulic binder which might only have a nominal lime content [10]. The binder may contain additives such as cement, blast furnace slag and fly ash. Due to the presence of potentially significant quantities of these additives and the potentially low proportion of lime these 'limes' are not generally considered appropriate for conservation work. Manufacturers' literature may be consulted to identify the product constituents and properties, although it should be kept in mind that not all additives are required to be disclosed.

Formulated limes

'Formulated lime' (previously termed NHL-Z) refers to lime-based (air lime or NHL) products to which hydraulic and/or pozzolanic materials, i.e. materials that promote the hydraulic set (including cement) have been added to change the performance characteristics [10]. Such materials might offer an increased ease of use over natural products, and may appeal to the less experienced 'DIY' market. Formulated limes may be labelled with a trade name; technical data accompanying the material should be consulted to identify its composition. Many such 'limes' have very different qualities to natural limes and may not always be suitable for repairs to traditional buildings. Formulated limes might be appropriate for certain applications, such as repairs to decorative or weathering details but should be used sparingly, with caution and only by an experienced tradesperson who fully understands their properties.

3.3 Pre-mixed lime mortars

Lime mortars are quite commonly sold in bags of pre-mixed binder and aggregate, which simply require water to be added. These pre-batched mortars have the advantage of reducing the preparation time of the mortar and allow an element of certainty about the mix, as they eliminate any error associated with incorrect proportions of binder and aggregate. Where pre-mixed mortars are used, batches should ideally consist of whole bags as the materials are likely to segregate within the bag during transport and storage, resulting in mortar variation where part bags are used.

Some pre-mixed mortars might contain additives. It is vital that this be clarified with the manufacturer prior to use, as the inclusion of additives undoubtedly alters the performance of the material. Additionally, as the aggregate used in these mixes is kiln-dried, there might be limited ranges available, therefore matching to historic mortars may not always be possible. Specialist suppliers may be able to prepare bespoke mixes so that aggregates can be matched to existing mortars, however these products will tend to be more expensive.

3.4 Gauged lime mortars

Hybrid or gauged mortars are mixtures that contain more than one type of lime binder. These might be hot lime mixes (see section 8) gauged with natural hydraulic lime (as is common in Scotland), or natural hydraulic lime gauged with lime putty. Lime putty is typically added to natural hydraulic limes to improve their workability and sometimes to reduce the hardness or strength of a hydraulic lime mortar. If prepared correctly gauged limes can be much easier to work with than natural hydraulic limes, although ultimately this practice can result in the production of a largely unknown material[14]. The term 'gauged' may also refer to the addition of cement to a mortar. Lime gauged with cement is not a suitable for traditional masonry work and should not be specified. Gauging with cement on site produces an unpredictable material with an increased risk of failure.

4. Properties of natural limes

Lime has a very wide range of applications in buildings, from concrete to bedding and pointing mortars to harling and paint (limewash). Building limes, both air limes and natural hydraulic limes, have certain qualities that make them perfectly suited for use on traditionally constructed masonry or timber buildings:

- Vapour permeability: The relatively high vapour permeability of lime allows moisture to move through it. The absorption and evaporation of moisture from the material helps regulate humidity within a building and diffuse penetrating water, subsequently protecting the structure from moisture-associated damage. Vapour permeability of lime generally decreases as compressive strength increases, although this may be altered using additives.
- Flexibility: The 'elastic' nature of lime enables it to absorb minor structural movement associated with the expansion and contraction stresses that a building undergoes due to changes in temperature and humidity. This means it is less vulnerable to crazing and cracking than are many cement-based products. Flexibility typically decreases as compressive strength increases.
- Environmentally friendly: Lime contains no volatile organic compounds (VOCs), petrochemicals, lead or other contaminants (unless included as additives to modify the material properties). Lime-based products allow water vapour to be dissipated, preventing the build up of condensation. In addition, the alkalinity of lime helps to inhibit the growth of mould and other pathogens. These factors contribute to a healthier internal environment.
- Aesthetically pleasing: Lime finishes complement the appearance and visual qualities of natural stone and brick. Lime finishes show up slight variations in texture and colour. Due to the light scattering properties of the calcium carbonate crystals in lime, it has a surface lustre which is pleasing to the eye. In contrast, cement-based finishes tend to appear flat and dull.

4.1 Compatibility criteria

It is the physical properties and associated performance characteristics of lime mortars that dictate their compatibility with traditional building materials. When used together with stone, brick and timber and specified correctly, lime mortars act sacrificially to prevent the adjacent material from deteriorating.

The relatively high vapour permeability of lime enables the diffusion of moisture through it – it allows the building to 'breathe'. Inappropriate repair of historic structures using less vapour permeable materials, such as cement-based products, can inhibit the movement of moisture through a building resulting in problems such as internal damp, rotting timbers and exterior deterioration of masonry (Fig. 13).

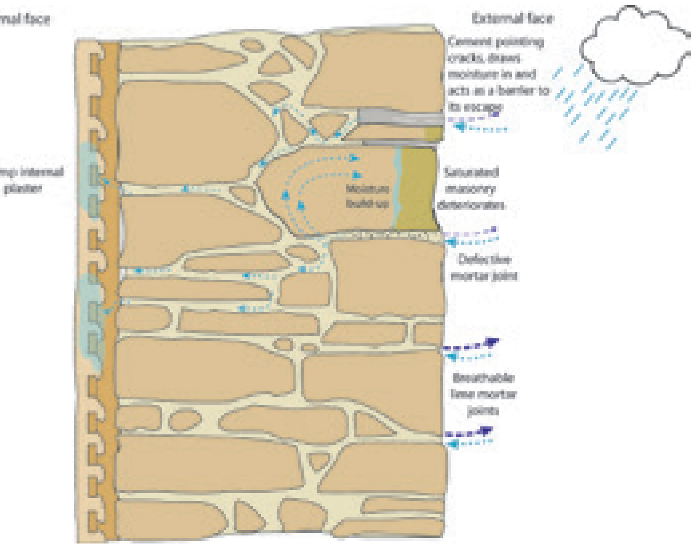

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Fig. 13 The effects of inappropriate repointing materials on moisture transmission in mass masonry walls.

There are clear links between compressive strength and vapour permeability of natural limes. However, the lack of precision in the current lime classification system (i.e. overlap in strength categories) means that this correlation cannot fully be taken advantage of, and the exact properties of many binders when combined in mortars is unpredictable. These uncertainties in material properties have often led to lime being considered 'difficult'. However, a thorough understanding of the properties of the lime can allow a workable specification to be fairly easily produced by most skilled building professionals, so long as the preparation, workmanship, and aftercare is appropriate. Where there is uncertainly as to the materials or procedure, the input of an experienced lime consultant may be advisable.

4.2 Technical considerations in lime binder selection

Lime mortars are a mixture of lime binder, aggregate and water. Despite this apparently simple formulation, there are an infinite number of variations that can be created by altering mix proportions and water content, as well as aggregate and binder type (the influence of aggregate on mortar properties is discussed in section 5). The properties and performance of a lime mortar are largely dependent on the chemical composition of the limestone from which the lime binder was produced and the composition of the manufactured product. Two important factors in understanding the performance of lime mortars are the relative bulk density (RBD) of the material and the 'free lime' content as these properties differ between limes and can impact upon the mortars' performance.

Packed relative bulk density of binder

The relative bulk density (RBD) of a material is simply a measure of the weight per volume unit. One lime binder may seem 'fluffier' or bulkier than another – this is due to differences in the RBDs of the two materials. Mortar mixes are quoted by volume (e.g. a 1:3 lime:aggregate mix refers to the relative proportions of the materials by volume) and batching constituents on site is typically done by the shovel or bucket full. This eliminates the need to weigh material on site. However, in many cases, differences in RBD from one lime binder to the next are not accounted for when batching is carried out in this way as many specifications simply state a binder category (i.e. NHL 2, NHL 3.5 or NHL 5), rather than indicating a specific brand of known RBD. Determining the weight of lime required for a mortar mix reduces the degree of error during batching.

