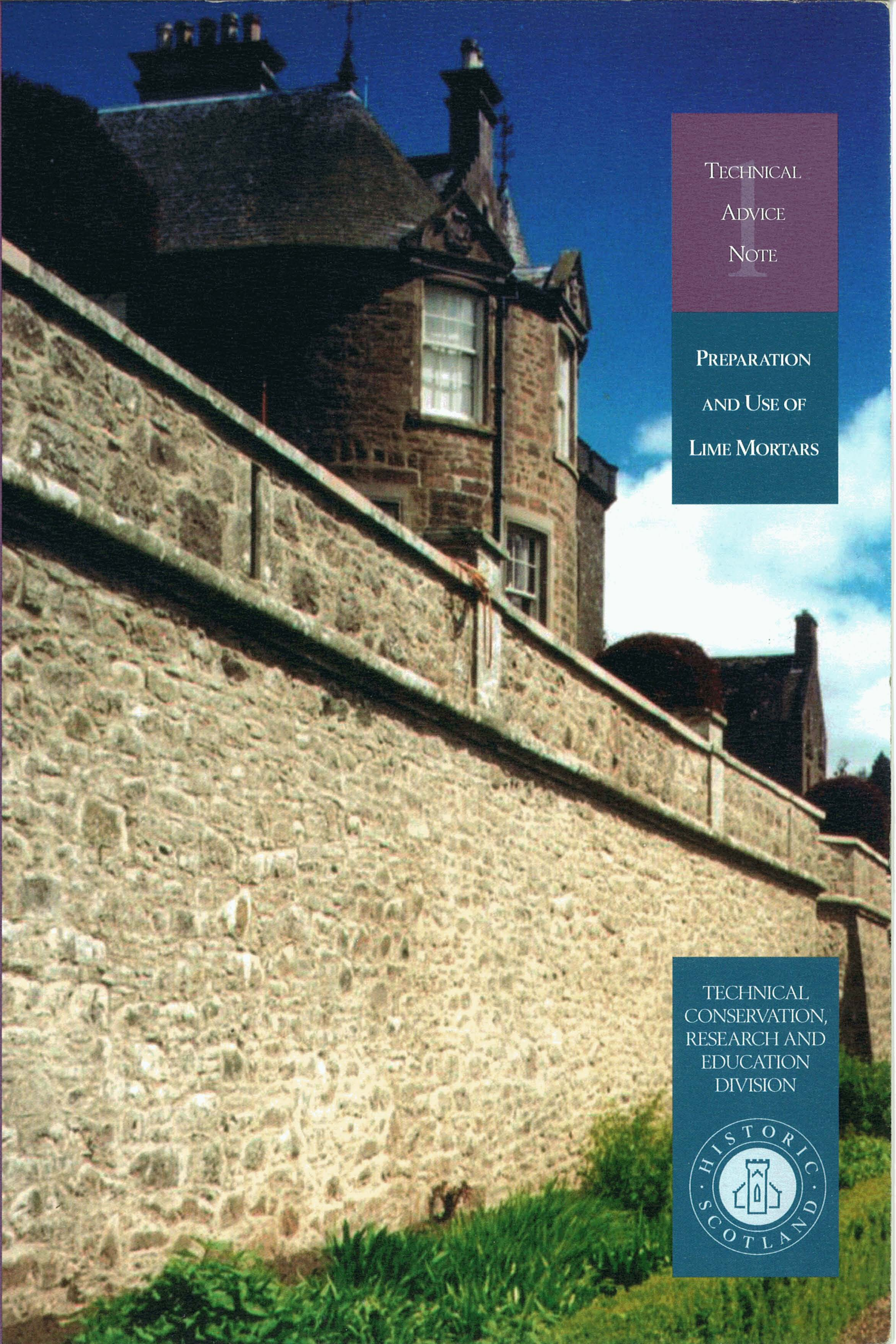

TAN 1

PREPARATION AND USE OF LIME MORTARS

Technical Advice Note 1

Preparation and Use of Lime Mortars

Technical Conservation, Research and Education Division

Historic Scotland

Historic Scotland Technical Advice Notes

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TECHNICAL

ADVICE

NOTE

PREPARATION AND USE OF LIME MORTARS

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This substantially revised and updated Technical Advice Note has been prepared by Pat Gibbons of the Scottish Lime Centre Trust. It draws on the text of the original TAN 1, updated to reflect developments since 1995, with additional contributions from Steve Newsom.

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Appearing as an embryonic "in-house" typescript document of 9 pages in November 1988, TAN 1 "Preparation and Use of Lime Mortars" was heavily revised and republished in expanded and illustrated format in 1995. That volume offered a public introduction to lime as the material central to the repair and conservation of traditional buildings. It aimed to promote the principles of the use of lime and to give pragmatic guidance needed by specifiers and contractors for the appropriate use of lime mortars for building, pointing, harling and rendering of existing buildings, and their application to new construction.

The years following that publication have seen much new research into the performance and characteristics of lime mortars in both in the United Kingdom and Europe. Related and necessary development of practical training to improve lime skills at craft, trade and practitioner level has also taken place.

Although lime products are now more readily available for building purposes, production in the UK remains at a low level. Specifiers must generally rely on material imported from elsewhere. Recognising the need for indigenous supplies Historic Scotland has researched sources of Scottish limestone with the aim of encouraging the reintroduction of lime production in Scotland for building purposes. (A research volume on this is pending publication)

Since 1995 public awareness of the intrinsic, cultural and economic value of the built heritage has also developed. This has been stimulated by a growth in tourism and a recognition of its importance to the economies of all nations. This is allied to a wider understanding of the conservation of historic buildings and what actions may be, or may not be, appropriate when these buildings are repaired. Public appreciation of historic buildings – whether as user, visitor or potential purchaser –continues to grow and those involved with the care and maintenance of such properties are increasingly aware of their responsibilities in the promotion of good conservation practice.

This enlarged and updated TAN supersedes the 1995 edition. It draws on the pragmatic research and accumulated experience of the intervening years, whilst adhering to the principles set out in the earlier release. It includes new or enlarged guidance on environmental issues, porosity, available types of lime, and British and European Standards. However, it retains the objective of offering best-practice advice for masonry repair and repointing work. (External lime coatings and internal plasterwork are covered by related publications in the TAN series).

Unfortunately, loss of the built heritage continues to occur at many levels - often resulting from misunderstood practices - and can remain overlooked until damage has been done. But loss can be prevented through a better understanding of the correct materials and methods to be employed in repair and conservation projects. This publication is intended to build upon earlier guidance to help ensure that damage to the built heritage is reduced to a minimum, and that good practice in the use of lime continues to be more widely recognised, understood and applied.

Ingval Maxwell
Director TCRE Group
Historic Scotland
Edinburgh
February 2003

SUMMARY

This Technical Advice Note covers a range of issues in connection with the selection, production and use on site of lime based materials, aiming to provide a comprehensive overview of current practice in Scotland. In addition to the basic technology of lime based materials, the publication concentrates on the use of lime mortars for masonry repair and repointing – guidance on the use of lime based mortars for internal plasterwork is contained in TAN 2 *Conservation of Plasterwork (1994) revised 2002*, and for external finishes in TAN 15 *External Lime Coatings on Traditional Buildings (2001).*

The TAN begins with a discussion of the reasons for using lime mortars and sets their use in the wider context of historical background and current practice.

This is followed by a section on the technology of lime – its origins in limestone or other calcareous materials, the processing and conversion of these materials, and their behaviour as building materials. Further sections provide a detailed explanation of the various materials which go to make up a lime mortar, including the range of limes which might be found in historic and traditional buildings in Scotland, a review of currently available limes, and notes on the selection of sands and other materials which may be incorporated in lime mortars.

The processes and techniques of making lime mortars, covering traditional and more recent practice, are described in detail. This is complemented by a section on site practices and skills in the application of lime based materials, which explains in detail the practical issues involved in the preparation of the work, in repointing and other types of work, and in the requirements for effective curing of lime based materials.

A final section provides guidance on specification, covering general issues, selection and production of materials, and specification of working practice. Because each project will be different the provision of model specifications is avoided, but the guidance contained in this TAN should enable informed choices to be made on selection of materials and their production, application and, importantly, aftercare, to ensure appropriate and effective repairs to traditional masonry buildings.

Appendices provide supporting information, including a summaries of good site practice and diagnosis of defects, a suggested approach to drafting specifications for lime based works, a note on safe working practices, a glossary of the terms used, a bibliography for further reading, and a list of useful addresses.

If used appropriately, lime based materials will be effective for the repair and maintenance of traditional buildings where these were originally constructed using these materials, but they do require to be used with a degree of understanding and care. The need for a grounding in the principles of building conservation and a sound, practically based, knowledge of the use of lime, remain the essential starting points for high quality work.

1 INTRODUCTION

"And nothing in nature can be imagined more serviceable for all manner of uses."

Reference to lime from Alberti's Ten Books on Architecture, mid 15th century.

1.1 Why use lime mortars?

Lime based mortars are an essential part of the longstanding Scottish tradition of 'stone and lime' building. The most effective methods of repairing and maintaining traditional masonry buildings almost invariably involve the use of materials and techniques employed in their original construction. Traditional lime mortars are made from a mixture of lime and sand or other aggregates. The type of lime used, the inclusion, or not, of various additives, the proportions of the various ingredients and the methods of production and use influence the final properties of the mortar. Traditional lime mortars are more permeable and more flexible than cement mortars, they are less likely to cause decay in adjacent stone arrises (but see below), and they are more 'environmentally friendly' than cement mortars. In their historic context they also look better. It is the mixing of two different building technologies which tends to cause the most serious maintenance problems in older buildings – hard, rigid, impermeable repair materials cannot be introduced into 'soft', flexible, permeable buildings without undesirable or damaging consequences.

Weatherproofing

Traditionally-constructed masonry buildings rely for their weatherproofing on their ability to hold and evaporate moisture. Both lime and stone are porous materials, some more so than others, and cannot be totally waterproofed even by the application of modern materials. Lime mortars and harlings can absorb water and subsequently allow it to evaporate from the building.

Experience over the last 30 years or so has increasingly demonstrated that the most effective method of maintaining lime-built structures is to repair like with like. Solid-wall masonry structures exclude water from the interior of the building by absorption and evaporation. A typical rubble masonry wall will consist of outer skins of masonry with a rubble and rough lime mortar core. The individual stones are closely laid, often in direct contact, and are stabilised by small pinning stones and by the mortar filling. This type of construction handles moisture, or even direct water penetration, by 'mopping up', or absorbing, the water before it can penetrate to the interior and by allowing the moisture to evaporate back to the outside air. With some relatively impermeable types of stone constructed with fine joints this drying process may be very slow, and it is important that the mortar remains as permeable as possible to assist in the drying process.

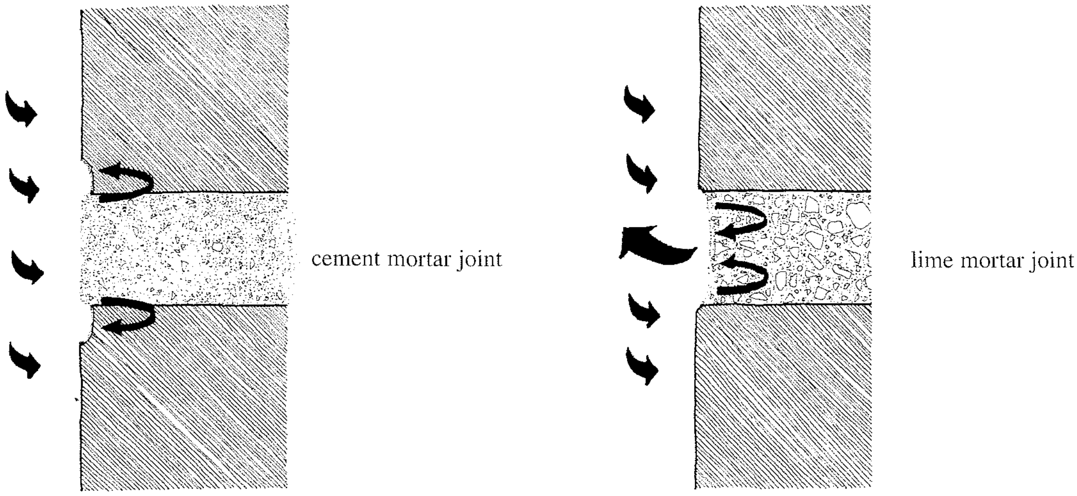
With dense impermeable building stones the presence of a mass of permeable lime mortar, in the wall core as well as the joints, is also essential if the structure is to exclude water. Without this ability to mop up penetrating water, wind driven rain may penetrate through open joints, through hairline cracks in cementitious mortars or through fissures in the masonry itself, and appear on the interior faces of external walls. In addition, the use of lime mortar in the joints or at the wall surface of these buildings, in the form of pointing or partial or complete harling, assists by providing a route for evaporation of moisture which is not available through the stones themselves. In fine jointed granite masonry, for example, the rate of evaporation through the stone is minimal and evaporation through the restricted joints will necessarily be slow but will, nevertheless, be better than could be expected with a cement based mortar.

Most traditional rubble masonry buildings were originally given a coating of lime mortar, which contributed to the effectiveness of the moisture holding and evaporation cycle. The loss of these coatings or, in the case of many more recent masonry buildings, their total absence, can in itself be a cause of water penetration which is not easily remedied by repointing.

Stone decay

One of the other significant disadvantages of hard impermeable mortars (usually cement based mortars) is their role in causing or accelerating stone decay. This form of decay involves two basic mechanisms: firstly, because the mortar allows for little or no movement of moisture or moisture vapour through the joints, moisture absorption and evaporation is concentrated in the stone immediately adjacent to the mortar joints; and, secondly, the setting process of cement based mortar results in the production of potentially damaging soluble salts. The interaction of these two mechanisms can be detrimental to many building stones.

The hydration of cement oxides (which occurs in cement based mortars) produces highly complex calcium silicates and calcium aluminates (C-S-H & C-



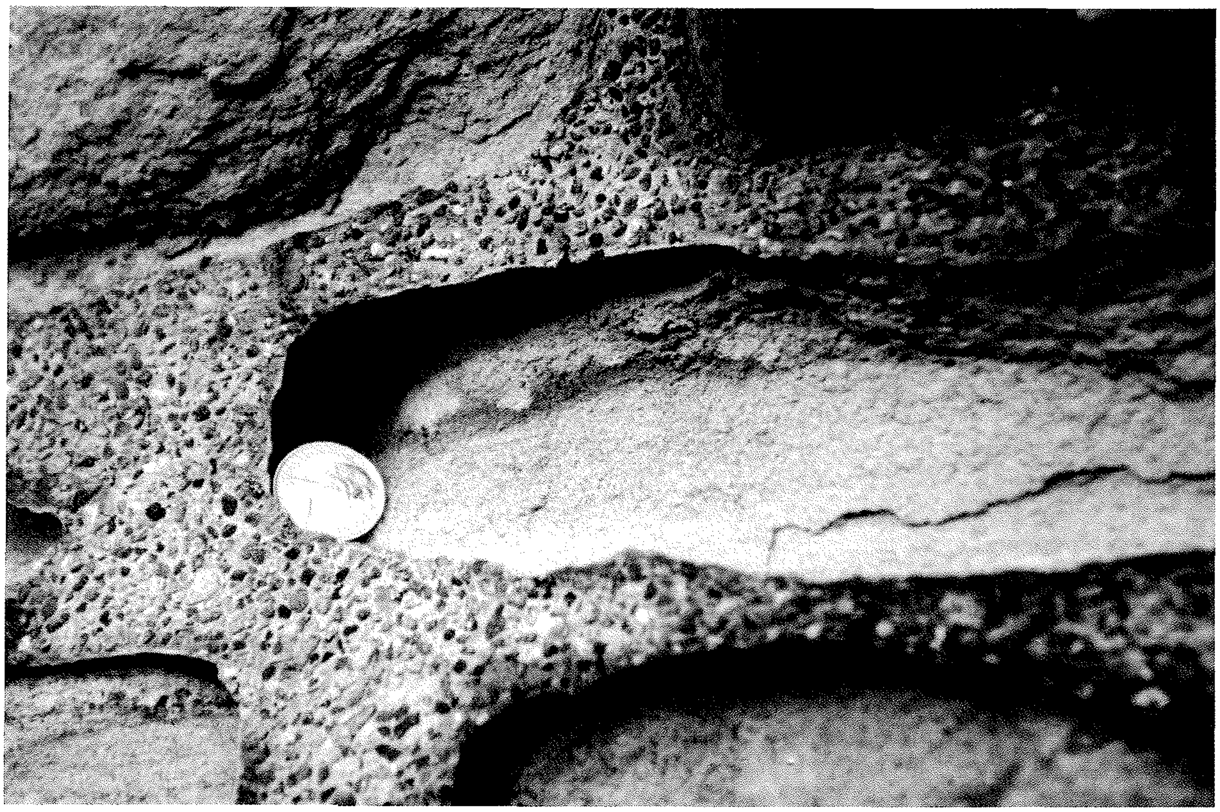
Moisture penetrates at the joint interface and evaporates through the stone. The face of the stone weathers back

Moisture penetrates and evaporates through the mortar. Over time the face of the mortar joint weathers back

Figure 1. Movement of moisture and associated decay at masonry joints.

A-H), resulting in a mortar which is generally harder, more dense and less permeable than the surrounding stone. Due to their reduced porosity and reduced permeability, these mortars tend to concentrate the movement of moisture within the stone, resulting in a local increase in water absorption and evaporation. Porous stone adjacent to cementitious mortar joints is thus liable to an increased risk of frost damage and the problem may be further exacerbated by water trapped by cement mortar standing proud of eroded stone.

If used in association with porous or friable sandstones, cementitious mortars may result in the transfer of soluble salts (originating in the mortar setting process or from ground water, road salts, etc), into the pores of adjacent sandstone, where subsequent crystallisation can induce rapid stone decay in the vicinity of joints. Over time, a combination of these two effects leads to an accelerating cycle of stone decay, water entrapment and further decay.



1. Typical stone decay associated with the use of impermeable mortars.

A similar, but usually less severe, mechanism can also be observed in some situations where the migration of calcium sulphate, from high-calcium lime mortar joints affected by acidic conditions, is deposited in adjacent stones. Moderately hydraulic lime mortars, which are less susceptible to leaching of free lime, are normally recommended for use with granite masonry.

Structural and seasonal movement

Masonry set in lime mortar has an ability to accommodate movement, both structural movement and seasonal/thermal movement, without significant damage.

The modulus of rupture and the bond strength of an appropriate, well cured mature lime mortar are such that movement joints are not normally required in new (traditional) construction. Any movement is taken up by minute adjustment over many joints and, in some situations, hairline cracks may subsequently be resealed by the deposition of lime in solution.

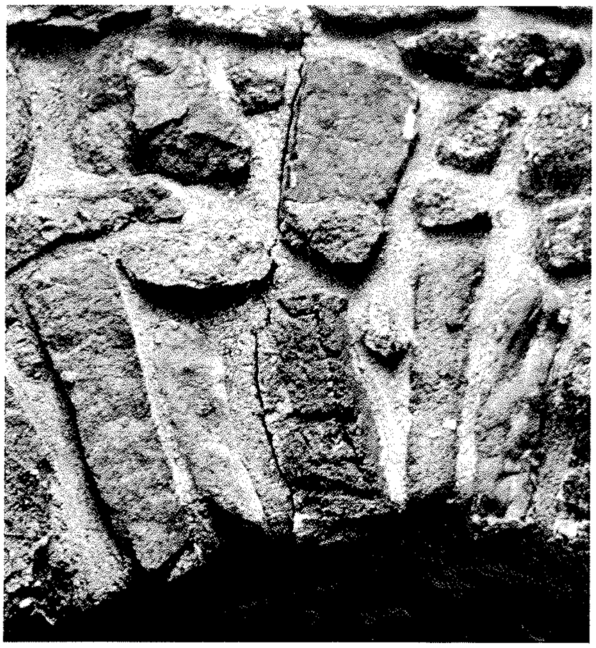
Where repair mortars, whether in structural repairs or repointing, have similar properties to the original mortar then the technology and behaviour of the building is not compromised. The use of alternative rigid mortars in masonry repair can result in cracking in association with the repair and, in extreme cases, in the development of movement joints in the structure. This in turn can lead to water penetration and thus to the start of a cycle of stone decay. Secondary problems, including decay of timbers in contact with the wall, may also follow.

Similarly the use of lime based renders on lime-built structures ensures a degree of behavioural continuity not possible with cement renders, which frequently develop movement cracks and subsequent water penetration problems.

Thermal insulation and condensation control

The external fabric of a building provides a degree of thermal insulation and its breathability will influence the extent to which condensation may occur. Generally, well maintained traditional lime mortared masonry walling, with external and internal coatings of lime-based materials, will provide better thermal insulation and reduced likelihood of condensation than the equivalent construction set, or repaired, in cement based mortars.

Many older lime-built houses have subsequently been coated with impervious cementitious renders and harder gypsum plasters. The tendency of these harder materials to retain moisture within the fabric of masonry walls can, potentially, result in a reduction in the thermal insulation value of the masonry. By allowing or encouraging evaporation, lime based mortars assist in the drying out of penetrating water from the masonry. In addition, because of their lower bulk density, traditional lime mortars have a higher thermal resistance and may therefore perform better as an insulating material. Being permeable, they also offer less resistance to the passage of moisture vapour and can, potentially, reduce the risk of surface condensation.



2. Movement joint in old masonry consolidated in cement-based mortar.

3. Cracking of cement-based render on sandstone masonry.

Environmental issues

In addition to its immediate practical advantage, the continued use of lime mortar in building has environmental benefits. In any environmentally conscious building work a balance needs to be achieved between the needs of the environment, the building occupiers and the building itself and, with growing emphasis on the need to reduce energy consumption and minimise the production of atmospheric carbon dioxide, all forms of building technology are coming under closer scrutiny.

Energy requirements and pollution levels associated with the manufacture of traditional types of feebly hydraulic and moderately hydraulic limes can be significantly less than those for industrial quality non-hydraulic limes and portland cement – generally speaking feebly hydraulic limes can be processed for an energy cost of approximately half that of industrial non-hydraulic limes and portland cements.

It is widely accepted that the best of our historic building stock should be preserved for future generations, but continuing maintenance and use of the wider existing building stock is also important, not least in reducing the need for new building material production. In the longer term, the reuse of building materials such as stone and brick, is facilitated by the use of lime mortars which allow subsequent alteration or dismantling of the building, and recycling of the materials themselves. The basic principles, of reversibility of repairs and the use of 'sacrificial' materials, underlying the conservation of historic buildings are equally applicable to the repair of all traditional buildings. Being a soft material, lime mortar is better able than cement mortars to fulfil these criteria and, in most situations, lime mortars for repointing or repair will be deliberately sacrificial to historic fabric. By employing appropriate lime based materials where there is a need to replace missing and decayed mortars, the surviving historic fabric of masonry buildings may often be protected from further significant decay.

Appearance

The appearance of Scotland's traditional buildings derives directly from the materials used as well as the 'architectural design'. In vernacular building the two are inseparable. Attempts to repair or recreate traditional details or finishes in non-traditional materials are inevitably unsatisfactory from a visual, as well as a practical, point of view. In the Scottish tradition of 'stone and lime' building, colours and textures are derived from locally available materials, which acquire an attractive patina with age.

Where repointing is required the use of suitable lime based mortars can assist in maintaining, or restoring, the original appearance of buildings. Rubble stonework was normally built with the mortar joints filled flush with the stone and, if the surface was not intended for harling, the joint lines were often lightly ruled in. The original character and appearance of such masonry cannot be reproduced in cement based mortar without the risks of water becoming trapped and of accelerated stone decay (see Illus. 4 and 5). Many of the exposed rubble masonry facades seen today were originally intended for harling, but the mannered approach to pointing stonework, developed during the latter part of the 20th century, has resulted in recessed joints placing undue emphasis on individual stones at the expense of the architectural integrity of the facade as a whole.

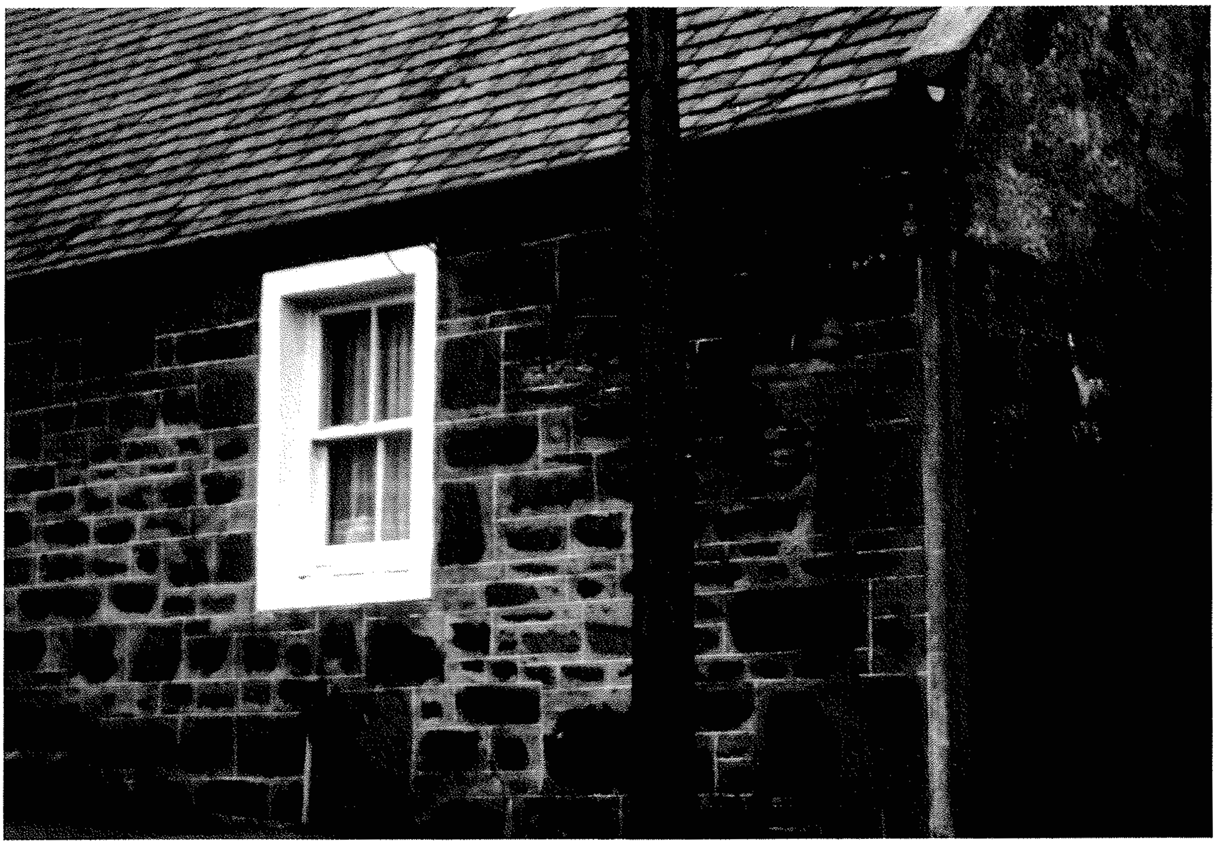
In Scotland many buildings were originally finished both internally and externally in a coating of lime mortar – commonly described as 'plaster' and 'harling' (or, occasionally, 'render'). Where historically appropriate, repair work involving lime based coatings finished in limewash will not only perform more effectively but will provide a sympathetic and attractive finish to the building. The widespread modern practice of applying cement renders gives a uniform blandness without subtlety or regional variation and, as noted above, is likely to compromise the behaviour of the building in the longer term. Where a building was constructed in lime mortar it can be assumed that any harling or render would also have been lime based, although exceptions may be found where 'Roman cement' or oil mastic renders were applied to some of the more sophisticated buildings of the 18th and 19th centuries. In addition to maintaining the practical performance of the building, replacement of harling or render using the original materials and techniques, will almost invariably maintain or restore the original appearance of the building. Technical Advice Note 15, External Lime Coatings provides detailed guidance on the application of lime harling.

1.2 Historical background

Lime, of various types, has been an important building material for many thousands of years and has probably been in use in Scotland for at least two thousand years. Before the use of portland cement became commonplace around the mid twentieth century, lime was the most widely used binder in structural mortars. In addition to its function as a construction mortar, lime was widely used as a finishing material in the form of external harling or rendering, internal plastering and as a protective and decorative coating in the form of limewash.

As might be expected, for all but the most important buildings, lime, like other materials, was sourced locally if possible, and was combined with local sands to make mortars. The nature and properties of lime

4. Original lime pointing and pinning stones.



5. Recent cement repointing to adjacent cottage.

mortars can therefore be seen to vary geographically and, because of the complex nature of Scottish geology, a number of different types of lime, and different sands, were in use.

From the evidence of standing structures and detailed writings we know that the Romans developed lime technology to a sophisticated level. The engineering achievements of medieval cathedrals and castles were largely dependent on lime technology. Late 18th century and 19th century civil engineering works, including lighthouses, harbours, canals, bridges and major industrial buildings, utilised lime based mortars of various types.

As a material, lime has played an essential part in the development of modern civilisation, particularly in the rapid developments associated with the agricultural and industrial revolutions. Its use in improving the quality and fertility of the land supported the expansion of population associated with developing industries. Lime in some form was essential to most of these industries, and was utilised in early medicine, sanitation and water purification. The widespread use of lime in building construction assisted in the greatly increased provision of housing and other structures necessary over this period. Modern industry still makes use of lime in steel making, neutralisation of acidic wastes, ground stabilisation and many other processes.

Traditionally, where ever it has been readily available, lime has been used as a mortar in the construction of buildings and other structures, and as a finishing material, internally as plaster, and externally as harling, render or stucco. The properties of limes from various sources were utilised to best effect and, where necessary, were modified by the use of pozzolans (setting agents) to create mortars suitable for a wide variety of uses. In some parts of the country lime was combined with clay to form mortars and plasters. Clay and earth mortars without any added lime are also found.

1.3 Lime mortars for building repair

Because it is important to understand the nature and behaviour of a building before attempting to carry out repairs, it is important to identify the materials originally used and to recognise the type of lime, the type of sand or other filler, the relationship of the lime binder to the filler materials, the relationship of the lime mortar to the stone (or other construction materials) and the function of the lime based materials in the overall behaviour of the building.

Lime is produced by calcining or 'burning' limestone. The simplest lime-burning techniques involved layering limestone and fuel in a clamp or simple kiln, or even firing in the open. More sophisticated kilns burned lime by means of a separate fuel source (flare kilns) or layered with fuel (mixed feed kilns). Modern large scale commercial lime burning in the UK utilises oil or gas fired kilns, exploiting deposits of high purity limestone to produce quicklime mainly for industrial use. Historic limestone sources in Scotland were more varied and generally less pure than the current English sources, and produced a range of types and strengths of lime, although none are currently in production. In the south of England, in response to continuing demand, hydraulic lime is produced specifically for building purposes from the traditional blue lias sources.

To produce lime for building the quicklime ('burnt' limestone) is slaked with water and combined with sand. There are many different traditional recipes for making lime mortar depending on the type of lime available and on the purpose for which the mortar is required.

Mortars based on pure lime set only by drying and carbonation, that is by absorption of carbon dioxide as they dry out, and are not able to harden if they remain permanently wet. For wet conditions, such as retaining walls, work in or close to the ground, work at parapets, chimneys and gable copes, etc, mortars based on hydraulic lime (of various strenghts) can be used. These mortars have a chemical set in addition to carbonation. For work to masonry buildings it is important to match the properties of the mortar to those of the stone or brick with which it is used, and also to the remaining original mortar, but the stronger modern hydraulic limes may result in a mortar too dense or brittle for use with some types of stone. The processes of carbonation and hydraulic setting are described in Section 2.

1.4 Porosity and permeability

There is inevitably a moisture content in the fabric of masonry buildings and it is essential that this moisture is enabled to evaporate away. Most building stones are porous (ie they will absorb a certain amount of moisture) and, to a degree, permeable to moisture vapour (ie they can allow moisture to evaporate away as moisture vapour). In traditional solid-wall masonry buildings the main route for evaporation is through the lime mortar filling and joints. Where lime harling is present this too makes a significant contribution to the evaporation of moisture.

The nature and behaviour of modern cement based mortars are significantly different from those of traditional lime mortars. Mortars for modern building construction are generally designed in accordance with the requirements of British Standards and Codes of Practice, such as BS 5628-3:2001 Code of Practice for Masonry – Part 3, or BS 8221-1:2000 Code of Practice for cleaning and surface repair of buildings – Parts 1 & 2, which specify minimum compressive strengths for mortars, and they are denser and less permeable than lime based mortars.

The internal structure of mortars affects the way in which they respond to both liquid water and water vapour. Small, linked pores within the body of the mortar will encourage capillary action and the absorption of liquid water. Both cement based and lime based mortars may contain this type of pore structure, and may be described as 'porous'. Whilst water will readily enter mortar by this capillary mechanism, assisted by driving rain and wind pressure, drying out will only occur through the *evaporation* of water vapour, and this requires a diffuse porosity throughout the body of the mortar, which is then described as 'permeable'. Typically this type of structure is found in old lime mortars. It is relatively difficult to achieve in modern lime mortars, and is not present to any significant degree in cement based mortars.

1.5 Comparison of cement and lime practice

Continuing development in the technology of cement and cement based mortars, particularly over the second part of the twentieth century, has resulted in the availability of fast setting, harder and less permeable mortars, and in the adoption of site practices and skills suited to these materials. Because cement based mortars generally have a strength significantly in excess of the actual requirements of traditional construction, shortcuts in preparing, using and curing these mortars have become commonplace and the achievement of exact performance targets (such as compressive strength, setting time, etc) has not been considered critical for general building practice.

6. Faired-out lime pointing with good open texture

In modern site practice it is relatively common to see significant variations in the site batching of mortar materials, and the trend generally is towards the use of pre-mixed mortars to eliminate this problem. Variations or shortcomings in site practice are also common. Although current Codes of Practice (eg BS 8000-3:2001 Workmanship on building sites – Code of Practice for masonry) recommend up to 12 weeks curing for cement based mortars before exposure to frost this is rarely implemented – the contractor preferring to take the risk and remedy any immediately apparent defects. Other defects, such as microcracking and water penetration into joints or behind renders, are likely to go un-noticed until moisture build up becomes a problem in future years.

For work with lime based mortars this approach is not viable as these traditional materials are much less tolerant of poor site practice. Defects arising as a result of poor site practice may show up very quickly if the material is friable, or they may not manifest themselves for several years until an apparently sound mortar is exposed to stress as a result, for example, of severe frost after a period of heavy rain.

Lime based mortars generally require more care in preparation, application and curing and are much less tolerant of poor site practice. The skills and techniques of site practice associated with the use of slower setting lime based mortars are therefore slightly different from those commonly associated with cement based products. If used appropriately, lime based materials will be more effective for the repair and maintenance of traditional buildings, but they do require to be used with a degree of understanding and care.

1.6 Good practice with lime mortars

The successful use of lime mortars relies to a great extent on good site practice. Almost without exception, failures of lime based materials are due usually to choice of inappropriate materials, to poor building detailing (and poor maintenance of building details) or to poor site practice in terms of preparation, application or curing. It is very rare to find failures due to inherently poor quality lime.

When working with lime mortars, provision should be made at the planning stage for appropriate scaffolding or other access to the work to allow for the necessary site practices and techniques and thorough preparation of masonry is required prior to application of lime based mortars. In the preparation of mortars, batching of materials must be accurate; and an understanding of the behaviour and curing of lime mortars is essential to inform working practices during application and curing.

The properties of lime mortars used in the past were dependent on methods of processing and production. It is becoming increasingly clear that traditional lime mortars were sophisticated and complex materials and that attempts to use over-pure, highly processed modern limes (which are produced primarily for the chemical industry) have not been entirely successful, particularly where an understanding of good site practice has not been present. Current practice, therefore, aims to replicate the more complex structure of traditional materials and to ensure that the basic principles of good site practice are applied. A summary of critical points is included at Appendix A.

2 MATERIALS FOR LIME MORTARS

2.1 General principles

Lime mortars are made by mixing lime with sand or other form of aggregate. They are used in a plastic state and once in place will harden to form a relatively permanent material. The nature of the hardening process and the properties of the final mortar are influenced by the choice of materials and by the conditions and techniques of use. For these reasons an understanding of the characteristics of the constituent materials and their inter-relationship is essential to the effective specification and use of lime mortar.

2.2 Production of building lime

This section describes the chemistry and production of lime for building. The term 'lime' is used to describe a number of related materials, either various ***types*** of lime, ie materials with different chemical compositions, or various ***forms*** of lime, ie material in different physical forms or at different stages in the lime cycle (see below).

The Lime Cycle

The basic principle underlying the use of lime as a building material is a simple one: limestone, chalk, or other material containing a high proportion of calcium carbonate, is rendered down to a malleable material by 'burning' and by 'slaking' with water. It is then placed in the building (often mixed with aggregate in the form of mortar) and encouraged to return to a form of calcium carbonate as an integral part of the building fabric. In practice the process can be a complex one and many factors influence the final outcome, including the detailed chemical composition of the original limestone and the techniques of processing.

The sequence of chemical changes involved in the production and curing of pure limes is frequently referred to as the lime cycle. Where the original limestone contains other specific minerals the setting process of resultant mortar may be modified to involve a degree of positive chemical set. This is referred to as a hydraulic set because the reaction is dependent on the presence of water. Some of the stronger hydraulic limes are therefore able to set under water. Limes with hydraulic properties are sometimes known as 'water limes', due to this ability to set in the presence of water.

Limestone sources

The basic raw material for making lime is limestone, or other material containing a high proportion of calcium carbonate ($CaCO_3$), such as chalk (widely used), marble, shells, coral, marl, etc.

Characteristics of limestone vary according to the 'impurities' it contains, and these impurities give rise to a variety of ***types*** of lime of differing quality and characteristics.

- High-calcium limestones are at least 95% pure calcium carbonate and can produce pure high quality fat limes.
- Argillaceous limestones contain clay in various proportions and produce limes with hydraulic properties.
- Limestones with silica inclusions can also be processed to produce hydraulic limes.
- Magnesian limestones contain a proportion of magnesium carbonate, and produce magnesian lime. (When they contain the double compound of magnesium and calcium carbonates they are known as dolomite limestones).
- Poor limestones contain quantities of inert non-calcareous material, which does not contribute to the production of lime, and tend to produce smaller quantities and 'leaner' lime.

In the south of England a traditional blue lias hydraulic lime is produced in Somerset and marketed in the form of a dry hydrate (powder) but, apart from this and one or two other small local operations, modern lime production in the UK generally is centred on the high-purity limestones of the Carboniferous series, producing high calcium non-hydraulic limes. Almost all UK lime production is intended for industrial use and the proportion used for building (including commercially produced dry hydrate and lime for the production of portland cement) is a small fraction of the market. At present the majority of hydraulic lime used in the UK is imported from Europe.

Historic Scottish limestone sources and local limes

The majority of surviving lime mortars in Scotland are likely to be derived from Scottish sources. Within the complex geology of Scotland limestone deposits are variable, giving rise, historically, to locally varied

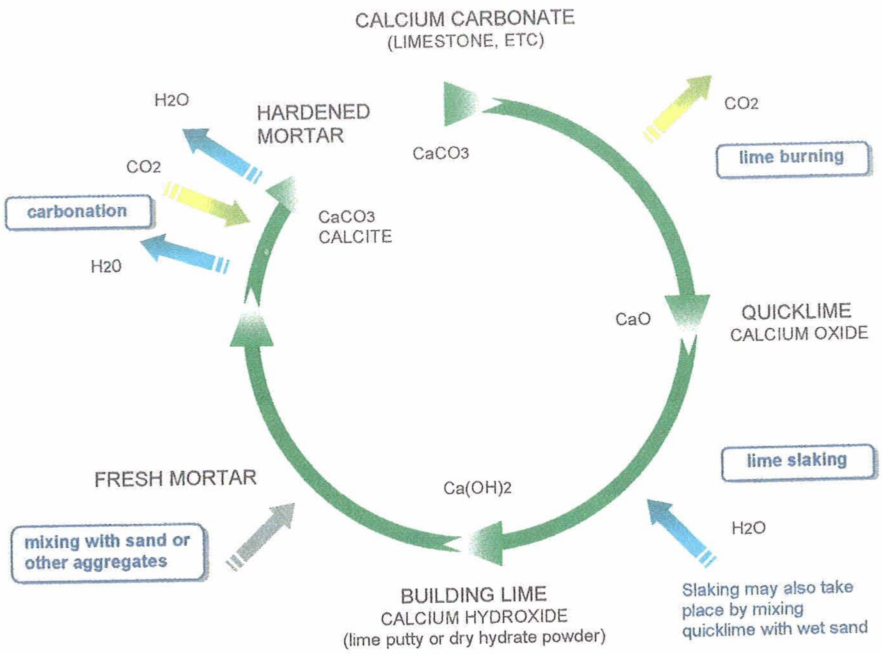


Figure 2a. Simplified diagram of the lime cycle.

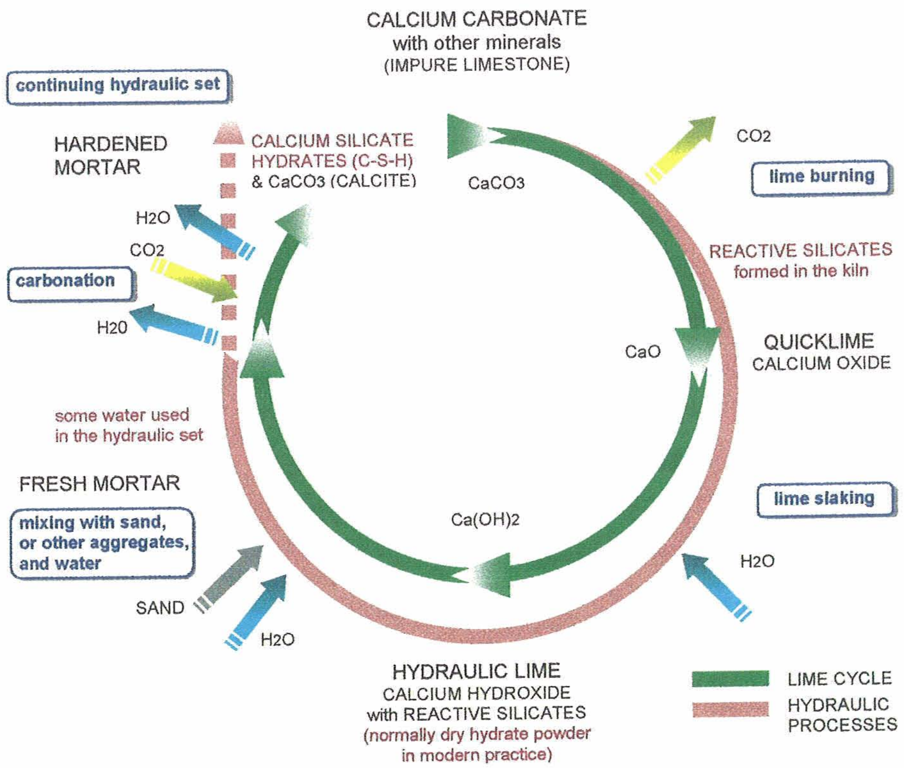


Figure 2b. Lime cycle for hydraulic lime.

mortars, as well as providing a rich source of potential types and strengths in lime mortars throughout the country. Scottish limestones generally produced feebly hydraulic lime mortars; others were non-hydraulic or strongly hydraulic. Even within clearly defined geological areas considerable variation occurred in the type and strength of limes produced. Limestones, or more accurately calcareous rocks, occur in the majority of geological formations, and historically exploited limestone deposits are to be found in all three main geographic divisions of the country: Carboniferous limestones occur in Southern Scotland and the Midland Valley, extending as far north as the Highland Boundary Fault; Dalradian crystalline metamorphic limestones occur in Grampian and the Southwest Highlands between the Highland Boundary Fault and the Great Glen Fault, and Cambrian limestones (often magnesian in character) and Jurassic sandy limestones are found in the North- and Northwest Highlands, with metamorphic limestone in Shetland.

Figure 3. Location of the major limestone deposits in Scotland

Limeburning and quicklime

The properties of lime are affected both by the nature of the limestone source and by the temperature and method of burning and may also be influenced by other materials such as fuel ash where this is in direct contact with the lime. When a relatively pure calcium carbonate material is heated to approximately 850°C carbon dioxide is driven off, leaving calcium oxide or quicklime, with a weight of just over half that of the original limestone. Impure limestones generally show a slightly smaller overall weight loss. Alternative names for quicklime include calcium oxide (CaO), lump lime, live lime, caustic lime and limeshells. Quicklime is a caustic material which can react aggressively with water, sometimes reaching temperatures in excess of 300°C. It is inherently unstable, highly caustic, and has an affinity for water. It should be handled with care (particularly during slaking), avoiding direct contact with the skin and especially the eyes, and avoiding inhalation of quicklime dust. (See Appendix D, Health and Safety)

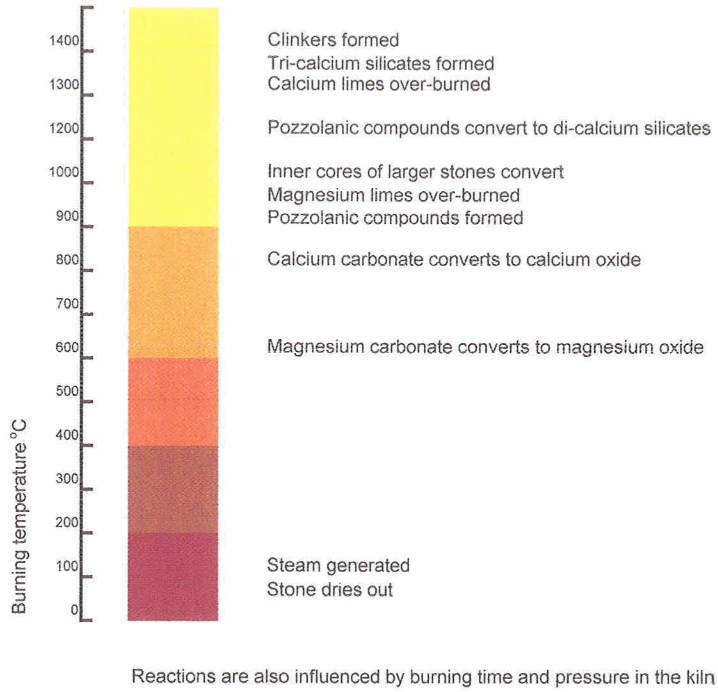


Figure 4. Kiln temperatures and reactions.

Many of the mortars surviving in traditional masonry buildings were made by firing limestone with coal, wood or peat. Small, single use, clamps were constructed by farmers to produce lime for sweetening the land, but could also produce lime for construction mortars and limewash. Stone-built kilns could either be loaded with a mixture of coal and limestone, or fired with wood fed into a firing chamber below the limestone. For commercial production continuous burning was possible by providing access to the kilnhead for repeated loading of coal and limestone.

7. 18th century commercial limekilns at Charlestown, Fife

The burnt limestone was withdrawn from the kiln when conversion to quicklime was completed and inevitably contained a small proportion of fuel ash which affected the characteristics of the resultant lime. This quicklime could be spread directly on the land or, for building purposes, was treated with water by a variety of techniques to produce lime (see below).

Large scale modern kilns in England generally burn at a relatively high temperature with gas or fuel oil, producing non-hydraulic quicklime free from fuel ash. Some of the hydraulic limes currently on the market are fired with anthracite in a more traditional way.

In the UK quicklime is available in bulk from large commercial producers of pure non-hydraulic lime and may be sold on in smaller quantities by some specialist mortar producers. There is currently no commercial production of quicklime in Scotland, but small quantities of locally burned hydraulic quicklime can sometimes be purchased from specialist producers in various parts of the UK. Imported and UK hydraulic limes are generally available only as dry hydrate, not as quicklime or putty.

Lime slaking

The controlled process of combining quicklime with water is known as slaking. This process is essential for the production of building lime. Calcium oxide (CaO) and water (H_2O) combine, generating heat, to form calcium hydroxide ($Ca(OH)_2$).

Historic methods of slaking

In the past, slaking of quicklime was often achieved by mixing with damp sand and the resulting material, known as coarse stuff, formed the basis of general purpose lime mortars. Various techniques appear to have been employed, probably influenced by the type of lime as well as the intended end use of the mortar.

- Lump quicklime was wetted down within a heap of sand and left to slake before being mixed in to form a mortar.

8. Modern kilns at St Astier Limeworks, France

- Reactive quicklime might be mixed with wet 'as dug' sand with the addition of sufficient water to 'dry slake' the lime. The resultant heat would also dry the sand, enabling the whole mix to be screened (passed through a sieve) if required, to remove unslaked lime and oversize aggregate, before being wetted down to make mortar.
- Lump quicklime was sprayed with water, or dipped briefly into water, until it fell to a coarse powder. If necessary this could be screened to remove large unslaked particles before being combined with sand. This process could result in a partially slaked lime ready for mixing with wet sand, or in a fully slaked dry powder. In either case the degree of slaking and refinement was considerably less than that achieved with modern commercial dry slaking.
- Non-hydraulic or feebly hydraulic quicklime was slaked to a putty which, if necessary, could be sieved, stored, run through weirs, etc, to refine the material for uses such as plastering and fine finishing work.

All the mortars made using these techniques, and variations of them, could be used whilst still fresh, and hot, or could be laid aside to mature and, with the exception of the refined putty, all would result in the production of mortars with a complex internal structure, very different from modern lime mortars.

On the whole, mortars made from modern slaked limes, of whatever hydraulic strength, tend to be uniform and bland in their internal structure compared with traditional lime mortars. At present there is insufficient understanding of the role of the internal structure of a lime mortar in ultimate performance, but it is clear that modern lime mortars do not always perform as effectively as the older mortars with their more complex structure.

Modern slaking

As in the past, quicklime can be converted for use by a variety of techniques. Modern slaked lime is generally available in two basic forms: lime putty or dry hydrate, depending on the quantity of water used, the method of slaking and the type of lime (hydraulic or non-hydraulic). In addition techniques of combining quicklime with sand provide possibilities for reintroducing an element of complexity into modern mortars. Techniques of slaking lime and sand together to make mortar are described in Section 3.2.

- Wet-slaked lime putty is slaked with an excess of water and will produce a mortar with better working and performance characteristics than a mortar made from a commercial dry hydrate. At present the vast majority of commercially available slaked lime putties are pure, non-hydraulic materials, although feebly hydraulic putty may sometimes be available.
- Industrial controlled slaking of non-hydraulic lime with steam or a minimum quantity of water produces a dry powder form of lime (generally known as

hydrated lime or builders' lime). This material, which is widely available from builders merchants, does not have the same reactive properties as traditionally burned, slaked and matured lime and, under the requirements of BS890:1995 Specifications for building limes, may contain anything up to 14% less usable lime than good quality traditional lime putty.