The RBD value assigned to a lime relates to the weight per litre, i.e. RBD of 0.5 indicates that 1 litre of the material weighs 500 grams while 1 litre of a material with an RBD of 0.6 weighs 600 grams. The same volume of two different limes will have different weights if their RBDs are different.

Converting volume to weight using RBD:

30l of mortar in a 1:3 lime:aggregate mix is required.

Note: lime is required only to fill the spaces between aggregate grains therefore the volume of aggregate is equal to the total volume of material required as the lime does not increase the overall volume of the mortar.

Volume of aggregate required = 30l, volume of lime required = 10l

Weight of lime (in kg) = volume of lime (in litres) x packed RBD of lime

For lime with an RBD of 0.5: weight = 10l x 0.5 = 5kg

For lime with an RBD of 0.6: weight = 10l x 0.6 = 6kg

This mortar mix, requiring 10l of lime, will equate to 5kg for a lime with an RBD of 0.5, and 6kg for a lime with an RBD of 0.6. Given that lime is typically sold by weight rather than volume, understanding the importance of RBD, and batching by weight, rather than volume, ensures consistency and accuracy. However, it should be noted that a lime should not be specified purely on the basis of its RBD. Other material properties including strength, flexibility and permeability should be considered first (see section 7).

Free lime content

'Free lime' is the term given to the calcium hydroxide in a hydraulic lime mortar that has remained uncarbonated. This lime is not involved in the hydration reactions with silicates and aluminates, but is available for carbonation, during which it converts to calcium carbonate [2]. Free lime itself can undergo a continuous cycle of carbonation, dissolution and reprecipitation, sealing microscopic cracks in a process known as 'autogenous' or 'self' healing. In conservation, this is generally considered to be a positive attribute of the material. However, this is an extremely long-term cycle and should not be seen as a substitute for necessary maintenance of limework such as repointing and limewashing, or the need for remedial action after failure.

It is the free lime in a lime mortar that, due to its relatively high solubility, is prone to leaching in areas, such as wallheads and basements, where the masonry is subjected to the continuous percolation of water [15] (Fig. 14). Free lime content of a specified lime should therefore be 'matched' to the condition of the masonry substrate – where masonry is damp, a lime with a lower free lime content is preferable. Likewise, if available protection of new lime work is limited, a lime with a lower free lime content will minimise the amount of damage and loss of material from the mortar in the event of frost or rain.

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Fig. 14 Example of streaking caused by excess free lime content on the lime mortar.

Limes of different hydraulicity typically have different free lime contents; in general, the higher the hydraulicity, the lower the free lime content, although there are exceptions to this. This should be acknowledged when specifying lime binders. It should also be noted that streaks of free lime on an elevation normally indicate saturation of masonry.

5. Selecting aggregate for lime mortars

As a primary constituent, aggregate has a major impact on the appearance and performance of a lime mortar[16]. Historically there was an almost infinite number of variations, depending on what was available locally, typical materials being river or beach sand or crushed shell. Aggregate is now commercially sourced from such deposits or may be crushed from rock extracted from quarries. Although there are generally fewer options commercially available, due to standards and regulations, these are generally of better quality for construction than historically sourced aggregate.

The type of aggregate required for a mortar is largely dependent on the intended use of the mortar. However, a good aggregate for a lime mortar should be 'sharp' (consisting of angular grains) and free of contaminants such as salt and organic matter. Using a sharp sand ensures that the grains interlock in the mortar, producing a stronger bond within the material. Rounded, or 'soft', grains might increase workability as the grains roll over one another, but this can result in poor adhesion. There are a number of other properties to consider when selecting an aggregate.

5.1 Aggregate grading

The term 'grading' refers to the size distribution of aggregate grains and is determined by passing samples of aggregate through sieves of a specified size[17]. Aggregate in which the majority of grains are of similar size is termed 'poorly graded' and aggregate with a wide spread of grain sizes is 'well graded' (Figs 15 and 16). A well graded sand typically has grain sizes between 4mm and 0.125mm, with the largest proportion of grains at the mid-point sieve fractions.

The grading, and specific grain size, required for a mortar is largely dependent on the intended mortar function. Well graded, sharp sand is often the best choice for mortars used in building and pointing. The largest grain sizes should typically be no more than one third of the width of the masonry joint. Ordinary 'building sand' is poorly graded, consisting of more rounded grains of uniform size and is not suitable for most lime work. A very fine sand or stone dust is more suitable for ashlar pointing.

Fig. 15 A well graded aggregate.

Fig. 16 A poorly graded aggregate.


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Matching of aggregate in a repair mortar to that of the existing mortar may be required on conservation projects, and in such cases an analysis of the existing mortar may be appropriate. Matching texture in this way can be of utmost importance in cases of harling repair, to maintain the visual integrity of the building. Where no currently available aggregate provides a similar match, a number of aggregates may be combined to provide the required appearance. Where a new render or harl is applied this is of less importance.

5.2 Aggregate composition

Sands from pits can vary in composition, and it is the geological history of the material that determines this; sands are formed from the weathering of rocks. Sands deposited close to their source may consist of numerous components including rock fragments, quartz grains and on occasion, fossil fragments. Sands that were transported for long distances, by water (river/alluvial sands) or air (dune/aeolian sands), prior to their deposition, tend to consist largely of quartz grains.

The composition of an aggregate can impact upon the colour of the mortar as well as its physical properties. Processed clay minerals and volcanic ash can act as pozzolans in lime mortars, enhancing the mortar's hydraulic set. Specifically graded aggregate produced from crushing stone is often used in cases where a colour match to stonework is required. Different aggregates do provide subtleties in shading and, where exposed on the surface, texture; however it is the fines of the aggregate, as well as the binder type, that have the greatest influence on the colour of a mortar.

Crushed shell

There is evidence from historic mortar analysis that crushed sea shell was added to lime mortar mixes, sometimes as the primary aggregate, and sometimes in addition to other aggregates. Shell is typically composed of calcium carbonate, which is the basic material from which lime is produced. Small particles of crushed shell appear to work as a catalyst in the setting of the lime mortar mix, by providing a surface or 'nucleation site' on which the lime reacts with carbon dioxide to form calcium carbonate. This is sometimes called 'seeding'. Lime mortars containing crushed shell are quite commonly found in traditional buildings in the Western and Northern Isles of Scotland where oyster, clam and mussel shells are found in abundance.

5.3 Void ratio

The volume of air between grains of aggregate can vary. Depending on the aggregate grading and particle shape, these air spaces, or 'voids', occupy different volumes. The role of a binder in a mortar is to fill the spaces between the aggregate grains. A mortar with too much binder may be liable to shrinkage and cracking during drying. A mortar with too little binder will be weak and friable as there is insufficient lime to bind the grains together. It may be necessary to strike a balance between the void ratio of the sand and the proportion of binder to achieve the desired workability.

It is the ~33 per cent void ratio of many commercially available well graded aggregates that makes the ratio of 1:3 such a common mix. However, poorly graded sand can have a void ratio of up to 60 per cent. A standard building sand with a 50 per cent void space will require an equivalent volume of lime binder (producing a 1:1 mix). This would be a relatively lime-rich mortar and costly, as the binder is typically more expensive than the aggregate.

If there is any doubt about the void ratio of an aggregate being used it should be checked with the manufacturer or supplier and/or tested on site. A simple site test called a 'void test' can indicate how well graded the sand is, whether it is suitable for use in a lime mortar and what the appropriate mix proportions (by volume) are. It should be noted that the weight of binder required will vary depending on the RBD of the lime. Section 4.2 shows how this should be factored in to calculations to get accurate batching measurements.

Determination of void ratio %

A simple void test can be used to determine the void ratio of a sample of aggregate, and therefore help in determining the correct amount of lime binder to use with the aggregate in question (Fig. 17).