- Similarly, the controlled slaking of hydraulic limes produces a dry powder material. If particles of unburned limestone remain from incomplete burning these might be ground up and incorporated in the product. This does not necessarily result in a reduction in quality and may in fact help to reintroduce an element of the traditional complexity into a new mortar.

To make traditional lime putty, fresh quicklime is gradually added to water (*not the other way round*) and stirred to a thick creamy consistency. Considerable heat is produced during the slaking of non-hydraulic and feebly hydraulic quicklimes and strict safety precautions are essential. (See Appendix D, Health and Safety.) Stronger hydraulic quicklimes are usually less reactive. They may require grinding or the use of hot water or application of heat to initiate the slaking process.

Lime slaking is a skilled procedure. Although it was often carried out on site in the past it requires experience to maintain the correct temperature and consistency necessary for production of a high quality lime. Too little water will result in excessively high temperatures and 'water burnt', unreactive lime. Too much water may result in temperatures too low for effective slaking and in 'drowned' lime. Much of the lime putty now used in building conservation is produced by specialist suppliers.

2.3 Available types of lime

As described in Section 2.2, the term 'lime' is used to describe a number of related materials, either various ***types*** of lime, ie materials with different chemical compositions; or various ***forms*** of lime (see Section 2.4), ie material in different physical forms or at different stages in the lime cycle.

9. Slaking quicklime on site requires at least two people. Appropriate health and safety equipment should always be available. (refer to Appendix D)

Historic variety of lime types

Surviving lime mortars exhibit a wide variety of properties and characteristics. The various geological deposits of limestone throughout Scotland resulted in the use of a variety of types of lime, with the ***type*** of lime available being dependent on the composition of the limestone from which it was produced and, to a certain extent, on the techniques of production. There is also evidence that the properties of mortars were selected to suit their performance requirements. Historically, the available range would have varied regionally and included non-hydraulic, through feebly, moderately and eminently hydraulic limes and natural cements. All had slightly varying properties derived from the varying composition of the source limestone and some, produced from magnesian and dolomitic limestones, contained a proportion of magnesium carbonate. Traditional production of non-hydraulic limes generally resulted in a material with more inherent complexity than a modern commercial lime putty. Close examination of historic mortars will often reveal a complex micro-structure quite unlike the homogeneous structure of a modern lime mortar. For all practical purposes the majority of surviving historic 'non-hydraulic' mortars in Scotland can be regarded as feebly hydraulic materials.

Locally and nationally well known limes included the eminently hydraulic Arden lime from Renfrewshire, moderately hydraulic limes from Charlestown and other locations in Fife and from parts of Ayrshire, dolomitic lime from the Durness area and the widely used, very feebly hydraulic, limes from Lothian, Ayrshire, Lanarkshire, and parts of Grampian Region. Within these broader categories significant local variations also occurred. The range of materials available today is far less extensive and comprises very pure non-hydraulic limes, generally produced from English high calcium limestones, one English-produced hydraulic lias lime and a selection of imported continental hydraulic limes.

Non-hydraulic limes - also known as fat limes, high calcium limes or air limes.

Non-hydraulic limes are derived from limestones which do not contain clay or other reactive silicates, and the most reactive non-hydraulic limes are made from limestones containing very high proportions of calcium carbonate. Used in their traditional form, these were the basis of fat lime putty for plastering, for building under favourable conditions and for working with soft sandstone or brick.

Non-hydraulic limes rely for their hardening on drying and on the process of absorption of carbon dioxide, known as 'carbonation'. The resultant gradual conversion of calcium hydroxide to calcium carbonate involves a series of reactions between the lime, atmospheric carbon dioxide and water and requires an optimum balance of moisture and temperature, sometimes taking many years to become fully complete. In the right conditions non-hydraulic mortars may continue to develop strength over a period of many years but initially they will not reach the high levels of strength which are commonly (and often unnecessarily) specified in modern masonry construction.

Hydraulic limes – also known as water limes.

If clays (or other suitably reactive forms of silicates and aluminates) are present in the original limestone the resulting lime will have hydraulic properties, ie it will have some ability to set in wet conditions. The nature of these hydraulic properties will vary according to the composition and methods of processing of the source limestone and traditionally, in the UK, these limes have been described as feebly, moderately and eminently hydraulic, depending on their speed of set and anticipated strength. Modern standards for hydraulic limes are described at Section 2.5. Generally speaking, the more hydraulic the lime the harder and more impervious will be the resulting mortar, although these properties vary according to the specific make of lime.

As far as possible the properties of the mortar should be matched to the characteristics of the stone and the original mortar, as well as to the degree of exposure of the site. Matching of the properties of historic limes can be difficult, given the loss of local production. Although some locally burned hydraulic limes can be produced to order by specialist suppliers, in modern practice generally it is normal to use one of the imported hydraulic limes, or the English blue lias lime, where a hydraulic set is required. The blending of limes of different types, or from different sources, can go some way towards matching the original properties but this approach should not be tried without specialist knowledge or advice.

Magnesian limes

Magnesian limes are derived from limestones containing a combination of calcium carbonate and magnesium carbonate. Where the raw material consists of the double carbonate of calcium and magnesium the material is known as dolomite and the resulting lime as dolomitic lime. Magnesian limestones and dolomite occur in some areas of Scotland. Where they were readily available magnesian limes were probably used for the same purposes in building as were calcium limes, but the lower kiln temperature required for conversion of magnesium carbonate may have resulted in overburnt quicklime which was slow to slake. Traditionally, magnesian and dolomitic limes required longer slaking and maturing times than calcium limes. Where lime mortars are currently exposed to sulphate pollution or dilute sulphuric acid attack, the risk of associated stone damage may be greater from magnesian limes, since the crystallisation pressure of magnesium sulphate is greater than that of calcium sulphate. Magnesian building limes are not currently produced commercially in the UK.

Selenitic lime

Another variety of lime used historically was known as 'selenitic lime'. This was made by incorporating calcium sulphate into the material, through the introduction of sulphur dioxide into the kiln during limeburning; the addition of sulphuric acid to the slaking water or by the addition of gypsum to a feebly hydraulic lime and subsequent grinding of the mixture. The calcium sulphate promoted a rapid set and increased the strength of the mortar, but unfortunately it can result in stone decay in situations where any remaining free calcium sulphate, which is more readily soluble than calcium carbonate, is transferred to adjoining stones. The extent to which this material was previously used in Scotland is not known at present. Magnesian and selenitic limes are not readily differentiated from other types of lime except by laboratory analysis.

2.4 Forms of lime

In principle the various ***types*** of lime are all available in various ***forms***, including crushed or finely ground limestone (ie modern agricultural lime), ground or crushed quicklime, lump quicklime, dry slaked lime powder (hydrated lime), wet slaked lime putty, milk of lime, and carbonated lime (usually in the form of matured lime mortar or plaster). In practice, however, the materials most commonly encountered for use in building will be non-hydraulic or feebly hydraulic limes in the form of traditional wet-slaked lime putty (or, less appropriately because of its inferior properties, as the dry hydrate powder commercially available as builders' lime) and as moderately or eminently hydraulic limes in the form of dry hydrate powder.

Crushed or ground limestone may be encountered as an aggregate in lime mortars (see Section 2.6), *quicklime* may be used to make various types of 'hot lime mortars' (see Section 3.2) ; *dry hydrate* is the form in which hydraulic limes are normally supplied, whilst *lime putty*, either on its own or in the form of 'coarse stuff' (see below) is the basis for a range of mortars and finishing materials. *Milk of lime*, formed from lime putty or freshly slaked quicklime with an excess of water, will be found as limewash.

Lime putty

Modern non-hydraulic lime putty is made by the wet slaking of quicklime. Where sold as lime putty it is normally sieved and matured for at least three months before use, to ensure all materials are fully slaked. (Under certain circumstances, for example where highly reactive quicklime is used and the mortar is to be employed in massive construction, unsieved and unmatured mortars may be used.) BS890:1995 Specification for building limes covers minimum standards of composition and performance (but see note below in relation to dry hydrate).

During prolonged storage of wet slaked lime putty the lime particles will progressively reduce in size producing an increasingly higher quality of material. For special conservation works non-hydraulic lime putty may be several years old. Lime putty should normally be matured in conditions which prevent drying out but which allow excess water to drain away. Suitable conditions may be provided by timber boxes, timber-lined pits, 'breather' bags or other similar arrangements. The storage of lime putty under water is only appropriate where the material is to be kept for long periods of time because, although putty stored under water will improve, it will always have a significantly higher water content than putty which has been allowed to lose its water in the traditional way and, for this reason, will not make a good plastic pointing mortar. Any water on the surface of wet putty should be taken off before knocking up. Beware of transporting putty to site in containers with water on the top as this will mix into the putty during transport and result in a very wet material. Lime putty should not be exposed to freezing as there is some evidence that this affects the later performance of the mortar.

Good mature lime putty has the consistency of soft cheese and should retain its shape when turned out of a container. The putty should rapidly return to a workable state when knocked up. Where available, feebly hydraulic quicklime may also be slaked to a putty, which will stiffen up if stored for several months, but can be knocked back up to a good workable material when required for use.

Coarse stuff and fine stuff

Lime putty may also be available already mixed into a mortar in the form of 'coarse stuff' (ie incorporating a coarse sand) or 'fine stuff' (incorporating a fine sand). These mixes may be designed for use without further modification, or may be proportioned to accept an addition of hydraulic lime on site. Techniques of making mortars are described at Section 3.2.

10. Mature lime putty retains its shape

Dry hydrate

Moderately and eminently hydraulic limes are not commercially available as putties. They are slaked to a dry hydrate (powder) and sold in bagged form. Dry hydrated lime, of both the hydraulic and non-hydraulic varieties, is produced by the controlled slaking of quicklime with steam or a minimum quantity of water.

The material widely available from builders' merchants in the UK is a *non-hydraulic* hydrated lime, and should not be confused with *hydraulic* lime. It is generally much less reactive than good lime putty and is normally only used as a component of cement/lime/sand mortars for modern building construction. BS890:1995 Specification for building limes covers minimum standards of composition and performance but, as noted below, this BS on its own is not an adequate basis for specifying lime for traditional mortars. Specifications for lime mortars should not normally allow for the use of commercially available dry hydrate for making non-hydraulic lime/sand mortars.

Although chemically similar to lime produced by 'burning' limestone, *by-product lime*, ie lime which is chemically produced as a by-product of other industrial procedures, has different physical properties and is not suitable as a basis for traditional lime mortars.

2.5 British and European Standards and quality of limes

Quality of limes

The quality of limes can be described in various ways all of which aim to ensure that the material is suitable for its intended use. The most important parameters for non-hydraulic limes are the proportion and reactivity of calcium hydroxide present and the fineness of the particles. Traditionally, limes were described as 'fat' or 'lean'. 'Fat' lime putties contain the highest proportion of reactive lime, largely in the form of very fine colloidal material, and will carry about three times their volume of sand when used for ordinary mortar. Fat putties are workable and sticky without being wet. 'Lean' or poor putties tend to contain a high proportion of larger lime particles and a proportion of non-calcareous, non-reactive impurities. They may also contain some finely divided unburnt limestone. Lean putties will therefore carry less sand and are harsher to work. In traditional building practice acceptable mortars could be made with lean as well as fat limes by varying the quantity and type of sand used.

Additional parameters for moderately and eminently hydraulic limes relate to the setting time, 'strength' and porosity of standard mortars made from various categories of lime, and vary with the proportion of hydraulic material present in the lime. The composition of hydraulic limes is more complex than that of non-hydraulic limes and satisfactory materials may show a wide range of proportions in their basic ingredients. Varying relative proportions of lime, silica, alumina and iron oxide can all result in a satisfactory hydraulic lime.

Current formal standards

The formal standards relating to the quality and performance of lime specify setting times and crushing strengths for standardised laboratory testing situations. These figures are 'factory gate' standards and do not directly reflect the actual performance likely to be achieved on site.

Three categories of Standards are relevant:

1 Quality standards for production of lime:
BS 890:1995 Specification for building limes covers material standards for non hydraulic and feebly hydraulic lime. This will be withdrawn when the European Standard ENV 459 is formally adopted as a British Standard.

DD ENV 459-1:1995 Building lime. Definitions, specifications and conformity criteria describes 'factory gate' standards for building lime. The standards applicable to work with traditional masonry buildings are those relating to natural hydraulic limes (NHL).

BS EN 459-2:1995 Building lime. Test methods describes methods of testing lime for conformity with 459-1.

2 *Standards for lime mortar:*
Current standards in the UK cover all modern types of mortar, but do not provide data for traditional lime mortars.

BS 5628-3:2001 Code of practice for masonry-Part 3: Materials and components, design and workmanship describes classes of mortar mix and performance for cement and cement / lime mortars for modern construction. Lime putty meeting the requirements of this standard is acceptable for production of traditional lime mortars, but use of the dry hydrated powder is not appropriate.

BS 8221-1:2000 Code of practice for cleaning and surface repair of buildings. Cleaning natural stone, brick, terracotta and concrete also describes classes of mortar mix and performance, but these are cementitious materials and are not appropriate for work to traditional masonry buildings.

It is anticipated that European Standards will include types of lime mortar which are more appropriate for traditional masonry:-

prEN 998-1 Specification for mortar for masonry. Rendering and plastering mortar.

prEN 998-2 Specification for mortar for masonry. Masonry mortar.

(UK versions of these are currently in development.)

3 *Standards for workmanship:*
Current applicable Standards in the UK include the relevant parts of BS 8000, which covers standards of workmanship on site.

BS8000-3:2001 Workmanship on building sites. Code of practice for masonry.

BS8000-10:1995 Workmanship on building sites. Code of practice for plastering and rendering.

Comparison of hydraulic limes

Descriptions of hydraulic limes used traditionally in the UK have included the terms 'feebly' (or slightly), 'moderately' and 'eminently' hydraulic. Current widely used definitions are those contained in BS890:1995, covering non-hydraulic and feebly hydraulic limes, and in ENV 459-1 (see above), ie NHL2, NHL3.5 and NHL5 (NHL stands for 'natural hydraulic lime'). Although the definitions contained in this European Standard might be roughly equated to the traditional descriptions they are inherently unsatisfactory, since the extent of overlap between categories is so wide that, in some instances, one material may be described by any of the three categories. The chart at figure 5 shows a comparison between the strengths of different categories of lime.

The most eminently hydraulic limes generally achieve a crushing strength of around 30% of that of portland cement, with the less hydraulic varieties reaching proportionally lower strengths. At the highest end of the scale, including some of the imported very strongly hydraulic limes, much higher strengths are reached and these materials are more akin to natural cements.

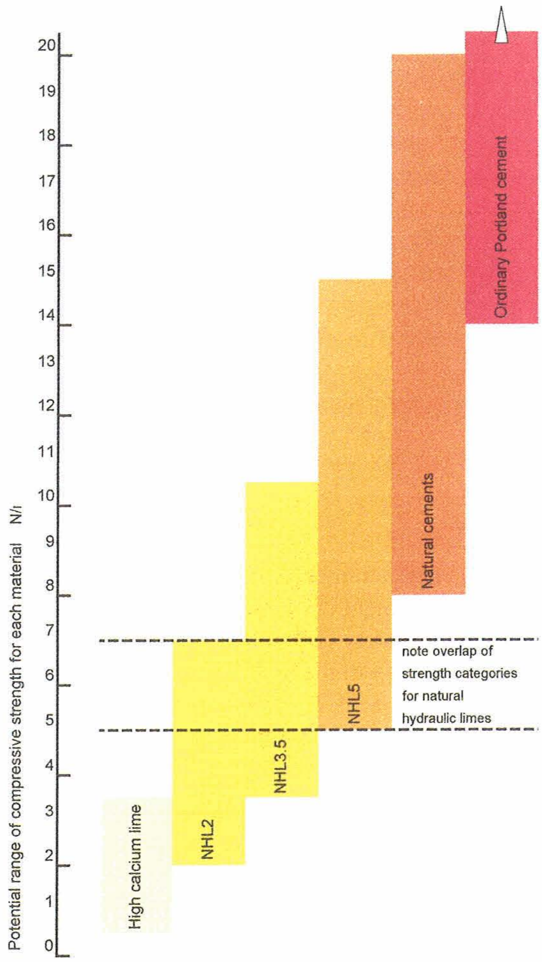


Figure 5. Approximate compressive strengths of typical lime and cement mortars.

2.6 Sands and other aggregates

Aggregates generally comprise up to 75% of the volume of a lime mortar, and the characteristics of the aggregate chosen are critical to the performance of the mortar. Guidance on the selection of aggregates for use in lime mortars is contained in Technical Advice Note 19, Scottish Aggregates for Building Conservation.

The function of aggregates in mortar

Aggregates in lime mortar perform a number of functions:-

- They act as a filler, reducing the amount of lime needed and thereby reducing drying shrinkage in the mortar.
- They may act as air entrainers and thus contribute some degree of frost resistance to the mortar.
- Their air entraining properties may influence carbonation and hardening of the mortar.
- They contribute to compressive strength.
- Aggregates containing pozzolanic material (see Section 2.7) may introduce a degree of chemical set to the mortar.
- Generally the finest particles in the sand will influence the colour of the mortar. (But note that if the material is not cured slowly and carefully lime will be drawn to the surface, resulting in a white finish no matter what the base colour of the mortar.

General requirements

Aggregates used in lime mortars include natural sands and gravels and materials such as crushed shell, various types of crushed rock, particularly sandstone and, occasionally, limestone, crushed brick and old crushed lime mortar. Other types of stone are used in mortars for specific purposes, for example, marble dust is used in stucco.

The nature of aggregate used in a mortar is critical to the workability and performance of the mortar. All aggregates should be clean, ie they should be free from very fine particles of silt and from salts or vegetable matter. For use in traditional lime mortars the most important parameters for any aggregate are; 'grading', 'feel', void ratio and geological or mineralogical characteristics.

If beach/shore aggregates are used they should normally be well washed to remove salt.

'Grading', 'Feel' and Void ratio

Grading describes the range of particle ***sizes*** present in the sand or aggregate. A well graded material will have a range of particle sizes showing the highest proportion of particles occurring at the mid range of sizes, with decreasing proportions towards either end of the size range. This is sometimes described as the grading curve.

Data on actual gradings may be available from the quarry and can be helpful in determining the overall grading curve, but further evaluation to determine the range of particle sizes and shapes actually present and the associated void ratio is normally advisable before selecting the sand to be used.

The ***shape*** of grains determines whether a sand is 'sharp' (with angular grains) or 'soft' (with rounded grains), and can normally be determined by the feel of the sand between finger tips and the 'crackle' it makes when the grains are rubbed together. Good mortar sands contain a high proportion of angular grains which will fit closely together. Rounded grains on the other hand roll easily over each other and too many rounded grains, whilst producing material which is easy to work on the trowel, will give rise to a poorly bonded mortar. Examination through a x5 or x10 magnifier or simple microscope will also allow an assessment of grain shapes and sizes. For a more accurate assessment the range of grain sizes can be determined by passing the material through a set of BS410 sieves or, more empirically, by shaking up a quantity with water in a narrow container such as a glass or clear plastic bottle, and observing the various grain sizes as they settle in layers. These two examinations will also indicate the degree of cleanliness of the sand, which should have no more than about 10% silt content.

11. Grain shapes. Large angular, sub-angular and rounded grains selected to show various shape characteristics.

For best results sand for use in traditional lime mortars should normally be a well graded, clean, sharp sand containing a balanced range of particle sizes and shapes, allowing all the grains to fit together and interlock into a well bonded mortar. The combination of grading and grain shape characteristics determines the 'void ratio' of a sand, that is the percentage of voids within a given mass of dry sand. The best mortar sands generally have a void ratio of around 33% to 35%, which means that they will require the addition of around one third of their dry compacted volume in binder paste in order to fill all the voids. It is this figure which is the basis of the traditional '1 to 3' lime to sand recipes for fat lime mortars (and for more modern mortars).

Proportions of lime and sand in a lime mortar should be such that the voids between sand grains are completely filled by a dense, good quality lime paste (or binder), making a 'complete' mortar. The smaller the total volume of voids the smaller will be the amount of lime binder required and the less will be the drying shrinkage of the mortar.

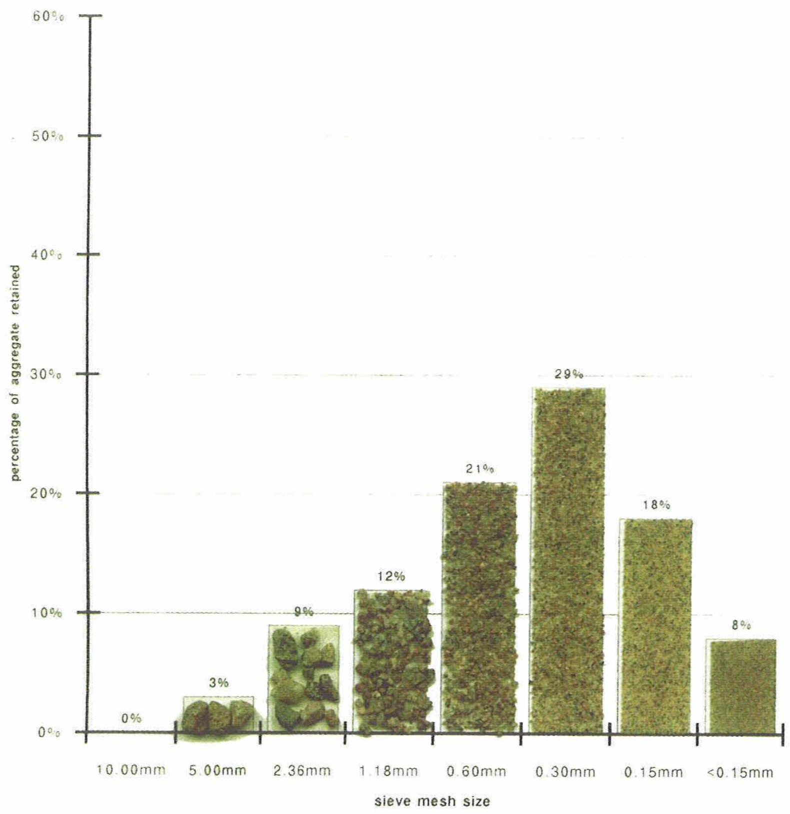


Figure 6a. A coarse sharp concrete sand, showing a good range and proportions of grain sizes. This would be suitable for general building and repointing work.

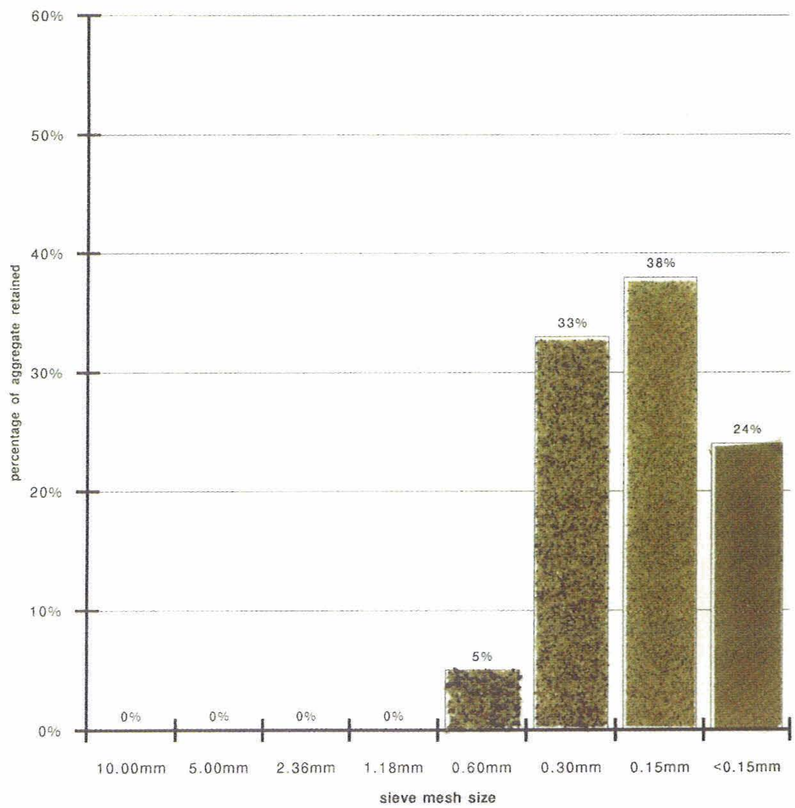
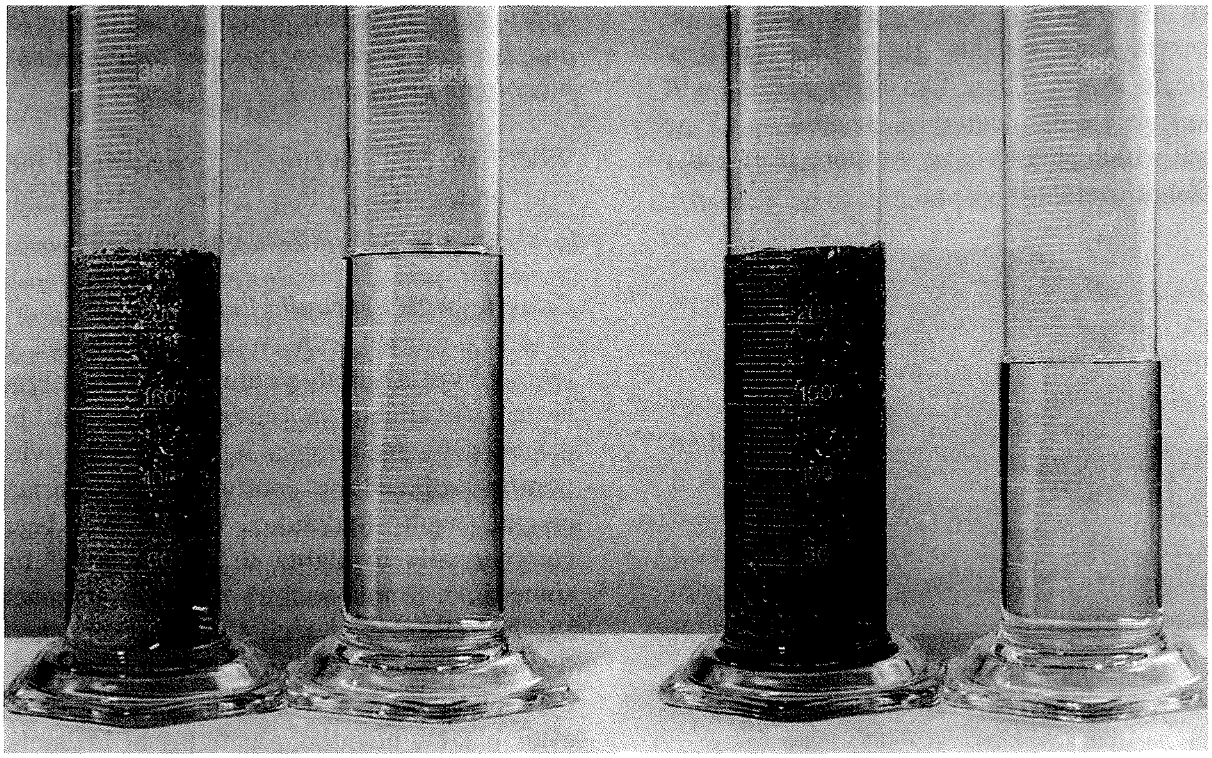


Figure 6b. A finer building sand, but still with sharp grains and a good range of smaller particle sizes. This would be suitable for repointing fine joints.

The void ratio of unfamiliar sands should always be checked before use. If necessary sands can be blended to achieve optimum physical characteristics, whilst still allowing a visual match to adjacent historic mortar. Void ratio can be checked by measuring the quantity of water required to reach exactly to the top of a measured quantity of dried sand in a container. (See illustration of measuring flasks used for this simple check.) The volume of water required will be equal to the volume of lime required to fill completely the voids in the measured quantity of dry sand. If less lime than this is used in the mortar mix the shortfall is likely to be made up on site by the addition of water in order to achieve a workable mix, and the result will be a weak mortar, prone to drying shrinkage.

mortar. Sands containing finely divided feldspars and schists may contribute a degree of mild pozzolanic set and may therefore assist in the longer term development of strength.

A proportion of carbonate aggregate, in the form of crushed limestone, calcareous sand, shell, or even old lime mortar, can improve carbonation and internal bonding of the mortar, and pore structure and frost resistance of lime mortars can be improved by the use of porous aggregates in the form of crushed low-fired brick and some types of shell. Modern expanded vermiculite materials may also be useful for improving frost resistance and thermal insulation values of lime mortar in some situations.



12. Measurement of void ratio.

Void ratio is measured by determining the volume of water required to fill all voids in a given volume of aggregate. The illustration shows volume of water remaining, having started with equal volumes of sand and water. By subtraction it is evident that 75ml of water have been used, which in this instance is 30% of the dry sand volume.

Geological characteristics

The geological composition of naturally occurring Scottish sands and gravels is very varied. Many are derived from glacial action and many have a high silica content in the form of quartz or quartzite minerals. Such sands generally provide filling and strength but may make little contribution to early setting of the mortar.

British and European Standards for sands and aggregates

BS882:1992 *Aggregates from natural sources for concrete* and BS1199/1200:1976 (with revisions to 1986), *Building sands from natural sources*, describe standards of composition and grading for sands, including those normally used in lime mortars. However the range of tolerance allowed on the gradings of these sands is very wide and, although complying with the relevant BS, many currently available sands do not necessarily have the characteristics required to make a good lime mortar. The selection of sand for lime mortars *solely* on the basis of compliance with a BS882 or BS1199/1200 specification is therefore not recommended.

2.7 Other materials in mortars

Pozzolanic additives

The addition of materials with a finely powdered reactive silica and alumina content will mimic the setting action of natural hydraulic limes by promoting a chemical set in the mortar. Pozzolanic materials used historically in this country include fine brick dust, volcanic ash deposits of various sorts (pozzolans), aggregates with mild pozzolanic properties and fuel ash, which may have been present in the lime as a result of firing processes. The reactivity of pozzolanic materials is generally enhanced in the presence of hot slaking lime, eg when used in hot lime mortars (see Section 3.2).

Natural imported pozzolans for use in modern lime mortars may be available from specialist suppliers. One of the best modern pozzolanic materials appears to be fine brick dust (below 50 microns) crushed from soft fired bricks or clay tiles. (Bricks fired at low temperatures tend to be the most reactive.) The formerly recommended high temperature insulation powder, HTI, is not now normally considered to be appropriate since it is a highly burnt material and may on occasion possess only minimal pozzolanic properties.

Wood ash, coal ash and certain other ashes of vegetable origin also possess pozzolanic properties. Commercially available pulverised fuel ash (PFA) may have a very strong pozzolanic reaction, and is not generally recommended as an additive to lime mortars. It is frequently used as a pozzolan in modern structural grouts.

Hydraulic lime gauging

By blending hydraulic lime and traditional lime putty it is possible to produce a mortar with characteristics resembling those of traditional mortars. Lime mortars gauged with hydraulic lime have been commercially available in Scandinavia for some time. Information on making up mortars containing hydraulic and non-hydraulic lime is included at Section 3.2.

Appropriately used, mortars gauged with hydraulic lime can be useful in damp or exposed locations but they are not directly equivalent to historic hydraulic limes and should not be used indiscriminately. The higher the proportion of hydraulic lime in the mix the greater can be the hardness and the loss of permeability and flexibility. Care must therefore be taken to ensure that mortars gauged with hydraulic lime are not too strong for the host masonry and that the properties of the mortar are matched to those of the stone as well as to the exposure of the site.

Even though they have some degree of hydraulic set these gauged mortars rely on adequate carbonation to achieve durability. They require the same level of care in production, use and curing as do plain non-hydraulic mortars.

Cement gauging

The use of cement in the repair of lime-built structures is not advised. Although the practice of gauging lime mortars with portland cement has been fairly widespread for a number of years, with the intention of producing an early set and/or increasing the strength of the mortar, this practice is not recommended. Where cement is used there is some evidence that proportions smaller than about one half part of cement to 1 part of lime (ie at a rate of 50% of the lime content) can reduce rather than improve performance, particularly in terms of frost resistance. Mixes containing 50/50 lime and cement, whilst usually achieving adequate frost resistance, are almost invariably too dense and hard for use with natural stonework. White portland cement, sometimes used to in an attempt to replicate the colour of lime mortar, generally produces an even harder mortar than ordinary grey cement.

Generally, if earlier setting or additional durability is required, this can be achieved by the use of an appropriate hydraulic lime mortar, or a composite lime mortar (see Section 3.2), or by the use of pozzolanic additives. All these are likely to result in a more sympathetic and potentially less damaging mortar.

If used in association with relatively dense and impermeable building stones such as granite or whin, dense cement gauged mortars can lead to increased water penetration and retention of moisture in the building fabric. The problem is generally brought about by driving rain penetration and capillary action into shrinkage or movement cracks at the joints, or into fissures in the stone itself, and by the reduced ability of the building fabric to re-evaporate moisture to the atmosphere.

Water for lime mortars

Where lime mortars are made up by combining traditional lime putty and sand, the water contained within the putty will be released on knocking up and should be sufficient to produce a good workable mix. If it appears that additional water is required to make a mix workable it is likely that a poorly graded sand with a high void ratio is being used. Remedies for this problem include changing the type of sand used, or enriching the mix with a small quantity of additional lime putty, rather than water.

In certain situations a wetter mortar may be required (for example to produce a sufficiently fluid mix for laying stones during the construction of masonry walls, or for harling work) and it may be necessary to add a small amount of clean water or, in the case of harling, some limewash, after the mortar has been thoroughly knocked up.

Water for lime mortars should normally be of a clean drinkable quality, free from impurities. Water from sources likely to introduce salts into the mortar, such as brackish water or sea water, should not be used.

Hair and other reinforcement

Animal hair has traditionally been used to improve tensile strength and reduce shrinkage in lime renders, harling and plasters. Hair is frequently found in internal lime plaster and in the undercoats to rendering or harling and, occasionally, in the original pointing of rubble masonry. The addition of hair to new lime mortars may improve performance and ease of use of mortars in other situations, such as repointing fine jointed ashlar work or making good surfaces before harling.

The hair should be clean, sterilised and grease free, untangled and around 25mm to 100mm long. Imported goat or yak hair is available and is widely used. Other types of hair such as cow or horse body hair (not mane and tail hair which can be too springy) are also suitable. In some areas hemp or jute fibres served a similar purpose and, in modern practice, polypropylene fibres have sometimes been used, although there is currently no evidence on their performance.

Hair is weakened by prolonged contact with uncarbonated lime and therefore should be only added to the mortar at the knocking up stage shortly before use (see section 3.2).

Air entraining additives

The use of air entrainers is sometimes suggested as a means of improving frost resistance. Various proprietary materials are available and those based on soaps are likely to be the most suitable. Products which include resin-based materials should be avoided as these can result in impervious mortars. English Heritage recommend that, where used, air entrainers should produce '4% to 7% of minute, discontinuous and evenly distributed air bubbles'. It is recommended that air entrainers should not be used without adequate sample testing and evaluation of the proposed mortar mix and air entraining agent.

Alternative methods of including air in the mortar are also possible.

Traditional 'hot lime' methods of mortar production (see Section 3.2) utilise the steam generated by slaking to create a diffuse pore structure. From experience with modern hot lime mortars it is clear that these have improved frost resistance compared with similar mixes produced from lime putty and sand, although no formal testing has yet been undertaken.

Porous aggregates, such as the traditionally used shell and crushed lightly fired brick or clay tile (see Section 2.6), have also been used to improve frost resistance, and the reuse of a lightly crushed old lime mortar in place of a proportion of the aggregate can also be very effective.

Polymer additives

Traditionally beer and urine (and other substances) may have been added to mortars to improve frost resistance. These materials are thought to act through the development of natural polymers in the mortar. Whilst there is anecdotal evidence for this practice very little research has been carried out and the actual extent of their use in Scotland is not known. The sugar content of these substances could have resulted in a delaying of carbonation which is probably not desirable in many Scottish situations.

The use of PVA, or similar, primers or additives in association with traditional lime based materials has in the recent past led to significant failures, due largely to disruption of routes for moisture movement. Small proportions of modern polymer additives are sometimes included in 'modern' limewashes and lime paints. Whilst these can be effective in conjunction with other modern building materials their use on historic buildings is not recommended.

Pigments

Where possible the desired colour of lime mortars should be obtained from the finest particles of sand in the mix (see Section 2.6) and from the natural colour of the lime. Some traditional Scottish limes included iron oxides which gave them a more mellow appearance than very pure limes, and slight colouring could also have been introduced by fuel ash from the kiln.

The addition of modern pigments to lime mortars is not recommended but if, exceptionally, pigments are used they should be lime-fast pigments to BS EN12878:1999 *Pigments for the colouring of building materials based on cement and/or lime.*

Pigmented lime mortars require particular care in preparation and use. Accurate batching and thorough mixing in of pigments are essential, as even small variations in consistency will result in noticeable colour differences. Working with the mortar too wet, overworking the mortar in situ, exposure to rain or rapid and uneven drying, will all result in movement of fine particles of pigment to the face of the mortar and will cause colour variations in the finished work. Variations in drying time, due to differential suction of the background or uneven thicknesses of material, will also result in migration of pigments and variations in final colour.

The use of natural pigments in limewash is traditional practice, but they do not appear commonly to have been incorporated in mortars. Ochre pigments (natural iron oxides) were often used and various small ochre deposits occur in Scotland, generally in association with coal workings. (Information on limewash and pigments is included in TAN 15 External Lime Coatings on Traditional Buildings)

3 MAKING LIME MORTARS

3.1 General principles of making mortars

The basic ingredients of lime mortars are sand and lime, compressed and beaten together and, in the case of non hydraulic limes, generally matured before use, the aim being to achieve an intimate coating of lime around every grain of sand.

Measuring and batching materials

For optimum performance and consistency in the final mortar, accurate measuring and batching of materials, especially of dry powder materials, is essential.

Mortar mix proportions should be based in the first instance on the requirement for a 'complete' mortar, that is one in which all the voids between sand grains are filled with lime paste. If there is insufficient lime paste the mix will be harsh and unworkable and the addition of water to correct this will result in a weak mix, liable to shrinkage. It is therefore important to consistently use the correct amount of lime. Sand is normally measured by volume. Mix calculations are based on a required volume of lime binder for a given volume of sand, and lime putty (which is already in the form of paste) can be measured by volume. (See Section 5.7 for a note on calculation of mix proportions.)

For dry powdered materials, the required volume of binder paste must be translated into an equivalent amount of powder. The relative bulk density (ie the amount of material contained in a given volume) of dry powder materials varies by as much as 20% depending on the characteristics of the original material and on the degree of compaction. Dry powdered materials should therefore be specified by weight and, if possible, should always be batched by weight on site. This can be done with a simple spring balance (available from fishing tackle shops, etc). An alternative, but less reliable, method is to weigh out the required quantity of the lime powder, check its volume after tamping down to remove as much air as possible, and use this volume as the batching measure. Weight checks should be made at intervals. Note that different varieties or strengths of hydraulic lime will give different weights for a given volume. (See Section 5.7 for a note on calculation of mix proportions.)

Methods of mixing

To make the most effective lime mortars from putty and sand the beating or compressing process is essential. A traditional roller pan mill is an effective method of mixing lime mortars with a low water content, although care must be taken to set the rollers high enough to avoid crushing the aggregate. Paddle mixers, which have a good beating action but do not provide compression, can also be used. Forced action paddle mixers (screed mixers) are also effective. The small rotary drum (cement) mixers often found on site are not recommended for making putty based mortars as they cannot provide compression, although they can be used to knock up small quantities of previously made mortar if wet mixes are required for harling or rendering. The full bag size rotary drum concrete mixers are more effective. Heavy duty hand held mortar whisks are also available. Appendix G contains a list of possible suppliers, and most of this equipment is also available for hire.

Small quantities of mortar can be made by hand but thorough mixing and beating is essential. Turning the material over with a shovel is totally inadequate as a means of preparing good quality lime mortars, whether they be made from non-hydraulic lime putty or dry hydrate of hydraulic lime.

It is apparent from investigation of surviving traditional mortars that the majority were made from quicklime and sand, or from fresh roughly slaked hydrate and sand. Whilst these methods may not always be appropriate for use on modern building sites it is possible to purchase ready made mortars of this type from some specialist suppliers.

3.2 Techniques of making mortars

Traditionally, a variety of different methods have been adopted for combining sand and lime into mortars. Variations in methods often reflect the type of lime available and the intended end use of the mortar. Some of the techniques which can be used for modern lime mortar production include mixing slaked lime putty and sand; mixing dry hydrated lime (usually hydraulic lime) and sand; mixing roughly slaked quicklime and sand; and mixing lump or crushed quicklime and sand. Various combinations of these processes are also possible.

Cold mixing

Preparation of mortar from lime putty or from hydrated lime are the methods most commonly used on site. In both these techniques the lime content of the mortar is slaked before mixing and the heat generated by slaking is not utilised in the production of the mortar. These techniques are described as cold mixing.

Lime putty mixes

Traditional techniques for making coarse stuff from lime putty generally involved beating, chopping and ramming on a wooden board or trough for at least an hour until the mix was sticky and workable. For best results the mix was then matured before use. For modern site use similar troughs may be constructed or small quantities of mortar may conveniently be made in a plasterer's bath. For larger quantities of material a roller pan mixer is recommended. To produce a modern putty lime mortar, fresh or mature lime putty is combined with sand (or other aggregate) by one of these methods.

Slaked lime putty is widely available from traditional producers and is frequently used for production of mortars on site: however, the practice of making lime mortars by mixing lime putty and sand and using immediately, or even within a few days, or weeks, of production is not recommended. If, exceptionally, this method is used it is essential that the mortar be mixed in a compression type mixer, such as a roller pan mill, to achieve a well beaten mortar with a low water content. Mortars made from putty and sand should normally be allowed to mature for around 12 weeks before use to improve the bond between sand grains and the lime binder, and to allow excess water to drain from the mix. *If appropriate maturing conditions are provided*, specifically conditions which allow the mortar to drain off excess water, and storage in these conditions for at least 3 months is possible, then putty lime mixes can be made in a modern rotary drum (cement) mixer. These mixes will have an excessively high water content and should not be used, even for harling, until they have been adequately matured. After mixing, putty lime mortars for general use were, traditionally, matured in earth or timber lined pits or timber vats, or in covered heaps, all of which allowed excess moisture to drain from the mortar but prevented drying out or freezing. Modern methods of storage and maturing should replicate these conditions as far as possible.

As an alternative to site mixing, ready made, matured mortars can be obtained from specialist suppliers.

Mixes based on dry hydrates

Modern hydrated non-hydraulic lime (commonly known as builder's lime or hydrated lime) is not suitable for the production of traditional lime mortars,

13. Traditional mortar trough and mortar making tools.

14. Knocking up mortar by hand using drag hoe.

although in some circumstances it may be used in combination with the strongest hydraulic limes, in much the same way as in modern cement / lime / sand mortars.

Dry hydrated hydraulic limes, of all different strengths, can be combined with aggregates and appropriate quantities of water to produce lime mortars. In modern site practice hydraulic lime mortars are often made in a rotary drum (cement) mixers. The lime powder and sand should be first mixed dry and the water added a little at a time. It is essential to avoid adding excess water, which will weaken the mix and increase shrinkage. With water content kept to the absolute minimum necessary to achieve mixing, the mixer should be allowed to run for *at least* 20 minutes. This will produce a plastic workable mix. Careless or inadequate mixing, with excess water, is a common source of later problems in hydraulic lime mortars. A more reliable mixing regime can be established by the use of a roller pan mill or paddle type mixer.

The nature of modern hydraulic lime mortars is significantly different from that of traditional mortars and, in general, the modern mixes tend to rely largely on their hydraulic strength for durability: as a result they are frequently much stronger than would otherwise be required.

Composite, or gauged, mixes

Techniques of combining lime putty, hydraulic lime hydrate and sand can be used to produce composite mortars with properties closer to those of traditional lime mortars. One method involves the addition of hydraulic lime hydrate, run to a slurry with water and beaten into a well knocked up putty / sand coarse stuff. As a base for this type of mortar, coarse stuff is made up with a reduced proportion of lime putty to allow for the incorporation of additional lime in the form of the dry hydrate. The resultant mix should be regarded as more akin in strength to a traditional feebly hydraulic lime mortar than to a modern hydraulic lime mortar.

Where a hydraulic lime mix is a little harsh to work a small proportion of lime putty (not more than about 5% of the lime content) can be beaten into the mix to increase workability.

Hot mixing

Hot-mixed mortars, ie mortars where the heat from slaking of the lime contributes to the production process, are available from suppliers of ready made traditional mortars. Hot-mixed mortars should not normally be made on site except by experienced competent contractors. Special health and safety procedures are required. (See Appendix D Health and Safety.)

Making hot lime mortars requires skill and care to ensure that sufficient water is added to the mix as slaking proceeds, and that the lime does not slake at too high a temperature and become 'water burnt'. Because of the quantities of quicklime required to generate sufficient heat for full slaking, these hot mixes are generally richer in lime that cold mixes. During the mixing process the action of the hot caustic lime on silica sand can potentially etch the surface of otherwise unreactive silica grains. This is thought to improve the bond between lime and sand and perhaps to create some mild pozzolanic activity in suitable sands. The initial slaking process has the effect of heating and drying the sand grains, which then form a good bond with the lime paste as water is added. The presence of steam, generated by the slaking process also has the effect of entraining air in the mortar and appears to improve the pore structure.

Quicklime and sand mixes for maturing

There are long established traditions of making mortar by laying down quicklime and sand in pits or heaps, either in alternating layers of material, or by covering a quantity of quicklime with a layer of damp sand. Suitably protected from the elements, including frost, this would be left to slake and mature over a period of time, then thoroughly mixed and knocked up before use.

In current practice a variety of 'hot' methods of mortar making may be utilised. Sand may be beaten into freshly slaked hot lime putty. This has the practical advantage that the mortar can be made relatively wet and is therefore easy to mix; the water content evaporates rapidly as the mortar cools.

Modern techniques, as used by specialist producers, can involve the use of either granular or powdered quicklime, which slakes rapidly when mixed with sand and water. Although, like any non-hydraulic mortar, these mixes can be stored for long periods they do not normally require the prolonged maturing recommended for cold mixed putty mortars.

Mixes for hot use

Recipes, from as recently as the early 20th century, also exist for mortars clearly intended to be used in construction (but perhaps not for plastering?) whilst still hot. These include the use of finely crushed quicklime mixed with sand and used hot for winter working, and the use of moderately or eminently hydraulic quicklimes in lime concrete where crushed quicklime is combined with aggregate and the mix is poured hot. It is thought that hot mixes may have been used as a form of grouting in medieval construction and there is evidence of such techniques from recent investigation of the Cathedral of Venzone in Italy. Examination of wall cores from many medieval and later structures shows the same evidence. Specifications for bridge construction in the 18th century also make reference to hot lime grouting.

Hot mixed mortars can be made with a relatively high water content, because the material very quickly absorbs water and starts to stiffen up immediately after mixing.

Traditional hydraulic lime mixes

Mortars based on moderately hydraulic quicklime and sand are common in traditional Scottish construction, and many of these mortars appear to have been used in general building work before any slower slaking lime had fully converted to calcium hydroxide. Close examination of traditional lime mortars from almost any historical period will show evidence of small unmixed balls of lime throughout the body of the mortar. These mortars may have been matured for a short period and used cold or they may have been used freshly made whilst still hot. Similar mortars are also frequently found as plaster undercoats and in harling.

Composite, or gauged, hot lime mixes

Experimental techniques to replicate the properties of traditional hydraulic lime mortars have included the addition of a proportion of modern hydraulic lime hydrate to hot quicklime / sand mixes. To achieve this a hot lime mix, based on non-hydraulic quicklime and sand, can be gauged with a proportion of modern hydraulic lime powder run to a slurry and well beaten into the hot lime mix. Alternatively all the ingredients can be mixed, first dry and then with the gradual addition of water. The microstructure and texture of these mortars is much closer to that of traditional mortars than that achieved with simple hydraulic lime mixes. For practical purposes these mortars should be considered as feebly hydraulic – they will probably attain up to 40% of the ultimate strength of the hydraulic lime used, but are likely to be more durable than simple hydraulic mixes of similar strength. Gauged hot lime mixes have successfully been used in modern practice for a variety of jobs, including winter working, construction of rubble masonry, repointing and harling.

3.3 Storage and maturing of lime mortars

Properly stored with the air excluded, non-hydraulic lime mortars continue to improve with age and can be kept indefinitely. Lime mortars should not be exposed to frost during storage since there is some evidence that freezing of lime putty reduces the later performance of the mortar. If ready made lime mortars, stored in bulk breather bags, are subjected to superficial frosting at the outer layer this can normally be beaten back into the main body of the mix without incurring problems, but materials which have been heavily frozen should not be used.

A maturing time of 12 weeks is often specified for mortars made from fresh putty. Although, where the lime putty itself is produced from high purity commercial quicklime, full slaking can take place within a few days, the quality of lime mortars is improved by an appropriate period of maturing before use. This allows excess water to drain away, encourages closer contact between the lime and sand and further reduction in the size of lime particles, resulting in a more plastic, workable mortar with a lower water content and, potentially, less shrinkage in use. After a period of maturing the mortar should be thoroughly knocked up before use.

It is clear from examination of old mortars that, historically, long maturing and thorough remixing were not always undertaken and the mortar appears often to have been used in a crudely mixed state.

Whilst it is generally accepted that only non-hydraulic lime mortars can be stored before use, there is some evidence that this technique was also used with feebly to moderately hydraulic limes, and that these hydraulic lime mortars were allowed to lie for several days, or sometimes much longer, before being knocked up for use. On the other hand some hydraulic lime mortars may have been mixed from quicklime and used whilst still hot and not fully slaked - a technique which would counteract shrinkage and promote a rapid set within the core of a massive masonry wall. In modern practice some producers recommend that hydraulic lime mortars should be allowed to stand for a number of hours, or overnight. Further research is required into the behaviour of hydraulic limes before these issues can be fully understood.

15. Typical mixing machinery. From top: paddle mixer, rotary drum mixer, roll pan mixer.

3.4 Knocking up for use

The quantity of mortar required for use should be taken from storage and thoroughly knocked up. During maturing lime mortars will stiffen up and they may initially appear too dry but will normally knock back up to a workable consistency. The purpose of knocking up a matured lime mortar is to regain plasticity without the addition of further water. The physical process of beating the mortar releases water from within the lime and the beating itself contributes to the plasticity of the mortar, thus achieving a workable mix with minimal water content. This knocking up process requires physical effort to compact the mortar, and, although small amounts may be successfully knocked up by hand over a period of 15 to 20 minutes using the techniques described for mortar making, larger quantities should be worked in a traditional roller pan mixer or paddle mixer. Some well matured mortars may be very difficult to knock up without a roller pan mill.