1. In two separate measuring cylinders or other graduated beaker or flask have equal volumes of water and oven dried sand.
2. Pour the sand into the cylinder of water and tap the base gently to level.
3. Note the amount of water that lies above the sand – void ratio is calculated by deducting this value from the original volume of water and expressing as a percentage.

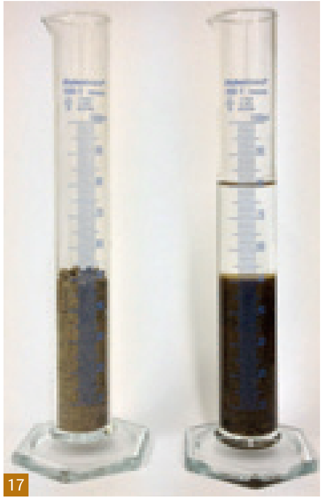

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Fig. 17 Void ratio determination.

5.4 Clay and silt content

A high clay or silt content will affect the performance of a lime mortar and can cause cracking and shrinkage. Sand used to make a mortar should be sieved and largely free from clay and silt; the European Standard [17] recommends no more than 4 per cent clay/silt in an aggregate. If no technical data is available on the clay/silt content of the aggregate it is worth testing a sample before purchasing in bulk or preparing the mortar. A simple 'jam jar' test can be used.

Determination of clay and silt content: jam jar test

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

6. Additives in lime mortars

The qualities of a lime mortar can vary depending on numerous factors including the composition of the lime binder, type of aggregate, mix proportions and curing regime. Historically, various other substances were sometimes added to lime mortars to alter the way they performed, for example to introduce a faster set, or to enhance the water resistance of the mortar. The lime binders produced historically may also have contained contaminants such as coal or burnt wood fragments, due to the nature of the kiln firing process. These contaminants may have impacted upon the colour and/or performance of the resulting lime mortars.

Pozzolans

Pozzolans are materials that contain reactive silica and alumina, which when finely ground and added to lime, impart a hydraulic property to the binder [18]. Pozzolans take their name from the town of Pozzuoli in Italy where the local volcanic ash and derived clays were found by the Romans to produce a binder that is harder than air lime, and which was found to set under water. The generic name Pozzolan is now applied to any reactive material which imparts these properties to a lime, and includes brick dust, ground tile/pottery, Pulverised Fuel Ash (PFA), Granulated Blast Furnace Slag (GBFS) and some processed clays (metakaolin), plus other similar materials. The one thing they all have in common is that they have been exposed to high temperature which has resulted in the alteration of the materials' components such that the silicates and aluminates present become reactive in the presence of hydrated lime.

The pozzolans used historically were generally coarser ground than their modern counterpart and were added to a mix as a part of the aggregate, or in lieu of aggregate in fine joint work, where volume mixes of 1 part lime to 1 part pozzolan can be found. Alternatively, where added to a sand lime mix, typical mix proportions of $^{1}/_{3}$ lime, $^{1}/_{3}$ pozzolan and $^{1}/_{3}$ aggregate, had the pozzolan added as part of the aggregate to maintain the lime binder content. This was an efficient use of the pozzolan as in the coarsely ground material, only part of the additive reacted with the lime, maintaining the binder-rich mixes that were common. However, when using the modern processed equivalents, which are more finely ground, the pozzolan can be added as a part replacement of the lime. Up to 40 per cent volume of the binder can be replaced with pozzolan, dependent on the form of pozzolan used and the requirements of the mortar. Some specifications still quote the additions of pozzolan in the form of a percentage of the mortar mix, up to 10 per cent of the mix by volume.

Tallow

Tallow is a rendered form of animal fat (normally beef or mutton fat) which was historically added to limewash to improve water resistance. This was common particularly where mortars were to be used for harling on exposed areas such as gable walls. Tallow would have been added to a 'hot' lime mix (see section 8.4). The heat of the reaction melts the tallow and allows its even dispersal throughout the mortar. The addition of tallow produces a water repellent finish. The disadvantage in using tallow is that it can initially reduce permeability, although permeability may subsequently increase as the alkalinity in the limewash breaks down the fat molecules.

Linseed oil

Like tallow, linseed oil was sometimes added to lime mortars and limewash to improve their water resistance. It has also been found to increase frost resistance and resistance to salt crystallisation [19,20]. Its use was most common for ashlar mortars, particularly in the Victorian era. Historically, linseed oil was an expensive product but nowadays it is readily available and fairly inexpensive. Only a small quantity is required to achieve the desired result; using excess can have an adverse effect on the mortar properties, and can alter the colour of pigmented limewashes, so care should be taken when batching, and trials should be carried out where necessary.

Casein

Casein is a protein found in milk that was sometimes added to mortars and grouts that required an enhanced level of plasticity. Casein provides a non-pozzolanic alternative to plasticisers like bentonite. Modern casein additives are now commercially available for use in mortars. Only a small proportion of the material is required to produce a plasticising effect so it should be used sparingly. Additionally, casein increases weather resistance, but to a lesser extent than tallow. Casein increases the durability of materials to which it is added and is most commonly used in limewash.

Hair

Animal hair has been added to lime plasters, and sometimes to mortars, renders and harls, for centuries to provide an enhanced level of tensile strength and to reduce the risk of shrinkage (Fig. 18). Today, numerous types of animal hair are commercially available, and more often than not, these are imported. Due to national requirements to control the spread of disease, there are regulations in place. Imported hair often undergoes extensive cleaning via boiling in bleach, or other strong chemical solutions. Research shows that certain treatment processes can result in a loss of hair structure [21], which could significantly reduce its effectiveness in the mortar.

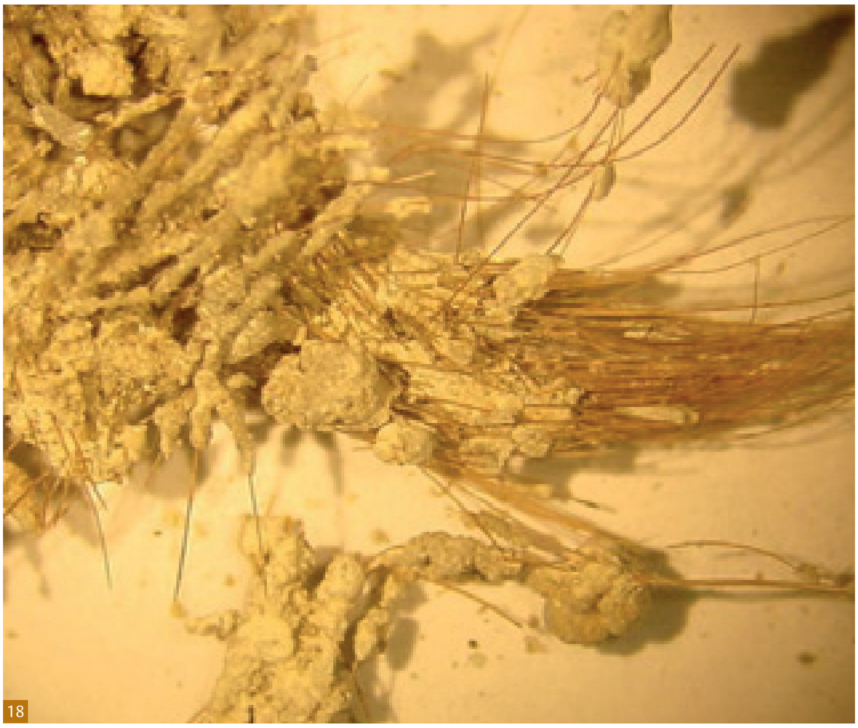

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Fig. 18 Hair in a historic lime plaster (© W. Revie).