In the case of well matured mortars a small quantity of water may need to be added, *after the initial knocking up*, to achieve the correct workability. The addition of water *before* the initial knocking up runs a very real risk of too much water being used, since it is almost impossible to predict exactly how much water will be released by the lime. Also the beating or compression process of the knocking up will be less effective in a wet mortar. Mixing with water, rather than knocking up, is thought to be a significant factor in the poor performance of some lime mortars. After being fully worked back to a good plastic consistency it is often convenient to transfer a small quantity of material to a bucket for individual use and to work the material in the bucket by beating with a mash hammer at intervals during use. On a warm day if work is proceeding slowly care should be taken to ensure that mortar does not dry out in the bucket or on the board before use. When ready for use, good lime mortar for repointing should have a consistency similar to modelling clay. For laying stones or bricks a wetter, spreading mix is required and for casting or spreading coatings, a fluid mix will be necessary. Where the mortar is to be used for harling or rendering, the addition of further water (or preferably limewash) after the initial knocking up may be required to give a suitable consistency.

If hair is to be incorporated in the mortar it should be added at this stage. The most effective method is to add it to the roller pan mixer towards the end of the knocking up process. For hand mixing, the hair is normally sprinkled thinly and evenly over mortar which has been spread on a flat surface and the mix turned over several times.

Knocking up hydraulic mortars

As noted above, some hydraulic lime mortars may be left to stand and fatten up for a period of time, after which they will require knocking up. The supplier's recommendations should be followed.

3.5 Fine ashlar mortar and ashlar putty

For repointing ashlar work a lime mortar based on lime putty, or feebly hydraulic lime, can be made using the techniques described above for lime putty mortars, but incorporating a very fine sand or stonedust. The size of the sand should be selected to be no more than 35% of the joint width. The inclusion of hair is sometimes helpful for inserting mortar into the joints.

Special 'ashlar putty' can be made up for repointing very fine joints. This consists of 1 part mature non hydraulic lime putty and an approximately equal part of whiting (powdered chalk), depending on the wetness of the putty. These materials are blended together by hand on a marble or similar surface, adding boiled linseed oil a few drops at a time and working thoroughly by hand to make a plastic material which can be rolled out to a thin sausage shape. The material can also be made up by a specialist supplier.

4 SITE PRACTICES AND SKILLS

4.1 General principles of site practice

The success of lime mortars depends as much or more on appropriate conditions and techniques of use as it does on the materials themselves. Skilled craftsmen and good site practice are of fundamental importance. In addition to the techniques of application of the mortar, attention should be given to preparation of materials, preparation of the masonry, provision of an appropriate working environment and appropriate curing conditions.

4.2 Site preparation for repair work

Preliminary actions

It is essential to consider the conditions in which the mortar will be used and, if necessary, to provide a fully protected scaffold. Ensure that all necessary materials, appropriate equipment and tools and adequate protective covers are available before work starts. Adequate access, equipment and health and safety requirements should also be available.

The architect, or other supervising officer, and mason should jointly examine the work at the start of the job and confirm the principles to be followed and agree a programme and sequence of work. If necessary the preliminary programme, perhaps used for obtaining the contractor's tender, should be revised and adjusted as necessary to suit the actual conditions found on site. The full range of conservation and repair treatments proposed should be identified, including those situations where surviving materials are not to be disturbed. It will also be necessary to define where further decisions may be required as work proceeds, such as where damage is likely to result from removal of hard mortar, where it becomes evident that the masonry is potentially unstable or where archaeological features are uncovered.

Before starting work on any important or sensitive masonry ensure that all wall surfaces are photographically recorded and have copies of photographs to refer to during the work to ensure appropriate details are followed. The use of a camera providing instant images can be helpful, particularly, for example, where pinning stones are being dislodged and replaced during the process of repointing.

Vegetation removal

All vegetation growth and roots must be removed from masonry joints before repointing. Vegetation growth generally promotes moisture retention and physical damage to the masonry, although minor lichen growth can sometimes be left without risk. On ancient monuments and other similar structures small herbaceous plants and lichens may be of interest in themselves, and may be better left in place unless they are likely to cause actual damage to masonry or joints. Information on the treatment of biological growth can be found in Technical Advice Note 10, 'Biological Growth on Sandstone Buildings: Control and Treatment'.

Preparation of joints and masonry generally

Carefully pick off non-original cementitious mortar, *taking care not to damage stonework*, and examine surviving original mortar behind. Further repointing may not always be necessary. Where necessary, carefully rake out loose or decayed mortar back to sound original lime mortar. Only mortar which can be raked out, rather than cut out, should be removed from the joints. Provided a sound backing mortar is present and a compatible lime mortar is being used it may not be necessary to cut deeply into the original mortar to provide a key. However, when working with dense impervious stone or in situations where the wall core mortar is unlikely to provide an adequate bond to new mortar, it will be necessary to rake out to provide sufficient depth for the new lime mortar. As a general rule the depth of a joint for repointing should be around twice its width.

Any cutting out, as opposed to raking out, should be agreed by the supervising officer beforehand and should be carried out using tools with suitably narrow blades which will not damage adjacent stones. In certain situations the least damaging way of removing hard cement mortars may be carefully to drill a series of small holes along the exact centre line of the joint and to tap the cement pointing to break it inwards. This technique should not be employed where there is risk of damaging masonry behind the cement, for example with very fine-jointed ashlar work, and must in any case be very carefully controlled to avoid problems. Fine air chisels may also sometimes be of help in removing hard cement mortars. Generally speaking, however, power tools should not be used in connection with any historic masonry, and if hard mortar cannot be removed without damaging masonry then serious consideration should be given to leaving it in place.

Where possible, loose stones and pinnings which are removed in the course of raking out should be clearly identified for replacement in their original location, and laid back in the joint or marked with chalk and placed nearby for reuse.

The presence of dust and loose material within joints prevents new lime mortar from forming an adequate bond with the stone and with existing mortar. After removal of old mortar loose material should be brushed out and the joints flushed with a fine jet of water to remove dust and debris. A general damping down of the wall face before flushing out will reduce suction and thus minimise the risk of staining.

4.3 Preparing the mortar

Where mortars are made on site, time will be needed for their preparation and maturing. Site mixed and ready made traditional lime mortars must also be knocked up prior to use. These techniques are fully described in Section 3.

Do not add water to pre-mixed lime mortars at the start of knocking up. The mix should return to a plastic state when thoroughly worked, and should retain its shape when moulded in the hand. For repointing, the mortar should be sticky but not wet, and should cling to the underside of an inverted trowel or hawk. For building a wetter mix may be required, but the additional water should only be added after the initial knocking up; for harling or other surface coating the final mix should be quite fluid, and may be thinned down with limewash after knocking up.

4.4 Pinnings

Much Scottish masonry, particularly traditional rubble work, was originally constructed with stone direct from the quarry, selected and shaped on site (or with field boulders). This resulted in the use of numerous small pinning stones which contributed to the overall stability of the masonry. These pinnings also reduced the quantity of the relatively more expensive lime mortar which would be required, and helped to minimise the effects of drying shrinkage in the mortar. In many situations these pinnings are now missing, often as a result of earlier repair work. In addition to chippings from the main building stone, other materials, such as slate and oyster shells, and soft brick or tile (generally from the late 18th century onwards) are sometimes found. Shells and slate were commonly used for levelling in ashlar work. Original pinnings were often exposed on the face of the wall, but were sometimes buried within the mortar. In some parts of the country the use of pinnings developed into a recognisable pattern and such patterns should be respected where they have a genuine history of use.

16. Good workable lime mortar should cling to an inverted trowel or hawk

17. Closely packed sandstone pinnings in a whinstone rubble wall.

18. Oyster shell pinnings used to level up courses in a sandstone rubble wall.

Replacement pinnings should be built in as the work proceeds, ensuring that their size, character and relationship to the masonry generally are matched to surviving details and reusing original pinnings where possible.

Where joints are being filled in preparation for application of harling or render the same principles apply. The new jointing mortar should be brought out to the required face, well packed out with pinnings to avoid the build up of a mass of mortar.

4.5 Filling voids and deep joints

It is recommended that, if possible, tamping (ie filling deep voids) and repointing should be carried out as a continuous operation and using the same mortar mix to ensure continuity and integrity of the jointing mortar, and to ensure adequate depth for the bedding of appropriate pinning stones.

Before tamping or repointing check that joints and adjacent stones are damp but not wet. Absorbent stones will require sufficient wetting down to prevent rapid suction of moisture from the new mortar, but impervious stones may require only minimal dampening. The objective should generally be to control suction to a level that will not immediately draw water from the mortar, since this would result in excessive drying shrinkage and a friable mortar. Excessive wetting of impervious masonry will only serve to add additional water to the new mortar and weaken the bond between lime mortar and masonry.

19. Tools and equipment for repointing.

Sandstone masonry:

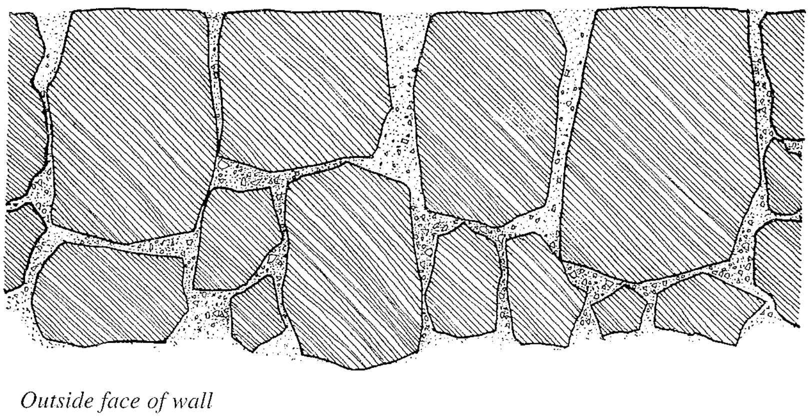
When working with non-hydraulic mortar in porous sandstone masonry, place mortar well back into deep joints and voids then tightly pack the cavity with small pieces of sandstone or similar absorbent material, such as soft-burnt clay tile or brick, firmly tamped into the new mortar. It is essential to keep to a minimum the overall volume of mortar in a joint and to thoroughly compact the mortar. The action of tamping in the pinnings will help compress the mortar into the depths of the wall and the use of porous pinnings will assist carbonation. This process should ensure that the mass of mortar within a joint does not general exceed around 15mm in thickness. Where non-hydraulic mortar is used in this way in conjunction with a porous sandstone, carbonation of the mortar within the wall will be possible, and the mortar may be brought out to the finished pointing in one operation. In excessively deep voids the mortar and pinnings may need to be placed in two operations, although this may cause difficulties in adequately pinning the joints.

For deep working within sandstone walls it may sometimes be necessary to use a mortar with a degree of hydraulic set. The basic principles of filling deep voids are described above but, in the case of softer sandstones, the hydraulic mortar may need to be kept back from the face of the masonry and the joints subsequently repointed in a non-hydraulic mortar. Where repointing is thus being undertaken as a separate exercise sufficient depth, usually at least twice the width of the joint, must be allowed for the later pointing. Where possible the pointing should be taken to a greater depth to accommodate adequate pinnings.

Impervious masonry:

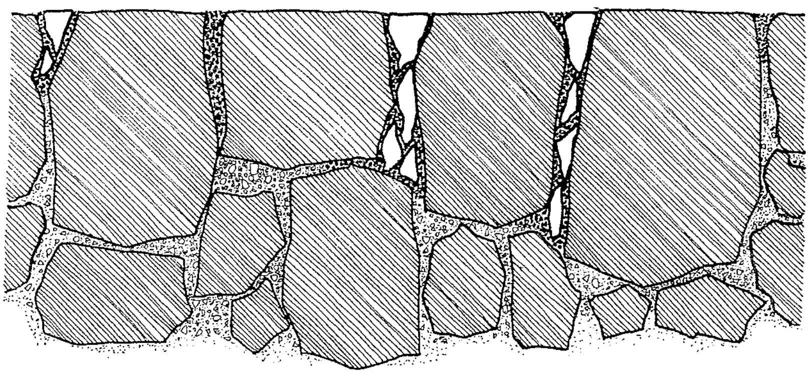
In impervious stone masonry, filling deep voids with non-hydraulic mortar may be problematical, as carbonation will be slow or non existent. If non-hydraulic mortar is being used it will need to be built up in layers within the voids, allowing time for drying and carbonation. This could be a very lengthy process and has the added disadvantage that pinning out of the voids and joints cannot be effectively achieved. It will often therefore, be necessary to use a mortar with some degree of hydraulic set in this situation. The decision to use a hydraulic mortar requires careful consideration, as discussed in Section 1, and care should be taken not to lose the benefit of permeability in the mortar which allows evaporation of moisture from an otherwise impermeable structure. For work involving deep tamping, particularly in exposed locations and with dense impervious masonry, it may be appropriate to use a moderately hydraulic mortar to provide some initial hardening within the depth of the wall. Hot lime

Outside face of wall



Cross section of rubble masonry showing large volumes of lime mortar packed into deep voids. In this situation the mortar cannot carbonate and lime washout and shrinkage are likely to result.

Outside face of wall



Cross section of rubble masonry showing pinnings packed tightly into the depth of the voids. The action of tamping the pinnings into place compresses mortar into deeper crevices and the reduced volume of lime mortar will carbonate more readily.

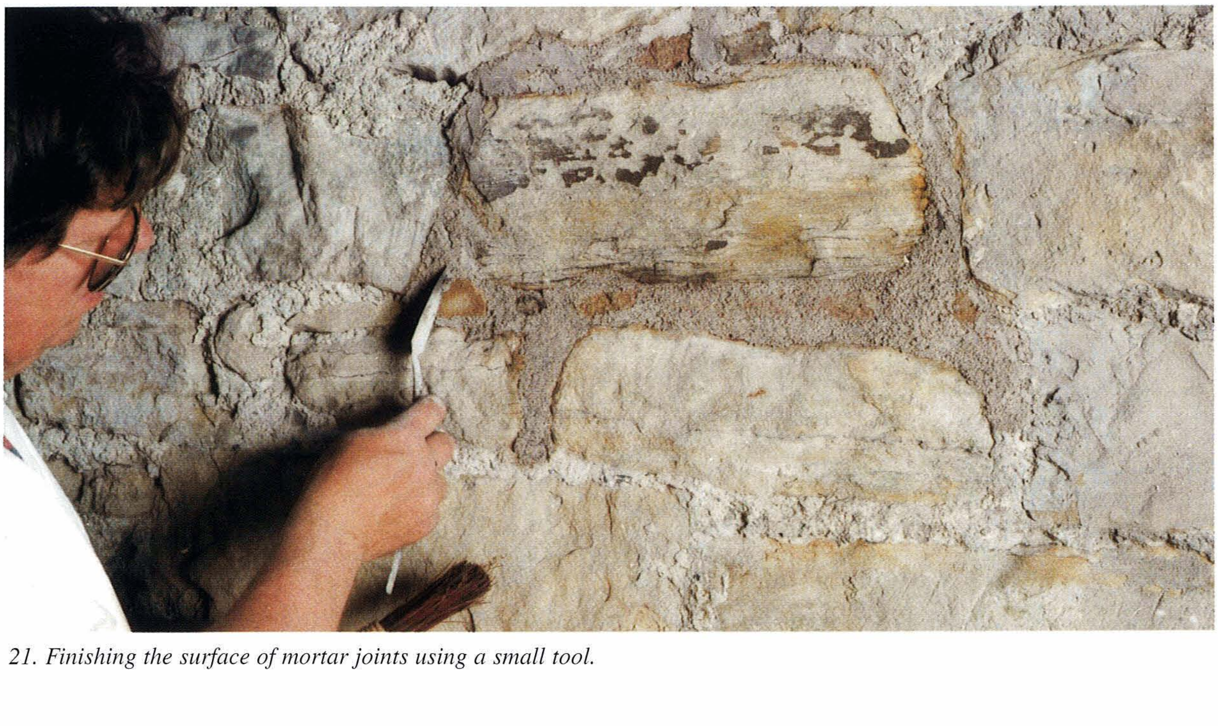
Figure 7. Tamping and pinning out deep voids.

20. Repointing rubble masonry.

mortars may also be of benefit in these situations. As with non-hydraulic mortars, the mortar should be placed well back into deep joints and voids and the cavity tightly packed with small pieces of sandstone or similar absorbent material, such as soft-burnt clay tile or brick, firmly tamped into the new mortar. If the original pinning stones are of an impervious material these should be reused at the face of the work, but porous permeable material within the deeper cavities will assist in encouraging carbonation.

4.6 Repointing rubble work

Rubble stonework was normally built with the mortar joints filled flush with the stone. In 19th century work, or sometimes earlier, if the surface was not intended for harling, the joint lines were often lightly ruled in. The original character and appearance of such masonry cannot be reproduced in cement-based mortar without the risks of water becoming trapped and of accelerated stone decay.



21. Finishing the surface of mortar joints using a small tool.

For repointing, joints should be prepared as described above, ensuring that there is adequate depth for replacement of pinnings. The use of appropriate tools and careful working are both essential in repointing work. Adjacent stone surfaces should be damped down prior to repointing to reduce suction and thereby minimise the risk of staining from lime being drawn into the stone.

Coarse rubble masonry: Where areas of coarse rubble masonry are being 'faired out' in lime mortar, in accordance with surviving details or local tradition, the mortar may conveniently be applied with a pointing trowel prior to later finishing. The new mortar should be stiff but plastic and pinnings should be firmly tamped into place as the work proceeds, thus ensuring that the mortar is well compacted into the joints. Additional compacting may be necessary within narrower joints, using a wooden tamper or similar tool. If the mortar is of the correct consistency the surface can be brought forward then cut back with the edge of the trowel to leave a flush pointed, open textured surface. Over-wet mortar, or inadequate protection may cause drying shrinkage which will require the mortar to be tamped back into place before setting is completed. Full flush pointing should never be used with cement gauged mortars as it is likely to lead to trapping of water and accelerated decay of stonework.

Regular-jointed rubble masonry: The prepared mortar should be placed carefully within the joints or beds, incorporating new or replacement pinnings as work proceeds, and pressed firmly into the joints with a small tool, pointing key, or small wood tamper, small enough to fit into the joint without causing damage to adjoining stones. It is essential to keep the overall volume of mortar in the joint to a minimum, by packing with suitable pinnings, and to thoroughly compact the mortar. This process should ensure that the mass of mortar within a joint does not general exceed around 15mm in thickness.

The mortar should be used as stiff as possible, whilst still being plastic, to avoid staining of adjacent stones. Where pinnings are to be exposed these should be set to the line of the wall face. Slightly overfilling the joints at this stage will provide the opportunity to take the mortar back to an acceptable profile and finish as it hardens up.

Generally the objective should be a natural, rather than mannered, appearance, which is often best achieved by pointing and finishing in one operation. The exact detail of surface finishing of the joints will normally be matched to adjacent surviving weathered mortar.

The final finish to the surface of repointed joints should be agreed before work starts. Finishing techniques vary

22. Section of rubble wall during repointing. (Lower right) wall prepared to receive lime mortar; (lower left) mortar inserted into joints and compacted and (top) repointing completed - in this example "faired out" to match the local tradition.

but the main aims of all finishing processes should be to:

- remove laitence from the surface, leaving an open textured finish;
- compact the mortar fully into the joint and ensure a good seal to the stone;
- give a visually acceptable finish.

Provided they meet these objectives the actual processes can involve a wide range of techniques:

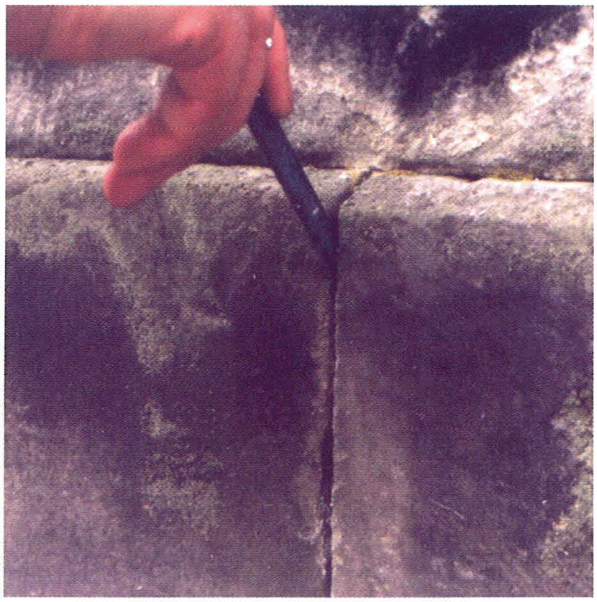
- lightly scraping off excess mortar from previously overfilled joints to leave an open-textured flush surface to the mortar - this can be particularly successful when used in conjunction with fairly regular masonry;
- tamping the surface of the mortar with the end of a stiff bristle brush to compact the material and to provide an open-textured surface;
- light scraping of the mortar surface with a wooden spatula or with the side of a pointing key;
- light water spraying to expose some of the aggregate.

Skill and care is always required to achieve a satisfactory finish but, in most situations, filling, compacting and finishing the joints can be achieved relatively quickly, often in one operation. It will usually be necessary to carry out sample panels to establish appropriate finishing techniques.

4.7 Repointing ashlar masonry

Although the same basic principles apply to the repointing of ashlar work, the fine joints require special care and techniques. Where ashlar pointing is required the time and skill involved should not be underestimated. In fine-jointed ashlar masonry, moulded work, fine ashlar dressings, or fine-jointed brickwork, even where joints appear to be open, repointing may not always be necessary unless water penetration is occurring.

Before starting, a detailed evaluation should be carried out to determine the extent of work required. Care is essential in raking out ashlar joints and no attempt should be made to use chisels to cut out mortar from ashlar work. Decayed mortar should be removed by carefully picking out with a fine steel hook (such as a dental tool) or easing the material out by means of a hand-held hacksaw blade inserted into the joint and pulled forward. Superficial cementitious over-pointing can often be removed by carefully picking off, but if the material is resistant to removal it will be necessary to evaluate the damage likely to be caused by leaving it in place against the damage which may be caused by removal. Sometimes the best option may be to leave the mortar in place and to accept the existing appearance and, possibly, ongoing masonry decay.



23. Cleaning out ashlar joint with a hacksaw blade.

After flushing out open joints with a jet of clean water and damping down, the process of inserting mortar into fine joints is usually best tackled by taping over the stone arises with heavy duty sticky-backed tape or similar material to protect against staining or

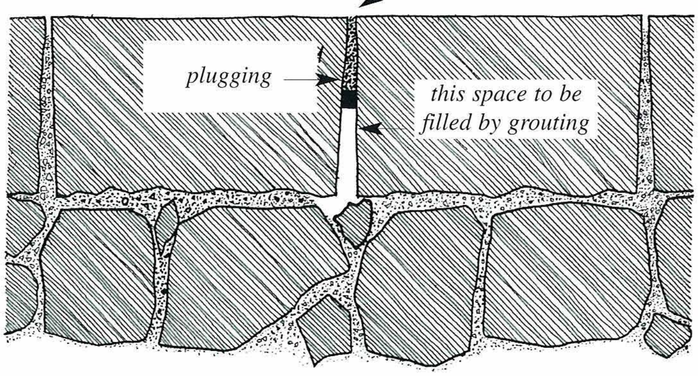


Figure 8. Cross section through tapered ashlar blocks, showing method of repointing.

mechanical damage. When working with ashlar stonework extreme care must be taken to avoid smearing mortar on to the stone faces and causing staining. Permanent staining is less likely to occur if the mortar is of a suitable plastic consistency, if the stone surfaces are well dampened before pointing and any accidental spillage washed off immediately with a fine jet of clean water.

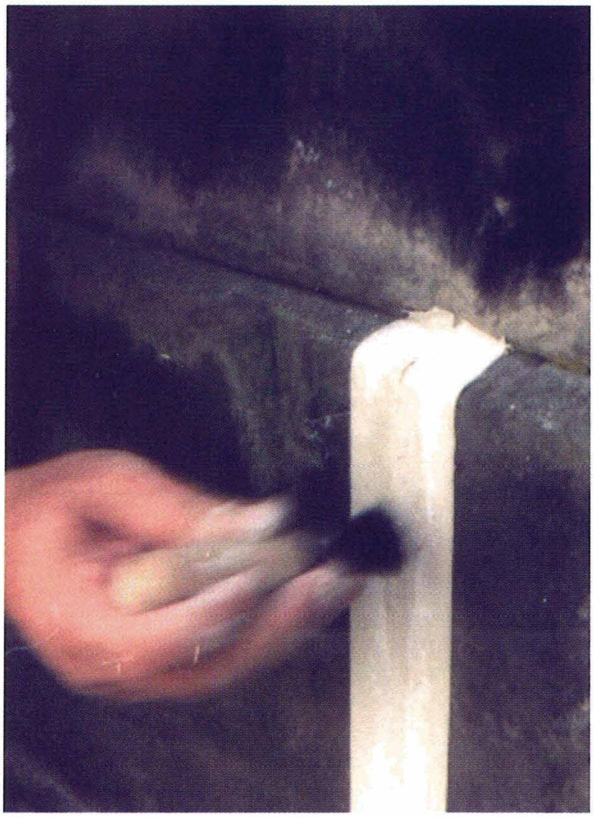
Mortar for repointing fine joints will normally include a fine sand or stone dust with a particle size no larger than 35% of the minimum joint width. To assist with the process of inserting this into the joints a small quantity of hair is sometimes teased into the prepared mortar before use.

Mortar can be placed into the joint in three basic ways - by inserting a suitable tool into the joint, by pressing from the face of the stone or by injection. Each of these processes has advantages and disadvantages and a combination of techniques may be required on one job. The actual techniques used will depend to a large extent on the skill and preferred working methods of the craftsman.

- Mortar may be inserted into the joint using the side of a steel blade or similar tool (for which the addition of hair is almost essential). If the joint width allows, the use of a thin wooden (or other) spatula within the joint to compress the mortar is a useful technique.
- To press mortar into the joint from the face of the stone, a 'sausage' of mortar may be formed and compressed against the surface of the joint with a flexible spatula blade or (wearing rubber gloves) with the ball of the thumb. Deep penetration into the joints can be difficult with this technique.
- The process of injecting mortar into ashlar joints is unlikely to be successful except, possibly, where a very fine putty mix with, for example, a fine stonedust filler, is used. The nozzle size required to inject a mortar, even with a fine sand filler, is generally too large for use with fine ashlar joints.

Whatever system is employed it is important to ensure that an adequate depth of mortar, normally a minimum of 30 to 40mm, is inserted into the joint. As the mortar starts to dry it should be tamped back with the tip of a bristle brush to eliminate any shrinkage cracks. Once it has firmed up sufficiently the surface of the mortar can be finished if required by lightly scraping with a small wooden spatula or similar instrument. Where protective tape is used it should be removed once the mortar is sufficiently dry but before it becomes hard, so that any disruption caused by the removal can be pressed back. Pointing in ashlar masonry requires careful aftercare in the form of protection and light mist spraying in the same way as other lime mortar work (see Section 4.9).

24. Pressing mortar into a fine ashlar joint protected by masking tape.



25. Tamping the mortar firmly back with a bristle brush.

Ashlar masonry was frequently constructed with tapered blocks to assist in achieving very fine joints on the face. As a result, perpends and, sometimes, bed joints may be considerably wider within the depth of the wall. If this is the case, it may be necessary to tamp in a backing or plugging of waxed string or similar material, or a wedge of hair mixed with a little lime mortar, to prevent mortar disappearing endlessly into the depth of the wall. Very fine joints are normally repointed with 'ashlar putty' – a mix of lime putty and whiting with a little linseed oil. (See Section 3.2.)

4.8 Dismantling and resetting stones

Where individual stones have become dislodged and require replacement or where new face stones are to be indented, the basic principles of using lime mortars will apply, as they do for repointing works. Cavities should be cleaned out and dampened in preparation for resetting the stones, and mortar and pinnings tamped into any deeper cavities in the wall core. An excess of lime mortar is applied to the surfaces inside the hole to be refilled and the original or new stone set in place, tapping firmly back and pinning up as necessary including, where appropriate, original or replacement pinnings built into wider joints to reproduce the original masonry detail. As in repointing work, dampening of the masonry and use of a fat, well worked and plastic mortar will minimise the risk of staining from mortar that squeezes out onto the face of the wall. If necessary the work should be repointed as described above.

In fine-jointed masonry this technique should ensure that joints and beds are well filled with mortar without the need for repointing. If it proves difficult to fully fill the perpend and upper bed joints local grouting will be necessary. This will require appropriate grooves to be cut into the upper surface of the replacement stone to allow a liquid lime mix to be poured into the cavity. A typical mix might consist of lime putty, water and a gauging of moderately hydraulic lime, with the addition of a small proportion of bentonite (a mobile clay) to facilitate pouring and penetration of the grout. Hot lime grouts were traditionally used for similar purposes. Grout is normally poured by means of small 'cups' formed against the face of the masonry using modelling clay. Before grouting the masonry must be wetted and the cavities flushed out with water.

4.9 Protection, curing and aftercare

Effective curing is essential, not only to control drying shrinkage, but also to minimise the risk of frost damage over later years. Appropriate protection and provision of suitable environmental conditions are critical to good curing and make a major contribution to both the short term success and the long term performance of lime mortars. The extent of ongoing vulnerability of lime mortars to frost damage is related to their pore structure as well as to local environmental conditions. Appropriate, well made, well applied and well cured lime mortars are less likely to be damaged than are mortars made with a high water content and inadequately cured.

Control of drying conditions: Good curing conditions promote a process of gradual drying and, when combined with use of a good, well compacted mortar with a low water content, should minimise shrinkage in the finished mortar. Early shrinkage may also be caused by too much water in the mix or by failure to compact the mortar as it starts to stiffen up. If initial shrinkage occurs in non-hydraulic lime mortars, it can be reworked and pressed back, providing the material has not been allowed to dry out. Any unsound work due to drying shrinkage in mortars which rely on a hydraulic set will need to be cut out and replaced.

Rapid drying, whether by wind, sun or artificial heat, will have a detrimental effect on lime mortar and, in addition to problems of shrinkage cracking, rapid drying can result in bossing, separation from adjoining stones or from the backing, and in crumbly or powdery mortar. In addition, hydraulic lime mortars may fail to cure effectively if insufficient water is available for full hydration in the early stages. Rapid surface drying can also lead to the pores becoming blocked with fine material transported to the surface by the movement of water, which in turn will inhibit the passage of moisture vapour through the outer skin of the mortar and inhibit carbonation of the underlying material. A dense surface skin will also be vulnerable to spalling when moisture trapped behind it is subject to freezing. One of the objectives of surface finishing of mortar joints is to remove any laitence or dense surface skin. The excessive whiteness often seen in new lime mortars is frequently caused by over-rapid drying which results in lime being drawn to the face of the mortar. Although such whiteness will weather away in time it is undesirable both visually and technically.

The new lime mortar needs to dry out slowly from within the depth of the material and to be maintained in a moist but not wet condition for a week to ten days. Control of drying conditions can usually be achieved by the use of fine debris netting on the scaffold, supplemented, in hot or windy conditions, by additional measures to provide shade and protection from drying winds, perhaps in the form of framed panels with hessian and polythene coverings, or sheets of hessian hung in front of the new work. In very drying conditions intermittent fine mist spraying with clean water may be necessary to prevent premature drying of the surface, and provision should be made for this to be undertaken at weekends or over holiday periods if necessary. It may also be necessary to keep the hessian covers wet in hot or windy conditions.

Protection from frost: All lime mortars (and cement based mortars) require protection from freezing until they are dry and cured. So long as an adequate protected environment is provided, winter working may be possible in some locations, and coverings should be designed to allow ventilation and drying, whilst preventing any risk of frost damage. Protective coverings for winter use might include a fully enclosed scaffold with 'Monoflex' or similar sheeting, plus additional close coverings and insulation batts. Whilst ventilation is required to encourage a controlled process of drying, care should be taken to avoid wind tunnel effects, which can cause localised rapid drying, even in winter conditions. Ducted warm air from propane gas heaters can provide a good, carbon dioxide rich atmosphere to encourage carbonation and drying, but the heaters themselves should never be placed within the scaffold enclosure. The use of any such appliances on a building site requires careful location and supervision.

Non-hydraulic mortars are particularly vulnerable to frost damage before carbonation is complete and should not be exposed to freezing within at least 12 weeks of placing. If, during this period, local temperatures are low, and / or conditions are wet, the mortar will be unable to carbonate and must therefore continue to be protected until at least 12 weeks curing is achieved. If work has been carried out late in the year carbonation may not become fully established for several months (activity is minimised below about 5°C) and protection may be required until the following spring. If there is any risk of freshly applied lime mortar being exposed to frost, additional protection will be necessary. This might include the need for some thermal insulation to prevent the temperature of the 'green' mortar falling below freezing point, since the formation of ice crystals will disrupt the integrity of the material. Bubble wrap and straw blankets have been used successfully to insulate lime work during the drying process.

Hydraulic lime mortars will normally develop some degree of frost resistance as they cure but, nevertheless, should not be exposed to freezing when wet for about 12 weeks. The length of time required varies according to the type of mortar and suppliers should advise on the minimum period of time required for the mortar to achieve a degree of frost resistance.

5 GUIDE TO SPECIFYING LIME MORTARS

5.1 Modern specification formats

In conservation work, and many other traditional building works, it is inappropriate to rely solely on generic specifications, such as the widely used National Building Specification (NBS) models. Specifications for conservation and traditional building works can be incorporated within these models, but must be specifically thought out and written for the job in question.

If the NBS format is to be used it is recommended that additional clauses relating to the conservation works are incorporated in the relevant trade Worksections, and that the production of lime mortars is described in detail in Worksection Z21 Mortars, Plasters, Renders and Grouts.

5.2 General principles of specifying lime mortars

In conservation work and general repairs to traditional masonry new mortars require to be designed for their specific location and application and to be compatible with surviving existing materials and, especially where patching is required, will generally require to be matched in colour, texture and finish. The specification of appropriate materials and techniques for the use of lime mortars in building repair and conservation will always require an assessment of site conditions as well as of the materials to be used. The selection of materials for repair mortars, particularly for external work, should be based on an understanding of the *performance requirements* of the mortar, taking account of the nature and current condition of the masonry, of the function of the new mortar, and the degree of exposure. For these reasons it is not feasible to use standard or model specifications.

As a general principle, surviving original lime-based materials should not be unnecessarily removed and the original appearance of the masonry should be retained as far as possible, (note: this may not necessarily be the *present* appearance). Joints will normally only be cleaned out and repointed to the extent required to ensure stability and prevent water penetration. To blend in the new work, repointing mortar will need to be matched to weathered original material in terms of colour, surface texture, and finished profile. Mortar for repointing and other repair works should be less dense and more permeable than the host masonry and, within this constraint, should be sufficiently durable to withstand the local exposure conditions. The choice of lime, sand and any other ingredients for the mortar should therefore be based on specific performance requirements for the mortar.

In practical terms the actual degree of *strength* achieved in a lime mortar for repair or conservation works is rarely significant - it is durability, overall behaviour and compatibility with the adjacent materials which are important. In modern construction, where mortar joints may carry significant compressive loads, an understanding of the compressive strength of mortars is important. In traditional masonry construction the actual compressive strength of the mortar is far less significant. (For example, provided it is contained, a sand filling to masonry joints in compression is as effective in load bearing terms as a strong mortar.)

Modern methods of describing and evaluating mortars tend to use compressive strength as a surrogate for durability, and these conventions are often transposed, inappropriately, to the evaluation and specification of lime mortars. In the majority of repointing work, by the very nature of the operation, there is little or no requirement for compressive strength in the mortar and, clearly, harling is not required to carry compressive loads. It is *durability*, as well as flexibility and permeability, which are important in lime mortars and, unlike cement mortars, durability is not necessarily correlated with compressive strength. On the contrary, compressive strength is often associated with an increase in density, impermeability and brittleness in a mortar.

It appears that durability is more likely to be related to the microstructure of the finished mortar, which in turn is related to choice of materials, techniques of processing and mortar production, and the quality of craftsmanship and site practice, including curing of the mortar. In any particular situation durability will also be related to the selection of appropriate materials and specifications.

5.3 Evaluating overall behaviour of masonry buildings

Lime mortars in traditional masonry do not function in isolation – they are part of an integrated building system where behaviour of one element is intrinsically linked to that of other elements. Before making decisions on the type of mortars to be used the overall characteristics and performance of the building and behaviour of the masonry generally must be ascertained. Many buildings where lime based repairs are proposed exhibit pre-existing problems, which may or may not have contributed to the deterioration of the lime materials. In addition to the immediately obvious situations, like failing rainwater goods or inadequate ground drainage, the nature of the building stone itself may be problematical. There may be persistent, but superficially hidden, water penetration problems or the masonry may contain high levels of soluble salts. The nature and extent of these problems should be thoroughly investigated and, where possible, the problems remedied. Any situations which cannot be resolved will impact on the performance of the lime based materials and should be taken into account in the specification.

As part of a comprehensive survey of the building this will normally include investigations such as:

- The nature and efficiency of rainwater handling systems and of water penetration and movement within the masonry fabric.
- Any evidence of movement in the building fabric.
- The nature and condition of the building stone.
- The extent and nature, if any, of salt contamination in the masonry.
- The nature and condition of existing mortar materials.
- Any specific local or environmental issues which could affect the performance of lime based materials.

Depending on the results of such investigations, other works may be required before the lime based works can be implemented.

Persistent water penetration: Persistent water penetration from hidden faults is a frequent cause of failure in lime mortars and, where this occurs, thorough investigation of the behaviour of the building is recommended. Thermal imaging techniques may be necessary to trace persistent problems. Re-application of lime based materials to such areas without identifying and resolving the problem will inevitably lead to failure.

Rising ground water: Rising ground water in buildings can often be dealt with by improved drainage. If damp proof courses are introduced the mortar below the dpc will remain wet and will decay more rapidly. Where appropriate, a hydraulic mortar might be used in this situation. In some locations, such as masonry bridge parapets, where the problem is exacerbated by road salts, both stone and mortar will be subject to ongoing decay. The specification of cementitious mortars in these situations is not helpful as it accelerates the decay of the stone, by diverting evaporation to the stone and, ultimately, forming hard ledges which trap further water.

Nature and condition of the masonry itself: Not all buildings are constructed with the best or most appropriate quality of stone and, in areas where poorly performing stone is known to exist, careful consideration is required for the specification of appropriate repairs. Certain stones may be intrinsically impervious and non-porous, but may be flawed due to quarrying techniques (some metamorphic stones were extracted by blasting in the 19th century and give rise to serious water penetration problems in exposed locations). Stones such as schists often draw water into themselves along bedding planes. In these situations specification of an appropriate lime mortar will need to be considered alongside the potential need for grouting with a lime based material which can prevent water running through the wall core (in addition to other remedial works). Some types of argillaceous (clay based) sandstone are prone to decay as a result of wetting / drying and freeze / thaw cycles. For these stones it may not be possible to arrest ongoing stone decay and, if acceptable, application of a protective coat of harling could be considered.

Salt contamination: If high levels of salt contamination are present the type of salt must be identified and the overall treatment of the affected masonry should aim to minimise movement and evaporation of moisture. Specialist advice should be sought if there are high levels of salt contamination.

Other problems: Whilst masonry bees are not a common problem in Scotland they do occur in certain isolated instances. Professional eradication is recommended.

5.4 Evaluating and defining preparatory works

Survey and recording

Before developing a detailed specification the proposed approach to treatment of the masonry should be identified, and a programme and sequence of work determined.

The building or area to be repaired should be inspected to identify existing or potential problems. Evidence of thermal or structural movement, of water channels through the structure and water or lime runs on the surface, of defects in rainwater goods and of rising or penetrating moisture are also significant. The causes of these problems should be identified and appropriate remedial works specified and completed before repair with lime based materials. Wall surfaces should be examined and the various existing conditions and likely repair or conservation solutions identified and recorded. This process should also include an examination of mortar joints to determine the extent of decay of lime mortar, the location of eroded and open joints, loose and friable mortar, excessively hard mortar, cracked and boss mortar, loose stones, missing pinnings, vegetation growth and penetrating roots, and joints acting as weep holes. Evidence of generalised or localised surface deterioration of stone faces, and of stone decay at joints and beds should also be noted. On the basis of this information decisions can be made on the extent, and nature, of repointing or other work necessary. It will often be found that less work is required than may originally have been anticipated. In some instances, even after removal of hard cementitious over pointing, original lime mortar may found to be sound and not in need of repointing.

Items such as surviving original mortar joints and surface finishes, including plaster, rendering, harling or limewash, may be identified for careful conservation treatment. Clay mortars and finishes occur in many Scottish buildings and care should be taken not to confuse these with deteriorated lime mortars. If in doubt about the composition or significance of any materials, seek specialist advice.

The various conditions and specified treatments can be recorded on drawings or large scale photographs (rectified photography is a useful way of recording) for use as a working document on site.

Evaluation and analysis of surviving lime based materials

Mortar analysis may be undertaken in order to provide guidance on the specification of matching materials or to record archaeological information on the building. It can also provide information on reasons for failure in recent lime mortars. Simple mortar analysis can provide useful information on the constituents of surviving lime based materials, but should never be translated directly into repair specifications without expert interpretation. The selection of materials for repair mortars, particularly for external work, is based primarily on an understanding of the nature and current condition of the masonry, on the function of the new mortar, and on the degree of exposure.

The first stage of analysis is usually examination with a x10 magnifying lens, which will frequently enable the binder and aggregates to be identified. Preliminary examination may be carried out in situ but for more detailed information representative samples of mortar will be required. These should normally consist of 400 - 500gms of coherent material taken by someone with a good understanding of the building and clearly identified by location and date of sampling and, if possible, by approximate date of construction. (To avoid unnecessary damage to historic building fabric samples should not be taken from scheduled monuments unless absolutely necessary. If samples require to be taken from a scheduled monument or listed building outwith an approved programme of work Scheduled Monument Consent or Listed Building Consent may be required.)

Laboratory procedures involving microscopic examination of the sample and of disaggregated material, acid dissolution of the lime binder, and separation and simple microscopic examination of the aggregates will often provide sufficient information, when coupled with an understanding of the performance requirements of the new mortar, to enable recommendations to be made for replacement materials.

Additional procedures may be required for some types of mortar. If the mortar contains a carbonate aggregate (such as shell, limestone, etc) microscopic examination of a specially prepared thin section may be required and, for firm identification of hydraulic lime in mortars, x-ray diffraction is necessary. If further detailed information is required more sophisticated procedures can be carried out. These could include scanning electron microscopy (for examination of the constituent materials and their relationship and pore structure) and infra-red spectroscopy (to identify the remains of any organic materials). Generally these procedures are expensive and they are not normally required for the purposes of the repair work itself.

Requirements for conservation of surviving lime-based materials

Original lime-based materials are an important part of the historic fabric of any building and should not be unnecessarily destroyed. Sound surviving historic material is too often cut out and replaced by new lime mortars which, even in the right conditions, may take many years to reach the quality of the discarded original. Careful evaluation is therefore recommended before deciding on the removal of any lime-based materials, balancing the likely life span of surviving materials against their historic importance and the potential performance and life span of proposed new work.

Where decorative or other unique original work is involved the objective should always be to conserve rather than replace, and such conservation work will normally be undertaken by a specialist conservator. Advice on conservation and repair of lime plasterwork is contained in Historic Scotland Technical Advice Note 2 'Conservation of Plasterwork'.

5.5 Specifying mortar properties for specific situations

Repointing and consolidation

Lime mortars for repointing and consolidating sandstone masonry should be as close as possible to the porosity and strength of the masonry but should always be slightly softer than the stones (or other construction materials) themselves. For use with denser stones mortar should also be as soft and permeable as exposure conditions allow to encourage evaporation of moisture from the masonry. Mortar which is to be contained within the depths of impervious masonry walls may require some hydraulic properties in order to achieve a set, and some degree of hydraulicity will also be required where the mortar is likely to be subject to freezing when wet.

Ashlar pointing

Mortar for repointing fine ashlar joints is usually based on a mix of lime putty and fine sharp sand. For very fine joints where the stone was originally bedded in 'ashlar putty' a similar mix can be used, made up as described in Section 3.2.

New building work

The specification of mortars for new building work in traditional materials will normally be based on the same criteria as those for repair or repointing but the mix will often be used slightly wetter. The use of lime mortars for new masonry work requires an understanding of the traditional techniques of masonry construction using pinnings to level and pack the stones as work proceeds, minimising the amount of mortar used.

Harling and rendering

Traditionally, in many situations, the same basic mix was used for building and surface coating. Harling was normally applied in thin coats, over well prepared and 'faired out' backgrounds. The use of a large pebble aggregate in the top coat of harling is rarely found in traditional practice. Many surviving traditional harlings seem to be non- or feebly hydraulic although some more hydraulic coatings are occasionally found. Specification of mixes for harling or rendering should be based on the established practice of the material being less dense and more permeable than the background and of each successive coat being weaker and thinner than the previous one. Guidance on the preparation and use of traditional lime harls and renders may be found in TAN 15 External Lime Coatings, on traditional buildings.

Grouting

If there are significant hollows or voids within the thickness of masonry walls, grouting may be required to fill and consolidate these voids. Careful evaluation is required before deciding whether to grout, and if so with what material. The addition of a heavy mass into the core of an unstable wall may do more harm than good, and the additional load could ultimately reduce, rather than increase, the stability of the wall. The introduction of over-strong grouts into flexible lime-built (or clay-built) masonry structures may create patches of rigid masonry and can lead to the formation of thermal cracks. The use of dense grouts may also induce 'cold bridging' by increasing the thermal transmittance of the masonry.

To avoid problems of differential structural or thermal behaviour the properties of grouting material introduced into masonry walls should be compatible with the original wall core mortar. Grouts for filling and consolidating lime-built historic masonry will normally be lime based. For use in conjunction with impervious or very wet masonry a grouting mortar with some hydraulic properties may be necessary in order to achieve a set within the depth of the wall. The addition of a small quantity of bentonite (a mobile clay material) is often required to improve mobility of the grouting material.

Chimneys, parapets and wall heads

The specification of mortar at exposed wall heads and for the repair of masonry parapets and chimneys requires particular care, both to ensure the continuing stability and safety of the masonry at these vulnerable locations and to reduce, or if possible eliminate, water penetration into the masonry below. Decisions on the type of mortar to be used in such locations should be made in conjunction with decisions on repair treatments.

Water penetration and frost damage are common problems at wall heads, parapets and chimneys and mortar used in these locations is frequently more vulnerable to damage than elsewhere on the same structure. Where there is thought to be a serious risk of frost damage, the use of a mortar with a moderately or eminently hydraulic set may be appropriate. Extra care should be taken over the protection and curing of lime mortars in these locations. Where the introduction of an impervious membrane is specified, or where damp-proof membranes may already exist in conjunction with masonry parapets and chimneys in more recent buildings, a non-hydraulic mortar will not be satisfactory. Masonry above the impervious membrane will tend to retain moisture, and therefore lime mortar may be more than usually vulnerable to frost damage in these locations. Unless carefully detailed, impervious membranes may also channel penetrating water out through the wall face resulting in lime runs on the face of the masonry.

Damp proof membrane are sometimes incorporated below chimney copes, but it should be noted that the coping stones above the membrane will be more vulnerable decay. The use of damp proof membranes at the base of a chimney stalk risks the formation of a shear plane, leading to instability of the chimney itself. If, exceptionally, a chimney is rebuilt over a full dpc the use of dowelling is recommended to anchor the masonry through the membrane. If chimneys are to be capped they should be detailed to allow for ventilation whilst preventing water from entering the flue.

It is possible that stones and jointing mortar at chimney heads will be contaminated by sulphates from flue gases. Some of the currently available natural hydraulic limes are resistant to sulphates but, in conjunction with repointing or rebuilding, it will be important to minimise water penetration, both to the masonry of the chimneys themselves and to masonry below.

Rough racking

Rough racking is the term normally applied to the consolidation of 'broken' masonry in ancient monuments or similar structures. Mortars for rough racking will normally be designed to reproduce the character and appearance of the original wall-core mortar and should be based on a careful evaluation of surviving materials. Wall cores may have incorporated well bonded masonry similar to wall facings or they may have been formed with rubble packed in lime mortar or with a poured mix of wet, often hot, lime mortar and smaller pieces of stone or boulders. Where the core of masonry walls is to remain exposed to weathering, for example in ruined structures, it may be necessary to introduce a mortar with greater durability (for example a more hydraulic mortar) than that of the original, but care must be taken to ensure that accelerated stone decay does not result from the use of too hard a mortar.

5.6 Specifying materials

The selection of materials generally

Specification of an appropriate repair or replacement mortar is important for appearance and technical performance. Where possible, the choice of repair materials and details should match surviving historic materials and reflect locally distinctive characteristics of the area. With the exception of a few major buildings and many 19th century buildings within towns and cities, the large majority of pre 20th century Scottish buildings used locally available stone, slate, lime, sands, clays (and other materials) in their construction.

Choice of lime

Although no Scottish limes are produced at present, an acceptable and workable match for most surviving lime mortars can normally be achieved by careful selection and, where necessary, combination of available materials.

Choice of the ***type*** of lime (ie non-hydraulic or with varying degrees of hydraulicity) to be used should be based on the performance requirements of the mortar and will generally be influenced by the nature of the stone, the nature of any surviving historic lime based materials and the environmental conditions or exposure of the site; ie by the performance requirements of the mortar. (See Section 2.3.)

For use with porous sandstone masonry, particularly in less exposed locations, good quality mortars based on non-hydraulic lime, if well made and appropriately used, may be suitable. This will be the case particularly where fragile surviving historic fabric would be vulnerable to damage by harder, denser materials, such as cement based mortars or, in some cases, even lime mortars with hydraulic properties. In these situations reliance will need to be placed on the use of high quality non-hydraulic or feebly hydraulic mortars, or mortars with a pozzolanic gauging, on the careful selection of sand or other aggregates, and on skilled craftsmanship and appropriate protection and curing to achieve as sound and durable a mortar as possible.

In the case of historically important masonry, or where the masonry is subject to decay arising from salt crystallisation, specification of deliberately sacrificial mortars may offer a means of minimising the rate of stone decay, through transfer of the salt crystallisation to the lime mortar.

For use with sound, durable stones a feebly or moderately hydraulic lime mortar can generally provide increased durability in conditions of severe exposure.

Many of the igneous and metamorphic building stones used in Scotland are relatively impervious and, for use in conjunction with these stones, especially in exposed locations, a mortar with some degree of hydraulic set may be necessary to overcome the difficulty of achieving effective drying and carbonation within the depth of the wall. Care must be taken to ensure that the mortar to be used is sufficiently permeable to allow evaporation of moisture from within the masonry fabric.