Other historical additives

Historically a number of other unusual materials were sometimes added to mortars to enhance their properties. Urine and beer could be added to mortars on site to increase workability and improve frost resistance. Additionally, urine is thought to act as a retarder in lime plaster, giving more time for it to be worked and moulded. Little research has been carried out in this area and the exact mechanisms at play are unknown. It may be the case that these materials introduce natural polymers into the mix, changing the mortars' properties or they may simply introduce entrained air, effectively lightening the mix.

The use of additives, whether traditional or modern should only be specified where a modification to the natural properties of the mortar is required to 'fine tune' its performance. The impact of the additive in question on the mortar's physical properties and performance should be thoroughly understood prior to its use. Trialling of sample panels can be useful before carrying out large scale work.

7. Specification of lime mortars

The process of specifying a lime mortar for conservation work requires an inherent understanding of the materials involved, the structures to be repaired and the site conditions in which the material is to be used [7,12,23]. Given the broad categories by which lime binders are classified and the number of commercially available products on the market, simply specifying 'NHL 3.5' for example, may not ensure the production of a suitable mortar. The type and amount of aggregate, the mix proportions, the substrate and its condition, and the location of the building in question are just some of the factors that must be taken into account [22]. There are a number of questions that must be asked to help identify the most appropriate mix. The advice of a building professional or specialist lime consultant may be required for some projects.

7.1 Important considerations

What is the mortar for?

Understanding what will be required of a mortar, once in place, is important to determine what the desired or required properties will be. For example, bedding mortars act primarily as a cushion to support and spread the load of the masonry units, and to a lesser degree as an adhesion medium, holding the masonry blocks together. Pointing mortars, specifically those to be used on skews and chimneys, should be resistant to frost and repeated wetting/drying. Mortars for rendering or harling should, in general, be breathable, to deal with the diffusion of the often large amounts of moisture to which they are exposed. Despite these different requirements, the basic rules of traditional mortars should be followed regardless of function and mortars should remain sacrificial to the masonry. If repairs are being carried out to an entire building, or on a number of different areas of a building, it may be the case that several different specifications need to be used.

What are the existing materials?

Compatibility of old and new materials is vital [24–26]. Choosing an incompatible repair material can result not only in the failure of the repair, but also the accelerated deterioration of the adjacent materials. Properties such as water absorption and vapour permeability are key to assessing this compatibility. Repair mortars should have equal or higher water absorption and vapour permeability values than the adjacent masonry to prevent problems associated with inhibited moisture diffusion. Technical data with this information can often be obtained from the lime manufacturers. The relative speeds at which a drop of water is absorbed into the two materials gives an indication of their relative permabilities and is a simple way of assessing this on site. Should it be required, determining vapour permeability of the materials is a more complex procedure that may involve laboratory analysis.

What are the climatic conditions?

The geographical location of the site and the repair location on the building itself influence exposure of the mortar to rainfall, wind and frost. Very exposed areas or parts of the building which stay persistently wet (e.g. chimneys and parapets), will require a stronger hydraulic mix than will a sheltered lowland or inland area. Additionally, the specified aftercare may need to be adjusted depending on the time of year when the work is to take place to protect the mortar from rapid drying, during periods of heating, and frost damage during colder months (see section 8.6).

What skills are available?

Whilst it is advisable to employ a contractor who is experienced in using lime mortar and understands its properties, it is not always possible to find someone locally who is an expert. Contrary to popular opinion, lime is not a difficult material to handle; any trained mason or bricklayer should be able to work with lime mortar, as the hand skills are essentially similar to conventional work. For amateurs (e.g. the home owner), or contractors less familiar with lime mortars, it may be advisable to use a pre-mixed mortar which has clear instructions from the manufacturer, as this will eliminate the error involved in incorrect batching of material proportions. However, an understanding of the curing mechanisms is essential to avoid failure associated with inappropriate application and/or aftercare.

Stone types

Scotland has a diverse geological history that has resulted in the formation of a wide range of stone types [27–29]; the hard granites and whinstones of the Highlands and Islands and the softer red and buff sandstones of the Central Belt and Lowlands are characteristic Scottish stone types used in vernacular construction. This diversity makes it difficult to generalise about the suitability of lime mortars for particular stone types as the specification of the mortar is so heavily dependant on the qualities of the masonry it is being used with. In addition, it is not uncommon for buildings, particularly in the Highlands and Islands of Scotland to be built with more than one type of stone, for example, whinstone rubble walls with sandstone dressings (Fig. 19).

Fig. 19 The use of lime mortar with multiple stone types.

However some generalisations can be made based on an understanding of materials' interactions:

- Most sandstones and limestones are relatively soft and porous and should not be repointed or repaired with high-strength mortars.
- Impermeable stone types cannot dissipate moisture. Mortars in such buildings should therefore be permeable and breathable to prevent any potential build up of moisture within the wall that could lead to internal damp; hard mortars are not appropriate. A lime putty gauged with hydraulic lime, or a fairly weak hydraulic lime may be appropriate in these circumstances rather than the perhaps more intuitive response of applying a stronger binder to match harder stone types.

7.2 Case study specifications

The following examples illustrate a successful specification, and an unsuccessful specification, highlighting the likely reasons for their respective success and failure. These simplified examples are intended to highlight the complexity of mortar specification and should not be viewed as appropriate specifications in themselves.

Example 1: Red sandstone dwelling in the Scottish Borders in a sheltered location showing some areas of masonry deterioration due to the previous use of cementitious pointing mortar.

Specification for pointing mortar: NHL 2 dry hydrated lime binder and a well graded sharp sand (maximum grain size 4mm) in a 1:3 ratio by volume.

The relatively soft nature of the red sandstone found in the Scottish Borders demands the use of a low-strength lime binder with high vapour permeability. Whereas an NHL 3.5 might be suitable for use on more durable sandstones, the masonry deterioration at this site calls for something weaker and more permeable to ensure that the mortar will act sacrificially to the stone. Using a well graded sharp sand with a void ratio of approximately 30 per cent in a ratio of 1 part lime to 3 parts sand, ensures that all grains of sand are coated with lime, producing a complete mortar. Specifying a maximum grain size of 4mm ensures that no grains are more than one third the width of the joint.

In areas of more serious masonry deterioration, the stone masonry was dressed back to a sound surface, eliminating the need for stone replacement or 'plastic' repair.

Example 2: Granite cottage in Aberdeenshire, exposed to driving rain from the east.

Specification for pointing mortar: NHL 5 dry hydrated lime and a well graded sharp sand (maximum grain size 4mm) in a 1:1.5 ratio by volume.

There is a common misconception that hard masonry requires strong lime mortar. However, due to the impermeable nature of stone such as granite and whinstone, the mortar is the only route for moisture transmission. In this case, the mortar specified did not adhere well to the masonry. This is often a problem with impermeable masonry, as the substrate does not provide a bond through suction in the same way that a porous substrate does, and any surface water can act as a film preventing adhesion. This lack of adhesion is often evident from the fine cracks between the mortar and the masonry that act as capillaries, sucking moisture into the structure. A hot lime mortar would have been more appropriate, providing the adhesion required on an impermeable substrate. Additionally, the lime-rich mortar specified was liable to shrinkage and further cracking, as well as having relatively low breathability, further exacerbating the problem and leading to damp conditions in the wall core.

Many historic buildings, which today have exposed masonry, were once harled. Where water is penetrating through the joints, the possibility of reinstating flush pointing, harling and/or limewash should be considered. This would provide the building with an added level of protection from the elements, as these coatings maximise the surface area from which moisture can evaporate, keeping the core of the building dry. In many cases the damp in a building is attributed to incompatible pointing mortar, when in fact the mortar is being subjected to more exposure than was ever intended. Furthermore, the interior faces of the building are also responsible for moisture diffusion. Breathable internal finishes (lime plasters and washes/paints) should be maintained to ensure maximum breathability and moisture diffusion from internal wall faces.