Although sandstone decay is generally associated with the use of harder cementitious mortars, occasionally sandstones (and granites) may appear to be affected by lime mortars. Where there is thought to be evidence of previous interaction between lime and sandstone this should be investigated and expert chemical analysis of the mortar and the affected areas of stone obtained before proceeding with repointing. The feebly to moderately hydraulic lime mortars may be more appropriate than pure non-hydraulic lime mortars in these situations since they may be less susceptible to lime leaching. In practice some argillaceous (clay bound) sandstones are susceptible to continuing decay, independently of the mortar. It has been suggested that clay mortars would be beneficial for these stones.

Specifying blended or composite mixes

A range of mortar strengths can be achieved using the hydraulic limes now available, but none of these replicate the complexity or characteristics of traditional lime mortars, where durability was often achieved without the use of a strong hydraulic set. One of the characteristics of historic mortars is the inclusion of particles of lime with varying properties, derived from traditional lime burning and slaking processes. Whilst currently these mechanisms are not fully understood, it appears that this complexity of structure contributes to the performance characteristics of old lime mortars.

Modern lime mortars combining two, or more, different types of lime, or limes from different sources, can go some way towards replicating the complexity of structure found in historic mortars. It is normally recommended that, in these composite mortars, the different limes should be used in roughly equal proportions, and certainly at not less than 1 to 2. The final performance of the mortar will be closer to that of the weaker lime component than that of the stronger, perhaps achieving no more than 30% to 40% of the potential strength of the hydraulic lime itself. Even though they have some degree of hydraulic set, these composite mortars rely on adequate carbonation to achieve durability. They require the same level of care in production, use and curing as do plain non-hydraulic mortars.

Properly used, composite mortars containing hydraulic lime can be useful in damp or exposed locations, but they are not directly equivalent to historic hydraulic limes and should not be used indiscriminately.

Choice of aggregates

Historically, most building sands were probably obtained from a source local to the construction work. Investigation of local commercial sand quarries may identify a good source of matching material for repair, but careful evaluation of the properties of any sand is required before including it in the specification.

As outlined in Section 2.6, the specification of sands or aggregates 'to BS1199/1200' or 'to BS882' is not in itself adequate. Choice of sand or aggregate should generally be determined by suitability in terms of physical and geological characteristics, by colour and, where appropriate, by matching to sands in existing mortar. Unless a specific material with known gradings has been chosen from a particular quarry source the specification should always include further information on the gradings required. The maximum size of grains should normally be no more than 35% of the joint width, but for the majority of situations it will be sensible to specify sands which fall within a readily available particle size range, such as the 2.36mm to 150μm envelope specified in BS882 or the 5.00mm to 75μm envelope in BS1199/1200.

The use of carbonate aggregates (crushed limestone, crushed marble, crushed old well-carbonated lime mortar, calciferous sand and shell) or of air entraining aggregates such as crushed lightly fired brick, should be considered where these materials have been identified in the original mortar or where there is a need to modify the properties or improve the durability of lime mortars. These materials tend to improve durability without necessarily increasing hardness or reducing permeability. If clean old crushed lime mortar is available this makes an ideal replacement for part of the sand aggregate. The use of freshly crushed limestone, preferably from one of the softer non-hydraulic limestones, has been demonstrated to improve the carbonation rate and the overall frost resistance of lime mortars.

Pozzolanic ingredients

Similarly the use of pozzolanic additives can impart a more positive set to non-hydraulic, or, in appropriate situations, hydraulic lime mortars. The specification of pozzolanic materials for use in lime mortars is based on certain general principles:- the material should be as finely ground as possible, it should be *freshly* ground, and where quantities in excess of around 25% of the lime content are being used, the sand content of the mortar should be reduced accordingly. Pozzolanic additives should therefore be fully specified by type of material, source, fineness and storage and handling requirements as well as by proportion required. (See Section 2.7.)

Freshly ground soft-fired brick dust is an effective pozzolan and should be included in repair mortars where the original material contained brickdust. It can also be considered where work is required to soft sandstones in an exposed location.

Commercially available pulverised fuel ash (PFA) is sometimes used as a pozzolan in modern structural grouts but it should be used with caution in repair mortars for traditionally built structures, as the finer particle sizes can result in a hard brittle material. Advice on the potential strength of PFA-gauged grouts should be obtained from the suppliers

Other ingredients

Hair, and occasionally other materials such as jute or hemp fibres, may be specified as a reinforcement for lime mortars where there is a need to increase tensile strength and reduce shrinkage cracking in new mortars. Hair may also be specified for repointing ashlar masonry where it will ease the problem of inserting mortar into very fine joints. Normal quantities of hair are around one handful per bucket of mortar (ie 2 to 4kg hair required per m^3 of mortar).

5.7 Specifying the proportions of mortar mixes

As described in Section 3.1 it is essential for optimum performance and consistency in the final mortar that materials are accurately measured and batched, especially dry powder materials. Proportions of lime to sand in a mortar should be based on the principle of completely filling all voids between the grains of sand with the binder of lime paste. Using a sharp well graded sand with an appropriate range of grain shapes, a mix of 1 part fat lime putty to 3 parts sand is likely to be correct but, with an unknown sand, a void ratio test is recommended (see Section 2.6), as proportions may vary. Sand with a higher void ratio will require an increased proportion of lime binder to fill the voids and produce a workable mortar.

In making mortar from lime putty, the lime and water are already combined to a paste and therefore the binder paste and aggregate can both be batched (measured) by volume. The quality of the putty is critical to accurate batching, as a mortar based on thin watery putty will contain less lime and more water than one based on a stiff putty.

To ensure the appropriate quantity of lime in a binder paste when using dry powdered lime, it is essential to know the relative bulk density (ie the relative weight of material for any given volume of the powder) of the particular lime and, from this, to calculate the weight of lime required.

Inconsistency in batching will affect the performance and appearance of a lime mortar, whether hydraulic or non-hydraulic. For absolute consistency in mortars incorporating dry powdered limes, weight batching of the lime proportion is recommended (see below). Where the actual exact strength requirements of the mortar are not critical, dry powdered limes may be batched in volume containers after calculation of the amount required (which depends on the relative bulk density of the particular lime used, see below). This will vary between different strengths of lime and lime from different producers. Some suppliers provide recommendations on the quantity of their hydraulic lime to be used with a given quantity of sand. The required volume of binder paste is based on the need to fill all voids in between the sand grains (see Section 2.6). To calculate the weight of lime required this volume must be multiplied by the relative bulk density of the lime to be used.

(Generally speaking the more strongly hydraulic limes have a smaller particle size and a higher relative bulk density than the feebly hydraulic limes. Typical values might be: NHL2 feebly hydraulic lime: 0.5, NHL3.5 moderately hydraulic lime: 0.55 to 0.65, NHL5 eminently hydraulic lime: 0.7 to 0.8, and the strongest hydraulic limes/natural cements: 0.9 to 1.2, but all these should be checked with the supplier. If batched by volume to make a 1:2.5 mix, 20 ltrs of coarse sand requires 8 litres of lime putty, or 8 litres of binder paste made up from lime powder. It can be seen from these figures that, using a feebly hydraulic lime powder, 4kg (say) of powder will be required, with a moderately hydraulic lime 5.3kg (say) will be required, and with an eminently hydraulic lime 6kg (say) will be required in order to make a binder paste with the appropriate quantity of lime. These figures are for illustration only and should be confirmed before use. If in doubt get specialist advice.)

The appropriate weight of lime may be measured out into a volume container and this volume may then be used for batching. It is critical, however, that a consistent degree of compaction of the powder is maintained if batching hydraulic limes in this way, rather than weighing each batch. Because dry powders may bulk up or settle down depending on the method of handling, variations of up to 20% may occur in the actual amount of lime between each measure if handling is inconsistent. Such variations will become apparent in both the appearance and the performance of the mortar in situ. Specifications for mortars incorporating dry powdered materials should always identify the powder component by weight and should make clear the need for accurate batching, if necessary by weight, on site.

Hydraulic lime mortars are generally specified with a slightly higher lime content than fat lime mortars (ie 1 part of lime to 2 or 2.5 parts of sand by volume) as these limes contain lower proportions of calcium hydroxide and tend to be less workable than fat limes. Traditionally, hydraulic limes are described as carrying less sand than good fat non-hydraulic limes.

Where sands and other aggregates are being used in combination it is equally important that the proportion of lime binder paste should still be such that it fills all voids in the mix. The use of high proportions of fine brick dust or finely crushed limestone will increase the surface area of particles to be coated with binder and may therefore require a compensating increase in the proportion of lime or reduction in the proportion of sand.

The practice of specifying a reduced binder proportion to reduce overall strength, which is sometimes used for cement mortars, is inappropriate for lime mortars as this will result in an inadequately bound mortar.

(See Appendix C for more information on producing specifications.)

5.8 Specifying production techniques

Ready made traditional lime mortars

The use of premixed and matured lime mortars can reduce the need for mortar production on site and can assist with quality control. Some specialist suppliers of traditional mortars carry a range of matured, ready mixed lime mortars or will make these up to order. Hot-mixed mortars can also be provided by some suppliers. These pre-made mixes are generally based on good well graded sharp sands with a choice of colour, or on fine sharp sands for ashlar pointing or fine plastering. Various mixes can be blended, if necessary, to achieve specific colours or other properties. These mortars will require knocking up on site before use.

Coarse- or fine-stuff is also available, made up in proportions of putty to sand suitable for making composite mortars by the addition of a gauging of hydraulic lime on site. Accuracy in batching hydraulic lime gaugings is essential and can best be achieved by weighing out the hydraulic lime. Techniques for knocking up pre-made mortars and for gauging with hydraulic lime are described at Section 3.

Standard commercial premixed dry 'lime' mortars, based on industrially produced dry hydrate and intended primarily for cement gauging on site, are not appropriate as a base for gauged lime mortars.

Before specifying or selecting a pre-made mortar, local conditions and performance requirements should be discussed with the supplier and, where matching is required, samples of the proposed new material can be compared with original mortar. For accurate matching, a specialist sample analysis and evaluation of the original mortar is recommended.

The current material costs for ready mixed traditional mortars are generally higher than comparable costs for purchase of the separate materials, but their use reduces site labour and wastage, improves quality control and simplifies the problems of producing and maturing lime mortars before the start of a normal building contract.

Site mixed mortars

Specifications for site-made mortars should follow the principles set out in Section 3. Accurate measuring of ingredients, low water content and thorough beating are essential for the production of good quality durable mortars. Issues of forward planning to allow an appropriate period of maturing will require special consideration if putty based lime mortars are to be used.

Particular attention should be paid to clear specification of working methods and quality control procedures to ensure availability of high quality mortars. On many modern sites, quality control of mortar production can be difficult to achieve. Batching of materials is particularly critical and it is recommended that dry powdered materials should be batched by weight as described at Section 3.1. Provision should normally be made for regular (random) sampling of mortars during production, for checking by a specialist laboratory.

It is not recommended that a requirement for contractor-made hot lime mortars is included in any general specification but, in special circumstances, and with the agreement of the contractor concerned, these mixes can be of benefit. (See section 3.) Where these mixes *are* used, slaking of quicklime should only be carried out by experienced tradesmen and will require adequate forward planning and particular attention to health and safety. (See Appendix D Health and Safety.)

5.9 Specifying site practices

General site practices

Good site practices, in terms of materials storage and handling, protection of adjacent building fabric, protection of work in progress and of recently completed work, and the employment of appropriate trade skills and practices, are critical to success when using traditional lime mortars. The specification should make clear that these requirements will be enforced and should highlight issues of particular concern, such as the provision of adequate protection and aftercare to ensure effective curing of lime mortars. It is generally insufficient to rely on standard 'protection of the works' clauses included in generic (eg NBS) specifications. Site practices are described in detail in Section 4.

Modern codes of practice

BS8000-3:2001 Workmanship on building sites. Code of practice for masonry, contains useful information on general site practices but is ***not*** applicable to traditional lime work in terms of materials, mortar mixes and site skills. Appropriate standards for general site working practices and requirements for protection of new mortars are included within this Code but are rarely implemented on modern building sites. A specification for lime mortar work should make it clear that adherence to these standards is a minimum requirement. Where necessary, specifications should also identify the need for more comprehensive measures, depending on the type of work, exposure of the site and the working season.

The need for preparatory works on site

Where possible, the following actions should be undertaken before the specification is finalised. If the necessary investigations and decisions cannot be completed before tendering, provision should be made in the specification for this to happen at the start of the project, and for any subsequent decisions to be incorporated into the works at an early stage:

- Evaluate and record the building before reaching final decisions on the extent and nature of work required.
- Consider when the work will be done and the need for protection.
- Allow time to prepare for and carry out the planned works.
- Analyse and evaluate existing/surviving materials.
- Source suitable well made and matured materials.
- Undertake trial panels and prepare control samples

Pre-ordering

In some cases it may be possible to purchase ready made mortars from stock but the availability of supplies should be confirmed in advance. If mortars are being pre-made to order, time should be allowed for the materials to be sourced and the mortar to be matured. If mortars are to be made up by the contractor, materials may have to be ordered and mortars made up in advance of the main contract, in order to allow time for the mortar to mature.

To avoid variations in the appearance of the mortar the sand required to make up the full amount of mortar should be purchased from one source at the start of the job. If blending or matching of sands is required these will also have to be sourced and ordered in advance.

The need for protection

All types of lime mortar require an appropriate environment for curing and for scaffolded jobs in normal conditions in Scotland this will involve provision of a protected enclosure. For smaller jobs methods of protecting the newly placed mortar will need to be devised and specified to ensure that provision is made for this in the contract price. Despite their increased ability to set in adverse conditions, hydraulic or pozzolanic lime mortars, like non-hydraulic lime mortars, rely for their overall performance on the carbonation of lime. It is therefore essential that all types of lime mortar are used and cured appropriately.

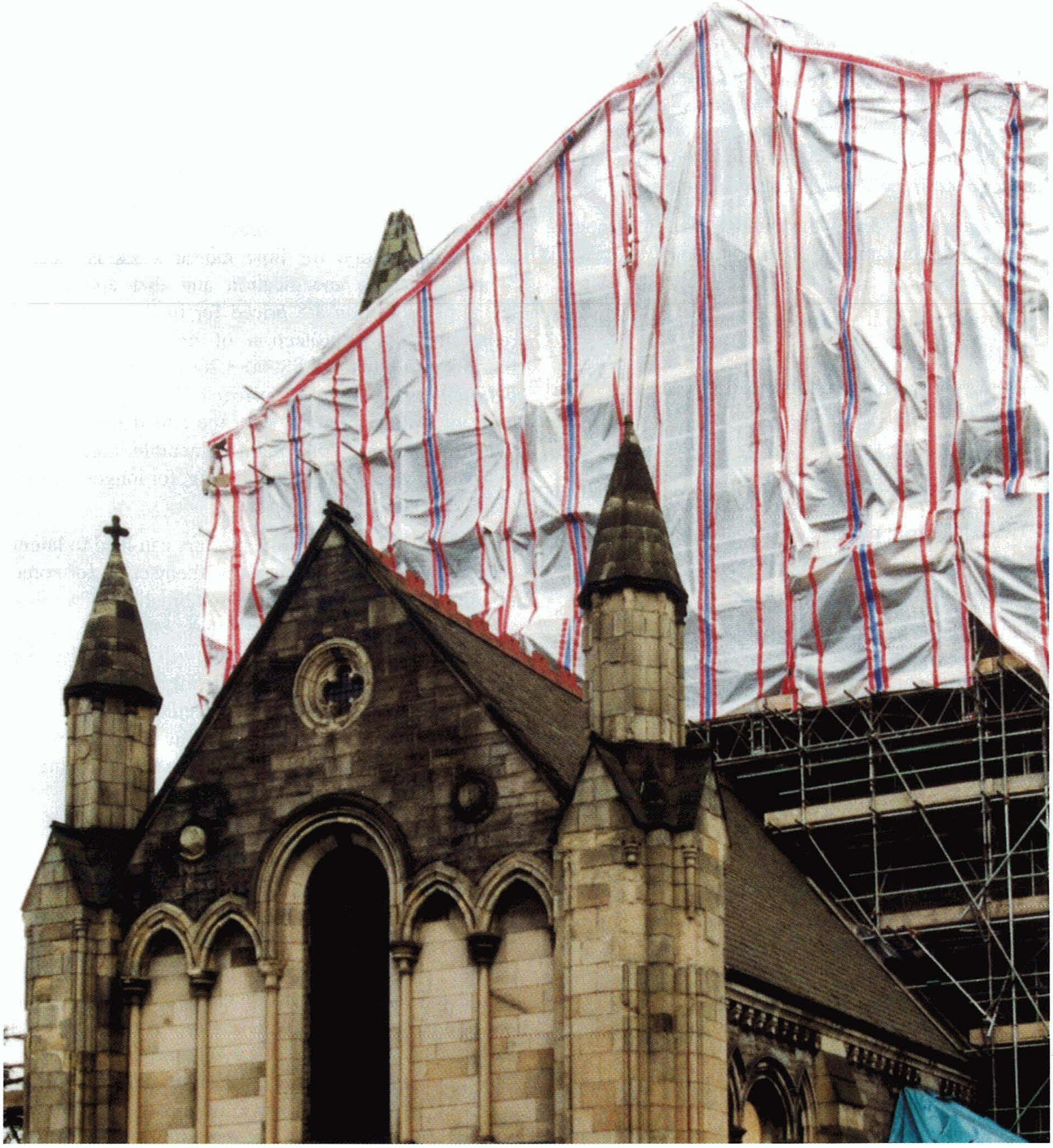
The basic purpose of protective coverings is to provide a suitable environment for the effective curing of lime mortar. This requirement should be made explicit in the specification and it should be noted that provision of an appropriate curing environment is *of the essence of the contract*. Within the terms of a modern building contract it is usually the responsibility of the contractor to provide 'adequate' protection for the works. Nevertheless it is generally insufficient to rely on standard 'protection of the works' clauses included in generic (eg NBS) specifications and it is strongly recommended that the scale and nature of the protection required for lime mortar work is clearly identified in the specification and that appropriate levels of protection are priced for in the tender. The requirements for protection of new cement based mortars, as set out in BS8000-3:2001 *Workmanship on building sites, Code of practice for masonry*, are relevant to lime mortars, with the added requirement that lime mortars will remain vulnerable, particularly to frost damage or over-rapid drying, for longer periods than will cement based mortars.

Because poor curing of lime mortars can lead to latent defects, which may not manifest themselves for some time until exposed to a severe combination of wetting and freezing, it is critical that effective curing conditions be maintained. It will normally be appropriate to specify in some detail the methods and materials that might be required to achieve an acceptable and effective curing environment, particularly in relation to the situation and exposure of the site.

In most situations the *minimum* level of protection will be fine debris netting to break the wind and provide shade, since over-rapid drying is a major cause of failure in lime mortars. This scaffold protection should be supplemented by, for example, frames covered in hessian and polythene sheeting placed over newly completed work, to control the rate of drying and provide protection from rain or frost. In more exposed locations, or for work in wintry conditions, reinforced sheeting, such as Monoflex or similar material, will be required and this will have implications for wind loading on the scaffold. The provision of sheeting or temporary roofing at upper levels to exclude rain from the wall face will also be necessary.

Small jobs where scaffolding is not required can usually be adequately protected by hanging haps over the new work or by the construction of temporary shelters. Care should be taken to avoid direct contact between new lime work and materials such as hessian which may cause staining when wet.

New lime mortars also require protection from mechanical damage whilst other works are in progress and from accidental damage before they are fully hardened.



26. *Sheeted scaffold protection.*

For work on ruined structures in exposed locations it may be necessary to provide a weatherproof envelope some time in advance to encourage drying out of saturated masonry fabric. The water content of the masonry should be reduced to a level at which lime mortar can dry and carbonate, which may take up to a year in some situations. Potential future sources of water ingress into the masonry fabric must also be eliminated.

Site samples

In unusual or uncertain conditions it is strongly advised that provision should be made for several sample panels to be carried out before confirmation of the final specification and, in certain circumstances, this may require trials or exploratory work to be undertaken well in advance of the main project. In addition, the provision of control samples illustrating the type of work required is almost always essential.

The quality and detailing of repointing work has a dramatic effect on the appearance of buildings and inappropriate repointing is one of the most visually, as well as physically, damaging repair operations which can be undertaken. To assist in defining appropriate standards of work, provision should be made in the specification for samples of the required techniques to be executed and, once agreed, to be retained for matching and control throughout the job. Where small areas of pointing are being 'patched in' to existing sound work the existing work may serve as a control sample. In some situations it may be necessary for samples to be prepared by independent, or other, specialists in the first instance, and for the contractor subsequently to undertake trial samples in order to develop satisfactory working techniques. With an inexperienced contractor, an initial period of familiarisation or specific skills development may need to be included at the start of a project.

Craft skills and the selection of contractors

The craft skills and procedures necessary for effective use of lime mortars include mortar making, application of the mortar materials and appropriate curing. These skills and procedures are described at Section 4 and should normally be fully specified following detailed investigation and decision making by the architect or other supervising officer. Not only will this assist in pricing the work, but it will serve as a support for experienced sub-contractors in their relationship with the main contractors, in establishing the level of skills, time and site facilities required to achieve an acceptable and effective job.

Where all potential contractors or sub-contractors are skilled experienced tradesmen, it may be appropriate to call for proposed method statements for evaluation as part of the tendering process. This approach allows the skills and working practices of experienced tradesmen to be taken into account in the execution of work on site and will readily identify those contractors who have the necessary understanding and experience to carry out the work.

Although there are a number of experienced contractors and skilled tradesmen available to undertake conservation and repair of traditional buildings, the building industry generally is suffering from a serious shortage of traditional skilled craftsmen and of building managers with the appropriate experience of traditional building crafts and techniques. Competitive tendering by contractors inexperienced in traditional work frequently results in unrealistic pricing even where comprehensive information is included in the specification.

Against this background it is important that only appropriate contractors should be invited to tender and specifications should place particular emphasis on the requirements for specialist site skills and working practices to assist in establishing a *realistic* level of pricing and reduce the risk of inappropriate work or irreversible damage to historic buildings. For work to important buildings only tradesmen who can demonstrate the necessary skills should be employed: historic buildings are not the place for inexperienced tradesmen to learn specialist skills.

5.10 Specifying requirements for supervision on site

However comprehensive or well written it may be, a written specification alone is not a guarantee of appropriate work on site. Because work to historic buildings can rarely be fully specified and quantified before the job is underway it is essential that day to day supervision should be provided by someone with adequate knowledge and experience, and with an understanding of the properties and limitations of traditional materials and of the skills and requirements of traditional building trades. It is recommended that this requirement for skilled supervision (as well as for skilled craftsmen) be written into the specification for all but the most direct jobs. The contractor may assume this role, or it may be necessary for the client to allow for a specialist site based representative during critical periods of the work.

Detailed site diaries, including weather records, should be kept and any agreed changes to the original specifications recorded and explained. At the end of the job a re-evaluation of the original intentions and of the work actually undertaken will provide a useful starting point for future projects.

APPENDIX A
SUMMARY CHECKLIST OF GOOD PRACTICE

Investigate the existing situation

- Investigate the overall condition and performance of the building and remedy basic defects.
- Investigate any existing lime mortars on the building.
- Preserve existing materials wherever possible.
- Investigate characteristics of masonry, local climate and conditions.
- Investigate materials available, using local sources where appropriate.
- Be aware of other influences or constraints, particularly in urban locations.

Use materials appropriate for the job

- Select an appropriate type of lime mortar for the type of work and local exposure.

  Many traditional Scottish mortars are feebly hydraulic.

  Feebly to moderately hydraulic mortars are likely to be required in many external applications in Scotland.

  The strongest hydraulic lime mortars, ie those based solely on NHL5, are not generally suitable for use with friable sandstones.

  Non-hydraulic limes cannot harden in wet conditions and are not suitable in situations of continuous saturation.

  Modern non-hydraulic and feebly hydraulic lime mortars will be vulnerable to damage by frost action when saturated.

- Select a lime mortar appropriate to the type and condition of masonry.

  Lime materials should always be weaker than the host masonry.

  Materials which are too strong for the host masonry will trap moisture in the wall leading, potentially, to stone decay and interior damp problems.

- Select aggregates, and any additives, for required performance and appearance.

Appropriate detailing of the work

- Bed or rebuild masonry appropriately, matching the character of original work.
- Keep masonry joints and beds as narrow as possible.
- Use adequate pinnings in joints and voids to minimise quantity of mortar.
- Finish mortar joints with open textured surface.
- Avoid recessed joints which trap water in the masonry.
- Modify or improve problem situations where possible.
- Continuously saturated masonry will be prone to lime leaching and accelerated decay of mortar (and stone).
- Water splash from adjacent hard surfaces may carry road salts which can damage lime mortars (and stone).

Prepare materials correctly

- Ensure materials correctly stored and handled.
- Putty lime mortars should be well matured.
- Hydraulic lime hydrates should be fresh.
- Use clean well graded sharp sands.
- Ensure ratios of lime to aggregate are correct for the types of lime and aggregate.
- Ensure gauging is accurately measured and thoroughly mixed.

  Uneven gauging or measuring of lime/aggregate ratios will result in variations of strength in the material.

  Inadequately mixed gauging may result in leaching-out of concentrations of free lime.

- Knock up materials thoroughly.
- Do not add extra water to substitute for knocking-up; use only as much as is required after knocking up.

  Inadequate mixing or excess water will result in lack of cohesion within the mortar resulting in friable material.

Good working practices

- Fully prepare walls prior to application of lime mortar.

  Remove all dust, debris and vegetation.

  Dampen down sufficiently to control suction.

  Lichens and vegetation not fully removed may grow back through the new mortar. (Refer to TAN 10, 'Biological Growths on Sandstone Buildings: Control and Treatment', for advice on treatment.
- Allow saturated masonry to dry out fully before applying new lime mortar.
- Use the correct tools for the job.
- Avoid the use of large volumes of mortar and pack voids and deep joints well with pinnings.