8. Site practice

The successful use of lime mortars depends to a large extent on good site practice. This relates to numerous aspects of the repair procedure from storage of materials to batching and mixing, surface preparation, application and aftercare. A lack of attention to detail in any one of these areas can result in the failure of lime mortars. The following sections detail simple steps that should be taken to prevent failure as well as some basic steps to make site work safer and easier.

8.1 Health and safety

Risk assessments should be carried out prior to starting work on site and measures taken to eliminate and/or reduce the exposure to any risks identified. COSHH (Control of Substances Hazardous to Health) guidelines should be followed when using potentially harmful substances such as lime [30].

Lime is a highly caustic product and can be irritating to eyes and skin. It is recommended that slaking of quicklime and mixing of dry powdered lime should be carried out in a well ventilated area. Hot mixing is an additional risk on a building site as temperatures can reach as high as 300°C. Personal protective equipment (PPE) should be worn at all times. The following PPE is advised for all work involving lime:

Gloves: lime will dry and irritate the skin.

Breathing apparatus/masks: powdered lime dust is highly irritating if inhaled.

Goggles: especially when slaking quicklime; lime dust is highly irritating to eyes and splashes of lime can cause burns. As a further precaution, eye wash should always be available on site.

In addition to the health and safety considerations relating to materials, provision should be made at an early stage for appropriate scaffolding to be built so that access can be provided in a safe and appropriate manner.

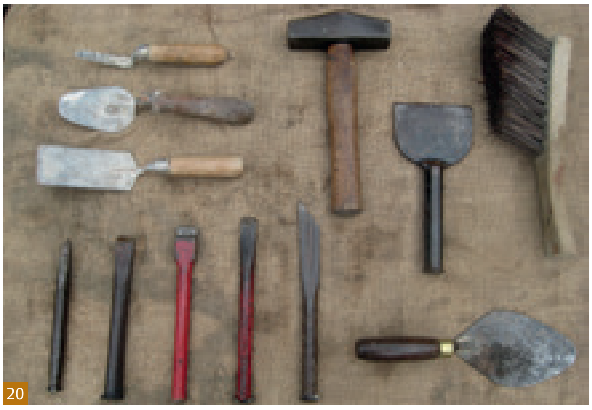
8.2 Storage of materials

Improper storage of raw materials can result in their degradation and the subsequent failure of their resultant lime mortars. Correct storage of both binders and aggregates is essential in preventing contamination and degradation.

Quicklime is highly reactive and should be stored in dry tubs and protected from moisture to prevent it from slaking. An easy way to determine whether the material has prematurely slaked is to pour water onto a small piece of lime – if it reacts, producing steam and breaking down to form a powder it is still useable; if it fails to react after a period of time, it has prematurely slaked and is no longer good for building work, although reactions of dolomitic and some types of calcium lime might proceed at a slower rate (see section 3.1).

Dry bagged lime should be kept in a dry, ventilated area which is protected from rain, frost and dew. Opened bags should be carefully sealed shut. Protecting the binder from both rain and moisture in the air helps prevent the onset of air hydration and/or carbonation. Lime that appears lumpy is likely to be blown and must not be used.

Lime putty should be stored in tubs covered by a layer of limewater to prevent drying and carbonation. Lime putty improves as it ages and can be stored indefinitely in the correct conditions. The longer it matures in these conditions, the more workable it will become as it continues to 'fatten up'.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Sand should always be stored on a ground sheet to prevent contamination from ground water salts and organic material. Covering the sand with tarpaulin protects it from the weather and prevents ingress of other contaminants and debris.

Damp sand is prone to bulking and can increase in volume considerably from the dry state, dependent on grading and moisture content. This should be factored in to the measurement on site to avoid error; failure to account for this can lead to batching errors of up to 40 per cent (weight)[12].

Fig. 20 A selection of hand tools traditionally used for lime and masonry work.

Fig. 21 Use of an oscillating tool to rake out fine joints (© G. Frew).

8.3 Tools

As well as understanding the specification of lime mortars, using appropriate preparation and application methods is important in ensuring the success of the material. Although traditionally work was carried out using hand tools (Fig. 20), the availability of mechanical, or 'power' tools for removing old pointing is becoming more commonplace. There are pros and cons to using such tools; in the wrong hands any tool can cause damage, but when used carefully and only where appropriate, some power tools can result in an increased turn-around time for work and/or increased accuracy, for example, when raking out ashlar mortar joints (Fig. 21).

It is possible that a number of similar tools may technically be used for the same purpose (e.g. different sized chisels, or different types of pointing keys) but to avoid damage to the masonry it is important that the correct tool is chosen for each task (Fig. 22). For example, the size of tool used for raking out, pointing or tamping should be selected based on the joint width. A 'small tool' or chisel may be appropriate for scraping out soft mortar in wide joints, but fine ashlar joints will require a greater degree of precision that can only be achieved using a very fine scraping tool or blade, or, only when used by an experienced operative, a mechanical oscillating tool with fine blades. Conventional rotating disc cutters should never be used as these are difficult to control and can very easily cause damage to the stone. Additionally, the damage caused can alter the surface characteristics of the building that impact upon the moisture distribution and can lead to accelerated deterioration of mortar and masonry.


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Fig. 22 Damage to the arrises of tooled ashlar masonry due to the use of inappropriate tools for removal of pointing mortar.

8.4 Mortar preparation

Preparing the substrate

Preparation of the masonry substrate is essential in preventing the failure of lime mortar. There are a number of steps to follow in preparing the masonry for application of mortar.

Removing existing mortar: Where mortar is deteriorated, damaged or has been wrongly applied, it will need to be removed before any new pointing can be applied (Fig. 23). Sound lime mortar should be left in place. In cases of repointing, the existing pointing should be raked out to at least twice the width of the joint, normally around 25-35mm for rubble masonry, and certainly enough to remove any remnants of later cement mortar if present. Where removal of a hard, well adhered mortar such as cement is likely to cause excessive damage to the masonry (i.e. more so than if it were left intact), then it should be left in place.

Brushing off: Once defective mortar has been removed back to sound mortar, the joints should be thoroughly brushed down to remove all dirt, dust and debris; joints can be washed out with water at low pressure. Joints must be clean before repointing is carried out to ensure the mortar adheres to the masonry (Fig. 24).

Dampening down: Where mortar is being applied to a porous masonry background the areas to be repointed should be thoroughly dampened just prior to mortar application (Fig. 25). The amount of water required for this will vary depending on the porosity of the stone and the weather conditions. The wall should be damp but not saturated and there should be no standing water on the stone surface. Dampening down the masonry in this way prevents the mortar from rapidly dewatering (losing water due to suction from adjacent materials) upon application to the porous masonry. Dewatering results in failure of the mortar as the rapid drying of the mortar makes it weak and friable.

Hard impermeable stones should not be dampened. Their inability to absorb water results in the formation of a film on the surface, preventing adequate adhesion between mortar and stone, which can ultimately lead to failure of the mortar.

This substrate preparation stage is a good time to address issues relating to masonry deterioration or damage. Where required, stone repair and/or replacement should be carried out in conjunction with repointing works. Information and guidance on the repair and replacement of stonemasonry can be found in other publications [31,32] (see section 9).

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Fig. 23 Raking out old decayed mortar.

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Fig. 24 Brushing off.

Fig. 25 Dampening down.

Preparing the mix

The following principles should be followed although manufacturers' guidance should always be consulted as some variations in preparation regime may be required for different materials:

- When using bagged lime, use a set of site scales (fisherman's scales are adequate) to weigh material. This helps avoid inaccuracy. If this is not possible, measure out by the full or half bag (weight) to ensure correct quantities. Measuring by volume can be inaccurate as this does not take account of the variations in RBD of different binders, which can affect binder:aggregate ratios.
- Use sand which is washed and free from dirt and contaminants. When calculating mixes based on RBD, remember that damp sand and dry sand have different bulking values. Where sand has been exposed to rain, adjust the sand content and water content to account for moisture in the sand.
- Only use clean, potable water so as not to introduce ground water salts and/or other contaminants to the mix.
- Add water cautiously, starting with the minimum quantity – mortars will become more plastic and wet as they are thoroughly mixed. Adding too much water can result in failure of the mortar due to increased shrinkage and associated cracking. The mortar should be fit for purpose – stiffer, stickier mortars for repointing hard, impermeable stone; more workable mortars for more porous stone.
- Ensure adequate mixing time is allowed for the mortar to reach a workable condition. Mortar should generally be mixed in a forced action mixer as this ensures more homogeneous, consistent mixing of the mortar (Fig. 26), although some lime binders may be mixed using a bell mixer (the standard builder's mixer). Check manufacturers' guidance for best practice.
- Do not attempt to mix, or apply, mortar to elevations in very cold conditions (<5ºC), or in direct sunlight, strong winds or heavy rain, without the use of protection. Failure to protect the mortar from these conditions during preparation and application can result in excessive drying and incomplete carbonation.

Lime should only be used in temperatures of 5ºC or more. Low temperatures will inhibit carbonation and make the mortar more vulnerable to frost damage (Fig. 27). Lime mortars should ideally be allowed to cure for three months prior to exposure to frost; this allows the mortar to build up a degree of protection against imminent and future episodes of frost. As the working season is so short in Scotland, there is a temptation to push the materials to their limit and work in curing conditions that are far from ideal. To avoid unnecessary failure of lime mortar it is vital that work carried out in cold conditions be adequately protected (see section 8.6).

Fig. 26 Batching up using a 'forced action' or 'paddle' mixer.

Fig. 27 Frost damage to lime harling.

Cold mixed lime mortars

Most lime mortars used today are prepared as cold mixes due to the ready availability of bagged limes. Dry aggregate and powdered lime should be thoroughly mixed together before adding water to ensure an even consistency of the mix. Water should be added to the mix slowly until the desired consistency is achieved; excessive amounts of water can result in shrinkage and cracking of the mortar during drying, ultimately leading to failure. Leaving the mortar to stand for several hours allows it to 'fatten up' (become more workable) although the ability to do this is largely dependent on the hydraulicity of the lime as hydraulic limes begin to set relatively quickly.

When using a lime putty, the putty is mixed with dry aggregate in the appropriate proportions to produce 'coarse stuff' (or 'fine stuff' depending on the aggregate size). Lime putty has sufficient water entrained within it to produce a good mortar without the addition of extra water and if left for a period of time plasticity will be regained on re-mixing. Lime putty mortars improve if the mortar is allowed to mature for around 12 weeks before being used. This is rarely practical for modern sites but pre-made matured putty mortar makes the process more convenient.

Hot lime mortars

Traditionally lime mortars were generally made as 'hot lime' mixes [33]; that is a mortar made with quicklime (rather than dry hydrated lime) that generates heat as it reacts with water, either in the damp sand, or water added to the mix. Hot limes can either be used while still hot, or can be allowed to cool and then re-mixed before being applied in the same way as a cold-mixed mortar. The two processes can be differentiated using the terms 'hot lime' for the former and 'hot slaked lime' for the latter. Both methods give the advantage of enhanced adhesion within the mortar as the etching action of the slaking quicklime on the sand grains creates a mechanical key.

Hot lime mixes: Quicklime is mixed with sand and water in the desired proportions and left to slake for a relatively short period of time. The resulting mortar is used hot or warm, and as a proportion of slaking continues *in situ*, the mortar expands to fill voids and to create a stronger bond with the substrate. This technique prevents large quantities of moisture being trapped to the body of the building as any free moisture is bound into the lime mortar as it slakes. This is particularly useful for thick walls and where speed of construction is important. Hot limes can be used for all applications but are particularly beneficial for use in repointing hard impermeable stones in exposed conditions. The mortar continues to expand a little once placed and becomes compacted into the joint; in conjunction with pressing back and scraping this reduces the risk of capillary crack formation and ensures a tight, compact yet permeable repointed joint.

'Hot slaked lime' mixes: Quicklime is mixed with damp sand in the desired proportions and left to slake fully for a substantial period of time (usually overnight, sometimes for several weeks). After this time the mortar is re-mixed. This type of 'hot slaked' lime mortar can be used for all types of lime work including bedding, pointing and harling.

Re-mixing mortar

'Knocking up' is the re-mixing of a mortar that has been left to mature. As mortar matures in storage it will stiffen up and can appear dry and solid. However, a lime mortar will regain its plasticity as it is knocked up, as the entrained water is released during mixing. Therefore, additional water should not be added until after knocking up as this may make the mortar too wet, increasing the risk of shrinkage, cracking and failure; additional water is not always required.

Strongly hydraulic limes hydrate relatively rapidly, and re-mixing of the mortar can break the bonds that form during hydration, which cannot be re-established, resulting in a weaker mortar with lower adhesion. There are maximum time lapses that should not be exceeded for the knocking up of natural hydraulic limes. Typical times are 24 hours for NHL 2 and NHL 3.5 and 16 hours for NHL 5 mortars. Variations in this timing will exist between different binders so it is always advisable to consult manufacturers' guidance on re-mixing.

8.5 Mortar application

Mortars used for different functions not only require different specifications and preparations but are often applied using different tools and techniques. The following sections provide some useful information on what to consider when carrying out different types of repairs.

Repointing rubble masonry

Whilst lime mortar is a robust material, over time it will erode and walls will periodically require repointing to reinstate any loss in function (Fig. 28). The natural weathering processes that occur over time may cause the appearance of both lime mortar and masonry to change, and often an aged 'patina' can form. It is important to note that changes such as these, and others relating to biological growth for example, do not necessarily indicate a need for remedial action [34,35]. The decision to repoint mortar joints should be based on an assessment of the physical state of the mortar and the likelihood of it causing potential damage if action is not taken.

Mortar that has become 'friable' can often act as a sponge, retaining water, rather than promoting its evaporation, and can ultimately lead to the ingress of moisture into the masonry. Additionally, mortar that has been weathered back forming a recess often requires attention due to the pooling of water on this surface, and its subsequent penetration into the building core. Where mortar has decayed significantly, it increases the risk of displacement or loss of stone from the wall fabric.

There is a general assumption that where cementitious mortars have been used in conjunction with stonemasonry, their removal and replacement with lime is essential. Although this might be the best course of action in many cases, there are instances where the removal of hard cement mortars that are well adhered to the substrate can cause excessive amounts of damage to the masonry. Cement mortars should only be removed where it is clear that they are damaging the masonry, and where removal would not cause greater damage.

Repointing requirements vary from site to site, depending on the level of deterioration of the existing mortar. Where degradation is localised, patch repairs might be appropriate, but if larger areas require attention then it may be worthwhile to repoint the whole wall in order to prevent a patchy appearance. Where repairs are to blend in with existing material, analysis of the aggregate in the original mortar can assist in matching colour and texture. It should also

Fig. 28 Repointing rubble masonry.

be kept in mind that historically it was local materials that were used for mixing mortars, and the aggregates found in historic samples may not always be the most appropriate for the job. Specification of materials should be sought from an experienced consultant prior to commencing any repair work to prevent unnecessary failures. Furthermore, it should be acknowledged that replication of the existing mortar can be inappropriate in some situations as the weathering of the mortar and potential leaching of lime binder over time results in the apparent alteration of mix ratios. Ratios determined by analysis do not necessarily reflect the original mix proportions.

Pinning stones

The joints in traditional rubble stone masonry walls were commonly filled with small 'pinning stones' which served several purposes [36]: to help stabilise and secure the larger stones in the wall and to minimise the amount of mortar required to fill the joints, reducing the risk of shrinkage and cracking of the mortar. Pinning stones were typically small off-cuts formed during the dressing of larger masonry units and often were used for decorative effect (e.g. ladder pinning, Fig. 29). Additionally, pinning (or 'galleting') saved money as mortar was more expensive than rubble masonry. Wherever pinning stones are found in a wall they should be retained and the finish carefully replicated. Many beautifully pointed walls have been damaged by careless repointing, where the significance of the pinning stones has not been understood (Fig. 30). Pinning stones are generally thought to be appropriate where joint width is in excess of 15mm.

Fig. 29 Ladder pinnings, 1790.

Fig. 30 Poorly replicated ladder pinning.

Styles of pointing

There are a number of different ways in which pointing can be finished. Although often chosen for aesthetic reasons, the different styles can have an impact on how the façade functions, particularly in relation to moisture transmission (Fig. 31). Original pointing styles should be valued. When repointing a structure, it is advisable to identify the original pointing style, and to replicate this in any repair work. Different phases of repair may have adopted different pointing styles, in some cases these may be technically incorrect; it is important only to replicate pointing styles that will not have an adverse effect on the condition of the masonry.

Flush: As the name suggests, flush pointing is finished smooth and flush with the masonry surface. The lack of any recesses or ledges at the mortar-stone interface means that water does not pool, but runs straight off the face of the building. Flush pointing was the primary style of pointing for most traditional rubble or squared stone buildings in Scotland. This method of pointing was typical for most buildings except where the masonry is ashlar, brick and/or other high quality or decorative masonry. On more formal elevations flush joints in rubble masonry were often lined-out to give the impression of more regularly shaped masonry units.

Slaister: Slaister pointing, sometimes referred to as 'harl pointing', involves the spread of mortar beyond the joints, partially over the surface of the adjacent stonework. This finish is often hard to distinguish from a thin, weathered lime harling.

Cherry caulking: Also termed 'cherry cocking', this pointing style involves the use of pinning stones, which are placed continuously along the joints, both vertically and horizontally. The use of pinning stones is in this method is equally functional and decorative.

Bucket handle: So called bucket-handle pointing is created by pressing back the mortar joint with a curved tool to leave a concave finish.

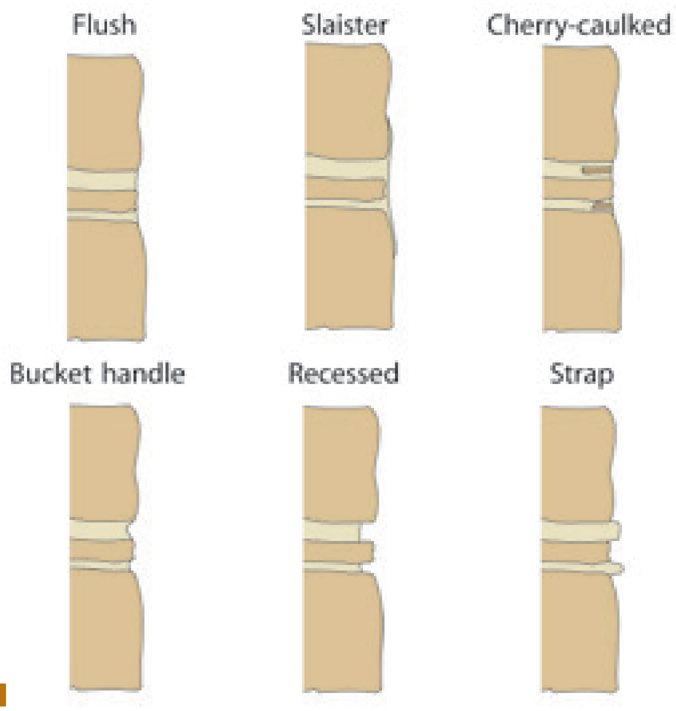

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Fig. 31 Pointing styles.

Recessed: This is a modern interpretation of presenting masonry. The mortar is finished in such a way that it is set back from the masonry surface. This type of pointing is not recommended as it promotes the pooling of water at the masonry-mortar interface and can lead to excessive ingress of water into the structure. This finish was developed in the mid 20th century in conjunction with the use of cement mortars.

Strap: Like recessed pointing, this is essentially a modern style. In this style of pointing, the mortar projects beyond the extent of the masonry (Fig. 32). This is commonly seen in cement mortars and was perceived to be 'fashionable' but causes the pooling and ingress of water and ultimately leads to accelerated masonry deterioration.

Repointing ashlar masonry

Ashlar is a type of masonry construction in which high quality regular stone blocks are tightly bedded with very fine joints, typically a few millimetres wide (Fig. 33), unlike the joints in rubble masonry, which can be in the region of 10mm or more. The tight spaces into which the mortar must be pointed mean that mortars typically used for pointing rubble are not suitable for ashlar work simply due to the size of aggregate grains. Based on the general rule of using a maximum aggregate size of one third the joint width, sand used for making ashlar pointing mortar is typically in the region of 0.25-0.5mm, although traditionally a straight lime putty or lime putty/whiting mix was often used. A small quantity of linseed oil was often added to the mix to improve workability and provide a degree of waterproofing. Although they are negligible in width, ashlar joints maintenance is important in weatherproofing the building façade. Degraded ashlar pointing can lead to water ingress through capillary action just as in rubble masonry, and missing mortar provides an open pathway for rainwater to enter the structure, especially at projections such as cornices.


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Fig. 32 Cement strap pointing.

Fig. 33 Repointing of ashlar with a lime putty mortar.

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Fig. 34 The distinctive texture of harling.

Fig. 35 Mechanical spray harling using a render gun (© G. Frew).

Extra care should be taken when repointing ashlar to ensure that mortar is applied only to the joints, and is not spread on the surface of the stone (injection may be appropriate). Taping of the masonry around the joints can help prevent staining from lime run-off, as can dampening the masonry prior to work, but where staining does occur, it should be washed off immediately. Ashlar joints should ideally be pointed to a depth of 30-40mm. The same aftercare guidelines for rubble pointing should be adopted (section 8.6).

Harling and rendering

Lime harling and rendering provides an important protective layer to masonry structures that enhances their breathability and ability to withstand the elements [5]. Its maintenance is vital in ensuring the longevity of masonry and in keeping the building or structure dry.

Harling was traditionally hand applied by casting it on to the wall, in contrast to renders which are typically worked to a flat finish using a float. Hand-casting gives harling a very distinctive finish (Fig. 34). In modern practice, both finishes can be achieved by mechanical spray harling using a 'render gun' (Fig. 35) but for conservation and repair work it is it is preferable to employ traditional application methods, at least for final coats.

Fig. 36 and 37 Before and after a patch repair to lime harling (© G. Frew).

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With the use of correct aggregate, patch repairs to harling can be made to blend in with the original material. To achieve as seamless a finish as possible, analysis of the original harling might be undertaken to provide details on the aggregate characteristics. Matching this texture as closely as possible helps maintain the visual integrity of the coating (Figs 36 and 37). A coating of limewash over the entire surface may also be beneficial for this reason. Where a suitably matching aggregate cannot be sourced, it may be advisable to use a combination of sands and/or gravels to achieve the desired texture.

Appropriate specification of mortar for harling is vital in ensuring it fulfils its role. Harling was typically applied as one or two coats, and in modern practice rendering has up to three coats. Initial coats of harling or render must be compatible with the masonry substrate and the pointing mortar, and successive coats should be compatible with those beneath. To ensure the outward diffusion (and evaporation) of water, breathability of coats should successively increase towards the outer surface. This is typically achieved using progressively weaker mixes.

Many modern formulated renders contain lightweight fillers and additives such as air entrainers and water-proofers. Such materials should only be used in conjunction with historic stone masonry if their compatibility has been assessed and is deemed acceptable. These materials can be pigmented ('through-coloured') eliminating the need for decorative limewashing. However, colouring in through-coloured renders can appear very patchy if the materials are inappropriately prepared and/or applied, where they are inadequately protected from the elements, or if drip details are not correct.

Limewashing

As well as being used as a decorative finish, limewash is a protective, sacrificial coating that provides a traditionally constructed building with its first line of defence against the elements. It was often pigmented with natural, locally sourced compounds such as iron oxide and vegetable pigments. Performance additives such as tallow (animal fat) and casein (milk protein) were added to limewash to enhance its properties [37,38], giving it a more durable 'weatherproof' finish.

As the most exposed element of a traditional building, limewash often weathers at an increased rate and as such will require a greater degree of care and attention. Limewash can develop a patchy appearance as it weathers, although discolouration can also indicate the presence of moisture or salts (Fig. 38); this may be a sign of more serious problems in the underlying masonry caused by a number of factors. Re-limewashing should be seen as a form of maintenance and should be carried out periodically, perhaps every five to fifteen years depending on the level of exposure. Limewash is intended to be sacrificial and will not last indefinitely. Where tallow limewash is used to provide a degree of waterproofing, it should be on the outermost layer only. The nature of this type of limewash means that subsequent layers will not easily adhere to it, therefore a period of time is required for it to weather before it can be recoated.

Limewash was traditionally applied by brush in thin coats, and burnished (worked into the substrate in circular motions) to ensure a well adhered consistent coating. Modern practice should follow these principles to ensure success of the limewash; recommendations to apply the limewash by roller or by spraying are not normally appropriate. Failure to apply the limewash properly can result in flaking or the formation of a powdery residue on the surface.

Modern limewash with an adhesive additive such as Polyvinyl Acetate (PVA) is sometimes used for coating relatively impermeable surfaces; the additive gives the material the ability to bond to the background surface. The introduction of

Fig. 38 Patchy appearance of limewash requiring maintenance.

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Fig. 39 Full façade protection of lime render with hessian covers (© G. Frew).

a synthetic polymer will undoubtedly have an impact on the breathability of the limewash, although the extent of this is somewhat unclear. Manufacturers' technical data should be consulted to identify any additives. Where technical data is not available, it is not advisable to use the material.

8.6 Aftercare

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

- After application of pointing, and once an initial set has been achieved, press the mortar back with a trowel or stiff brush to create an open texture and promote carbonation. The mortar should not be repeatedly worked, as this can cause surface laitance, weakening the mortar beneath.
- Prevent rapid drying of mortar in warm and/or windy conditions by covering the masonry with damp hessian (Fig. 39) or plastic sheeting to protect the mortar while it cures. Hydraulic mortars will need to be kept damp for several days to ensure the onset of hydration reactions. Air limes should undergo a number of dampening/partial drying cycles to promote carbonation.
- Provide protection from rain as failure to do so can wash out the lime or cause it to bloom on the surface. As well as being unsightly, this will hinder carbonation and weaken the mortar.
- Where winter working is required, there are a number of additional measures that must be taken to protect the mortar from frost. Protection options include using fully enclosed scaffold systems with heaters, or covering masonry with layers of hessian, bubble wrap, or other insulating material. When covering masonry with insulating material, ventilation should be maintained to allow carbonation to proceed.
- Allow time (several days) for the onset of carbonation of the mortar before applying render or surface finishes such as lime paint or limewash. The same practice should be adopted for applying subsequent coats of render or limewash.

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10. Glossary

Additive: *Any natural or man-made component added to a lime mortar mix with the aim of enhancing its properties in some way.*

Aggregate: *Sand, crushed rock and/or gravel that is used in conjunction with a binder and water to produce a mortar.*

Bentonite: *A natural clay mineral added to mortar when wet to enhance plasticity and increase workability.*

Binder: *The binding agent, used in conjunction with aggregate and water to create a mortar. Typical binders used in construction include lime, clay, earth, gypsum and cement.*

Breathability: *A measure of the ease with which moisture can pass through a material when in the vapour phase. Also known as vapour permeability.*

Burnishing: *The vigorous working of the surface, typically with an emulsion brush, after the application of limewash. Burnishing works limewash into the surface, ensuring even coating and aiding adhesion.*

Cement: *A binder produced from the burning of limestone and clay at high temperatures. The presence of calcium-silicates and calcium-aluminates gives cement a fast set. The dense network of these components in cements gives them low permeability and breathability.*

Concrete: *The material made from combining cement with aggregate and water.*

Cured: *The term given to a mortar that has set and hardened.*

Deterioration: *The degradation of stone due to physical, biological or chemical weathering mechanisms (see 'weathering').*

Dewatering: *The rapid loss of water that occurs when a mortar is applied to a porous substrate on which suction has not been controlled by dampening down.*

Fatten up: *The cyclical process of dissolution (or water absorption) and reprecipitation of uncarbonated lime particles that leads to an increase in the plasticity of the mortar due to the precipitation of increasingly finer crystals. Well matured lime is said to be 'fat'.*

Float: *A flat tool that can be used for smoothing off surfaces on renders and plasters.*

Hydrated lime: *Powdered lime formed from the slaking (addition of water) of quicklime. This term may be used in reference to hydraulic limes or air limes, but is typically used for the latter.*

Knocking up: *The re-working of lime mortar that has been left for a period of time to mature. Knocking up helps regain plasticity of the mortar. The suitability of this process is dependent on the type of lime. Hydraulic limes that have begun to 'set' should not be knocked up as this breaks the bonds in the hydrate components, and these cannot reform – the result of which is a weak mortar.*

Laitance: *The thin layer of fine lime particles that migrate to the surface of lime mortars. Laitance reduces the breathability of the mortar due to its very fine grained and less permeable texture. Laitance is made worse by overworking lime but can be removed by 'beating back' with a hard bristle brush, or gently rubbing with an abrasive pad.*

Lime: *Calcium oxide, the product of burning limestone to temperatures in the region of 850°C.*

Limestone: *A sedimentary rock formed by the compaction of calcium carbonate components, either from marine organisms (e.g. corals, shells) or precipitation from sea water.*

Lime mortar: *A mixture of lime, aggregate and water that can be used to bond building components together.*

Mortar: *A material used in construction for bridging the gaps between blocks of masonry. Mortar acts both as an adhesion medium, and a means for protecting the interior of the building from the ingress of rainwater. Mortars are 'plastic' or pliable when fresh and set to form a hardened material.*

Natural hydraulic lime (NHL): *A lime binder with a proportion of active silicates and aluminates that react with lime in the presence of water to produce hydrates. These silicates and aluminates originate from the limestone from which the lime was burned.*

Oscillating tool: *A mechanical (power) tool with blades that move back and forth, rather than in a rotary motion. Oscillating tools are thought to be less damaging to masonry than rotary grinders.*

Pozzolan: *A natural or man-made material that can be added to a mortar to enhance the set (i.e. speed up the curing of the mortar and give the mortar strength). Pozzolans are typically silicates and/or aluminates that bind with the lime to produce binding calcium-silicate-hydrates and/or calcium-silicate-aluminates, effectively creating a hydraulic lime. The term 'pozzolana' refers to a natural material of volcanic origin from which the more general term pozzolan is derived.*

Pulverised fuel ash (PFA): *Ash collected from exhaust filters (usually from power stations) that can have pozzolanic properties.*

Putty lime: *Hydrated lime binder that has been slaked with an excess of water forming a wet paste that can be left to mature over time.*

Seeding: *The nucleation of lime crystals on the surface of particles (usually of the same composition). Seeding particles can act like a catalyst, speeding up the carbonation of lime mortars.*

Sharp sand: *A well graded sand consisting of angular grains. Typically used in lime mortars for bedding, pointing etc.*

Substrate: *The base to which a material is applied. In the current context, the stonemasonry to which mortar is applied.*

Vapour permeability: *See breathability.*

Weathering: *The processes, both natural and man-made, that result in the physical and chemical change of stone. Weathering processes include salt crystallisation, wetting and drying cycles and frost action, as well as deposition of pollutants and growth of biological and/or mineral crusts on stone surfaces.*

Whinstone: *An informal term referring to several types of dark hard rock.*

Whiting: *The term typically refers to crushed chalk. Whiting is often mixed with lime putty for pointing very fine joints such as ashlar.*

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