  Excess thickness of material will be unable to carbonate fully and will lead to shrinkage on drying.
- Compress and compact mortar thoroughly.
- Leave an open texture to the surface avoiding excessive working of the material.

  Overworking of the material may bring free lime to the surface and cause a hard skin (laitence) to form. This will result in the material being unable to carbonate properly. Laitence skins will be damaged by frost.
- Any soluble salts moving into the mortar may lead to breakdown of the mortar, or pitting and spalling of the surface, showing a white 'bloom'.

Appropriate working environment and protection

- Provide appropriately designed scaffolding for the best working access and from which protection may be hung. Include protection to the top of the scaffold.
- Ensure roof coverings, flashings, rhones and down pipes are functioning before work begins, otherwise make temporary provision for rainwater disposal.
- During application and curing provide protection against rain, rapid drying by sun or wind, and frost.

  Rapid drying before carbonation is established will result in shrinkage cracking and friable mortar.

  Rapid drying may also draw lime to the surface making the materials appear over-white.
- Dampen down the surface on new lime materials, as required, to slow the rate of drying and improve carbonation.
- Hydraulic lime mortars may become friable if insufficient water is available for the hydraulic set to take place.
- Where new lime materials are placed during autumn or winter, protection from frost may be required for the full duration of the winter.
- Lime mortars will not carbonate in situations of continuous saturation: a hydraulic set is required.
- In continuously wet situations, immature or uncarbonated mortars, and non- or feebly hydraulic lime mortars, are likely to be damaged by frost action.

APPENDIX B
DEFECTS DIAGNOSIS

DEFECT	POSSIBLE CAUSES
Harsh mortar which is difficult to use	• Poorly graded sands may result in harsh mortar. • Insufficient lime for the type or quantity of sand. • Inadequate knocking up will result in a harsh mortar, difficult to work.
Over-hard mortar	• Usually due to inappropriate use of strong hydraulic lime or cement gauging
Cracking and water penetration	• Hard, brittle mortars will be susceptible to cracking as a result of thermal, seasonal or structural movement. • Over-rapid drying will result in cracking. • If excess water has been used, reduction in volume as the water dries out causes shrinkage cracking.
Dampness in the masonry	• Hard mortars inhibit evaporation and can trap moisture in the building fabric. Over time the quantity of trapped moisture may be substantial and can result in reduction of thermal performance of the masonry, internal dampness, condensation, and timber decay. • Hard mortars may be subject to extensive micro-cracking which will admit water under wind pressure and capillary action. • Soft mortars may also develop cracks if used too wet or overworked insitu.
Masonry decay	• Dense impervious mortars transfer moisture movement and evaporation to the masonry and encourage frost damage to the stonework. • Cement introduces soluble salts which will similarly be transferred to the masonry. Wetting and drying cycles will subsequently result in the disruption of the binding matrix of the stones due to crystallisation pressure. • Lime rich non-hydraulic mortars may cause decay in some stone types (eg granites and some clay-rich sandstones.)
Failure of the mortar to harden	• Non-hydraulic limes cannot harden in wet conditions, or where there is no access to air. Masonry which is likely to remain permanently wet cannot be constructed or pointed in non-hydraulic lime mortars. • Lime mortars need to dry out gradually from within the depth of the material whilst remaining slightly moist at the face. Intermittent damping (*not soaking*) and drying will assist carbonation. • Inadequate drying out of wet structures and failure to protect new mortar from rain or other water sources will inhibit drying and carbonation. • The use of mortar in large volumes will result in inadequate drying and poor carbonation.
Frost damage	• Non-hydraulic mortars which are saturated by penetrating water during the winter will be damaged by frost. • Inadequate frost protection will result in freezing of the new mortar and disruption of the surface layer.
Rain damage and washout of lime, lime leaching	• Non-hydraulic limes used in permanently wet situations, and any type of lime used without adequate protection from driving rain before it is cured, will be susceptible to wash-out or leaching of lime. • Any type of lime subject to driving rain before being adequately cured will be susceptible to wash-out or leaching of lime. • Leaching is often caused by water penetration, for example through exposed wallheads. • The insertion of a dpc through lime-mortared masonry, especially at parapets or similar locations, is likely to result in lime leaching from above the dpc. • Inadequately mixed gauging may result in leaching out of concentrations of free lime. • The action of water on uncarbonated lime will result in leaching. • Leaching may also be the result of continuous water flow, particularly of slightly acid water, through carbonated lime.

Over-white mortar	• Inadequate protection may result in rapid drying with lime drawn to the surface. • Movement of lime particles to the surface of the mortar during evaporation from excessively wet mortars results in a white surface.
Friable crumbly mortar	• Inadequate protection and over-rapid drying will result in friable crumbly mortar if drying takes place before carbonation is established. • Excess water will prevent the development of a close bond between lime and aggregate. • Poorly graded aggregates will produce an inadequately bound mortar. • Insufficient lime will produce a weak friable mortar. • Thin, watery lime putty will make mortar with a high water content and result in a weak, friable material. • High initial water content and rapid drying will both result in a friable mortar. • Inappropriate storage will reduce the performance of hydraulic limes. • Lime particles reduce in size during maturing and develop closer contact with the aggregate. Inadequately matured materials may be poorly bound. • The practice of using lime mortars shortly after mixing does not allow x crumbly lime to develop a close contact with damp sand grains which are already bearing a film of water. • Insufficient knocking up will result in inadequate cohesion within the mortar. • The addition of water to compensate for inadequate knocking up of mortar will result in a friable, poorly bound mortar. • Hydraulic mortars may be friable if insufficient water is available for the hydraulic set to take place.
Inconsistent performance	• Variations in lime / aggregate ratios will become apparent as variations in performance of the mortar. • Uneven mixing in of hydraulic or pozzolanic gaugings will result in variations in the final mortar. • Variations or inconsistincies in curing conditions will affect mortar performance. • Apparently inconsistent mortar performance may be due to faults, such as water penetration, in the masonry.
Separation of mortar from backing	• Dust and debris will prevent mortar adhering to the masonry. • Excessive suction from dry porous masonry causes shrinkage, loss of bond between stone and mortar and friable mortar. • Rapid drying may result in shrinkage cracking and loss of bond.
Frost damage	• Inadequately protected new work will be damaged by frost. • Apparently sound work may be damaged at a later date when mortars with inadequate internal structure will fail after wetting and freezing.

APPENDIX C
OUTLINE STRUCTURE FOR SPECIFICATIONS

Each project requires a different solution. It is not appropriate to rely on, or enforce, a standard specification. Because there is limited experience in the building industry of working with traditional materials and methods, it is recommended that the specification should cover production and use of lime mortars in detail. Depending on the nature and extent of the proposed works and their relationship, if any, to a wider project specification, the structure of a specification for masonry repair and repointing works may take a variety of forms.

For the simplest situations, perhaps involving limited repointing works, a description of works, setting out standards, materials and techniques may be all that is required. The specification should, nevertheless, include all the necessary information to ensure that the works are priced and executed appropriately. The topics set out below, in the context of more comprehensive project specifications, should provide a checklist of items to be covered.

For more complex projects it will often be necessary to integrate the specification of lime mortars and masonry repair and repointing with a wider job specification based on, for example, the NBS (National Building Specification) format, *but the actual specifications should be purpose written for the job in question.* The structure and suggested content of specifications described below mirrors that of modern specification systems, in particular the widely used NBS format, and the range of information suggested is not unique to works involving lime based materials - it parallels that which should be provided for any type of material and work practices.

Under the NBS format, specifications for the production of lime based mortar mixes would normally be included in *Worksection Z21 - Mortars, Plasters, Renders and Grouts*. Specifications for masonry repairs and repointing, and for new masonry work, might be developed under *Worksections F20 – Rubble masonry & F21 – Ashlar masonry*. It will normally also be necessary to include specific information on design of the scaffold to provide appropriate access and working conditions and ongoing protection for lime based external works. Information may also be required in other Worksections.

As a guide, a specification should include at least the following subjects. Other site-specific information will also be required.

SCAFFOLDING AND GENERAL ACCESS

- Specify the design requirements of the scaffold and other access etc requirements as they relate specifically to the masonry works, repointing, etc.

(It should be made clear which requirements are to be the responsibility of the general contractor or scaffolding subcontractor, and which are the responsibility of the (specialist) subcontractor for the lime based works. If this information is included in the general contract specifications a cross reference and appropriate additional information should also be included in the relevant trade Worksections.)

SPECIFICATIONS FOR MATERIALS AND MORTAR MIXES

Under *Worksection Z21 Mortars, Plasters, Renders and Grouts*, detailed information should be provided on materials and on methods and techniques of production of the various mortar mixes required for rebuilding, consolidation and wall core work, work at exposed locations, footings, etc, general repointing, ashlar repointing etc. The full range of mortar mixes should be individually identified and specified, including information on constituents and proportions, methods of production and handling, and location / use for each mix.

This Worksection is likely to include information such as:-

DEFINITIONS (if there is likely to be any doubt about the meaning of terms used in the Z21 Worksection, eg where contractors may not be familiar with terms or descriptions of traditional limes and lime based materials)

GENERAL REQUIREMENTS (covering matters of overall relevance to the production of mortars, such as workmanship and particular requirements or constraints)

Standards: -

- Specify standards of supervision, skills, experience required.

- Specify quality control procedures including, if required, arrangements for sampling and checking of materials and mixes.

Analysis of existing materials: -

- Specify requirements for analysis of existing materials if required, including acceptable specialist laboratories.

MATERIALS (covering sources, types and qualities of all materials to be used in the production of lime based mortars)

Purchase of ready made mortars: -

- Note acceptability of, and / or requirements for, purchase of pre-mixed materials.
- Specify constituent materials, production methods and maturing / storage conditions for pre-mixed materials, as below.
- Where appropriate, identify acceptable sources of supply.

Requirements for contractor-made mixes: -

- Specify constituent materials, production methods and maturing / storage conditions for contractor-made materials, as below.

Constituent materials for lime based mortar mixes:-

- Specify quality and characteristics (and sources where appropriate) of all limes, sands and other aggregates, and other constituent materials for lime based mixes.
- Note relevance and application of BS and ENV, or other, standards.
- Specify requirements for handling, storage etc of individual materials.

WORKS (MORTAR PRODUCTION) (covering the working methods and techniques required to make appropriate mortars)

Methods of mortar production: -

- Specify acceptable types of machinery and production methods.
- Specify requirements for measuring, batching and mixing the required lime based mortars.
- Specify requirements for storage and maturing of mortars.

Works required to mortars on site: - (or cross refer to other Worksections)

- Specify knocking up processes required on site.
- Specify techniques of adding gauging materials on site.
- Specify handling and storage requirements on site.
- Specify maturing times if appropriate.

Details of individual mortar specifications: -

- Note identification, location and constituents and proportions of each mortar mix.

This can typically be presented as

Mortar Type	--------------------
Location	---------------------------------------
Constituents:	nominally 1 : 2.5
	11.2 kg NHL5 (specify producer or supplier)
	40 litres concrete sand Type -----)
	Only sufficient water to make a plastic workable mix.
Production:	As clauses -------

SPECIFICATIONS FOR REPOINTING ETC

Under the relevant Worksections for application of materials (eg F20 Rubble masonry, and F21 Ashlar masonry), the following information will be required in relation to repointing works.

A similar range of information will be required for other activities, such as downtaking and rebuilding, etc.

DEFINITIONS (where there is a need to clarify or establish definitions for the purpose of the contract)

- Cross refer to definitions in BS 5390 : 1984 'Code of practice for stone masonry.
- Define what is meant by 'tamping', 'fairing out', etc.

GENERAL REQUIREMENTS (covering matters of overall relevance such as workmanship and particular requirements or constraints)

Access, etc: -

- Identify responsibilities of the (specialist) subcontractor and general or scaffolding contractor.

(See notes on scaffolding and general access, above.)

Standards: -

- Identify the required skills/experience of site supervisory staff.
- Note the relevance (or not) of individual British Standards etc.
- If appropriate refer to BS7913: 1998, Guide to the principles of the conservation of historic buildings.
- Note the requirement for a matching standard of workmanship to agreed samples.
- Specify required skills/experience of tradesmen.

Methods of working: -

- Note the need to follow instructions, always allowing for agreed contractor variations, for preparation, application, protection, and curing.
- Highlight the differences between lime and cement practice.
- Note the requirement to produce mortar in accordance with specified methods.
- Note restrictions on the use of power tools for cutting out or applying mortar.

Timing of the work: -

- Specify any requirements for sequence of works etc.
- Specify preferred period of work.
- Specify special requirements that apply to work outside this period.

Protection of work: -

- Specify requirements for general protection of works, protection of adjoining fabric etc, and cross-refer to the requirements for working and curing.

MATERIALS (providing information on type, quality, size, source, handling and storage, etc, for all materials to be used in this section of the work)

- Specify any requirements for obtaining mortars, whether to be purchased, site mixed etc.
- Specify type of mortar for all applications (Under the NBS format this will normally mean cross reference to specific mortar types defined and specified in Worksection Z21), including mixes for all proposed work operations.
- (As an alternative, perhaps where the works do not form part of a wider contract, information on production of mortar mixes can be included within the Worksections covering repointing, etc works. In this case it will be necessary to include information on constituent materials, proportions, and methods of production, maturing, etc.)
- Specify methods of knocking up and, where required, gauging mortars on site before application.
- Note the degree of flexibility (if any) to be allowed to the contractor for minor adjustments to suit site conditions.
- Specify need for and type of pinnings or gallets.
- Specify replacement stone if required.

PREPARATION (describing any preliminary or preparatory actions required before the actual works are undertaken)

- Specify any requirements for recording, identifying exact locations of various treatments etc, before and during work, and for recording of actual mixes as used on site.
- Specify extent and methods of removal of vegetation.
- Identify requirements for sample areas of work, to be undertaken in advance of the main works, for approval and quality control, and the location of these samples.

WORKS (describing the location and extent of work to be undertaken, and the methods of carrying out the work, actions required, etc)

Extent of work: -

- Clearly describe, with drawings if necessary, specific areas that are to be repaired or worked on and identify the mortar mixes, finishes, etc applicable at each location.

Preliminary works / removal of old mortars, etc: -

- Specify locations and methods of temporary support etc, before work proceeds.
- Specify location and method of removal of existing mortar from joints.

Preparation of joints and surfaces: -

- Specify preparation of masonry and joints by brushing / washing down, etc.
- Specify measures to control or improve suction and adhesion.

Repointing works: -

- Specify requirements for handling and knocking up mortar on site.
- Specify methods of filling deep joints,
- Specify methods of repointing of rubble work.
- Specify methods of repointing ashlar work.
- Specify techniques for finishing joint surfaces.

Protection and curing: -

- Specify minimum level of protection.
- Identify conditions requiring further special protection.
- Specify procedures for curing.
- Specify requirements for special measures for out-of-season working.

APPENDIX D
HEALTH & SAFETY

These notes are intended only as an awareness guide. Full health and safety documentation should be provided for all materials (including lime-based materials) and methods to be used in a building contract.

D1 Legislation

Working practices with lime mortars will generally fall within the scope of the Health & Safety at Work Act, 1974. The Construction (Design & Management) Regulations 1994 will normally apply to the design and management of contract works.

D2 Materials

- Lime products should be handled with care. As with most other common building materials, slaked lime products can be used without danger provided a few simple precautions are taken.
- Limestone and carbonated mortars are largely inert. They present some danger to the eyes from dust or particles.
- Slaked lime products are a caustic alkali and are irritant or drying to the skin. There is some danger if slaked lime is maturing, as the slaking process can still be active. This will be most dangerous to the eyes.
- Quicklime is potentially the most hazardous form of lime. It is highly caustic and can cause skin burns. It is extremely dangerous in the eyes. Quicklime should not be specified for use on site unless experienced personnel are available. The use of quicklime requires particular attention to health and safety issues.

D3 Potential hazards

D3.1 Skin Contact

Hazards:

- Quicklime causes irritation or burning of skin.
- Slaked lime materials are drying to the skin and can be an irritant.
- Always avoid skin contact with quicklime. Avoid skin contact with other lime materials wherever possible. Especially in warmer weather, shaven parts of the face and neck are liable to irritation.

Personal Protective Equipment:

- Wear clothes that provide maximum skin cover.
- Wear protective gloves. In wet conditions, or where the hands may come into contact with lime putty or milk of lime, waterproof gloves should be used.
- Use barrier cream on the hands, wrists and exposed areas of skin.

D3.2 Eye Contact

Hazards:

- Hydrated lime dust in the eyes is extremely painful, and may cause damage.
- Quicklime in the eye is particularly dangerous. It can cause severe burns, and can easily cause permanent eye damage.

Personal Protective Equipment:

- Use eye protection when slaking quicklime, working with lime based materials overhead, and when applying harling or limewash.
- Wear goggles to prevent lime entering the eyes. Wide vision, full goggles with anti-mist properties are preferred.

D3.3 Inhalation

Hazards:

- Inhaling slaked lime dust may cause throat irritation.
- Inhaling quicklime dust can cause caustic burns to the mucous membranes.

Personal Protective Equipment:

- Wear a dust mask when exposed to lime dust. A dust mask consisting of gauze-covered aseptic cotton wool filter pads, held in a wire frame with a headband, is effective for protecting the mouth and nose.

D3.4 Ingestion

Hazards:

- Slaked lime is likely to cause irritation of the gastro-intestinal tract if swallowed in large doses.
- Ingestion of quicklime will cause internal caustic burns.

D4 First Aid Treatment

D4.1 Skin or eye contact

- Any lime materials in contact with the skin should be washed off immediately with soap and water.
- Keep a first aid box to hand when working with lime materials. Cuts and abrasions should be cleaned and covered.
- If serious burns are sustained, medical attention should be sought.
- Any lime material in the eye should be removed immediately.
- Use a cotton wool bud to remove lime particles from the eye.
- Irrigate for at least 20 minutes with clean running water or proprietary eyewash. If possible the water should be distilled and as close to the body temperature as possible. (Some people recommend the use of a very dilute sugar solution which, being slightly acidic, counteracts the alkalinity of uncarbonated lime).
- Make sure eye irrigation equipment is close to hand when using lime materials.
- Medical attention should be sought if quicklime has entered the eye, and irrigation continued until attention is available.

D4.2 Inhalation of Lime Dust

- Thoroughly irrigate the nose and throat with water, ensuring that the airway remains clear and that aspiration of water is avoided.
- Remove the affected person to fresh air, keep them warm and at rest.
- Medical attention should be sought.

D4.3 Ingestion of Lime

- Do not induce vomiting.
- Wash the mouth out with water and ensure copious quantities of water are drunk.
- Medical attention should be sought.

D5 Fire hazards

- Slaked lime products are non-flammable and inhibit combustion. No special fire fighting equipment is required.
- Storage of quicklime requires special consideration, due to the heat generated if it comes into contact with water.

APPENDIX E
GLOSSARY OF TERMS

Aggregate: any material which, when combined with a binder, forms a mortar. This can include sand, crushed rock, brick dust, or any other appropriate filler.

Air limes: limes that set through carbonation, rather than through chemical reaction with water. So called because they set in air.

Aluminates: compounds of aluminium and oxygen.

Argillaceous: containing clay substances. May be used in connection with some types of sandstone.

Ashlar: stones with hewn or polished surfaces built with tight joints, to be seen as face work.

Binder: material that binds together the aggregate particles in a mortar, e.g. the lime, gypsum, clay, cement, etc.

Calcium carbonate: chemical state of the raw limestone material, and of fully set lime mortars.

Capillary action: a phenomenon arising from the surface tension of a liquid, whereby it is drawn up through thin tubes or pores within the structure of a host material.

Carbonation: the process by which fresh lime mortar re-absorbs carbon dioxide in moist conditions and reverts to calcium carbonate. As a result of this process the lime mortar becomes relatively harder, more stable and less soluble.

Cement: a quick-setting binder for making mortars. Commonly available as portland cement. Historically, natural cements were also available, produced from naturally occurring combinations of limestone and clay.

Cementitious: a description of the setting property of a mortar, by the chemical action of formation of tri-calcium silicates and aluminates.

Cherry cocks: small stones placed into the surface of joints between stones in a wall, often in a formal pattern.

Coarse stuff: a mixture of lime and coarse sand or other aggregate used as lime mortar.

Concrete sand: a marketed commodity, of siliceous aggregate comprising a range of particle sizes including small pebbles or grit, suitable for use in making concrete. Also generally suitable for use in lime mortars, harling, etc.

Coursed stonework: Built masonry where each layer has a clearly defined horizontal alignment of uniform, or near uniform, height. It is often dictated by the size of the largest stones used in the construction.

Debris netting: a form of protective barrier used to enclose a safe working area. Often an open-woven polypropylene material is used.

Dry hydrate: hydrated lime in which quicklime has been slaked with just enough water to form calcium hydroxide in the form of a dry powder.

Eminently hydraulic lime: lime prepared from limestone containing a high proportion of re-active silica or silica/alumina, often in the form of clay minerals. Hydraulic limes have the ability to set in wet conditions, unlike non-hydraulic limes. Approximately equivalent to European classification NHL5.

Fat lime: non-hydraulic lime, consisting almost entirely of calcium hydroxide, plus water. Also known as 'air lime'.

Fatten up: the slow absorption of water into an uncarbonated lime material, making it more plastic.

Feebly hydraulic: a hydraulic lime which has the lowest reactive silica / alumina mineral content, and therefore has a weak chemical set in conjunction with its rate of carbonation. Approximately equivalent to European classification NHL2.

Friable material: a mortar that can be easily crumbled. This can also be used to describe the state of the masonry.

Gauging: literally, the measuring of materials in combination. Used to describe a measured amount of material added to a lime mortar in order to modify the properties of the mortar.

Green: the transitory state of a mortar in the process of drying out. The mortar will have developed a little mechanical strength, but full carbonation or hydraulic set will not have been achieved.

Grouting: filling joints, crevices or voids in walls, which are too small or inaccessible to be filled using mortar of normal consistency, using a very fluid binding material.

Harling: a thrown, or cast on, finish of lime and aggregate.

HTI: a finely ground powder with pozzolanic properties, derived from high-temperature ceramic insulation material.

Hydrated lime: see dry hydrate. In modern building practice the term is commonly used to describe non-hydraulic lime powder, ie 'builders' lime', used in modern cement / lime / sand mortars.

Hydraulic limes: lime prepared from limestone containing reactive silica or silica / alumina, often, but not necessarily, in the form of clay minerals. These give the mortar a chemical set that is quicker and harder than the carbonation of pure limes, and a degree of ability to set in wet conditions. Limes can be feebly, moderately or eminently hydraulic. Hydraulic limes come in a range of strengths – NHL2 (feebly hydraulic), NHL3.5 (moderately hydraulic) and NHL5 (eminently hydraulic), are the most commonly used descriptions. Hydraulic limes cannot normally be stored as putty for any length of time because the chemical set will cause them to harden, and they are therefore stored as dry hydrate. Also known as 'water lime'.

Knocking up: the re-working of a mortar mix to re-gain plasticity before use.

Laitence: a surface skin that develops on over-worked mortar surfaces, drawing fine material to the surface and reducing permeability.

Larry: a long-handled hoe used to mix lime putty and coarse stuff.

Lean limes: limes which contain a proportion of non-reactive impurities, which behave like a very fine sand and reduce the quantity of sand which can be used in the mortar, in contrast to fat lime mortars which can carry more sand.

Lime (hydraulic): See Hydraulic lime.

Lime (non-hydraulic): See Non-hydraulic lime.

Lime putty: hydrated lime which has been slaked from quicklime using sufficient water to form a thick liquid and subsequently settled out to a putty during storage.

Lime-water: a saturated solution of calcium hydroxide in water. Left when lime putty settles out of slaked lime. Used for consolidation of porous surfaces.

Limewash: a form of paint, a suspension of lime (putty) in water.

Moderately hydraulic lime: lime with a moderate degree of hydraulic set. Approximately equivalent to European classification NHL3.5. See Hydraulic lime for definition of different degrees of hydraulicity.

Mortar: any material which can be worked or placed in a plastic state, becomes hard when in place, and which can be used for bedding, jointing or finishing the materials forming the component parts of a wall.

Movement joints: a function adopted in modern building practice, where joints are created between inflexible sections of wall or wall finishes. They permit thermal movement of the wall to occur without cracking brittle finishes.

Milk of lime: a free-flowing suspension of hydrated lime (lime putty) in water, in such proportion as to resemble milk.

Non-hydraulic lime: a pure lime, consisting almost entirely of calcium hydroxide without reactive silica or silica / alumina. Non-hydraulic lime mortars harden only by slow drying and carbonation, and cannot set in wet conditions. Also known as fat lime or 'air lime'.

Perpend: a vertical joint in masonry walling.

PFA: pulverised fuel ash is a waste product from power stations; used as a pozzolan in modern cementitious mortars and grouts. Tends to produce a very hard set.

Pigment: colouring material, not normally used in lime mortars.

Pinning stones: small stones (or shells, etc) placed in joints to stabilise masonry and reduce the volume of mortar required. Used in conjunction with mortar in re-pointing etc.

Plasticity: a description of the ease of spreading and cohesiveness of a mortar mix.

Portland cement: the common form of cement made by grinding clinker formed by firing clay and limestone at high temperatures.

Pozzolans: materials containing fine particles of reactive silica and alumina, and sometimes iron oxides, which will react with calcium hydroxide and water to produce a chemical set in mortar, similar to the set achieved by hydraulic limes.

Putty: see Lime putty.

Quicklime: calcium oxide. A highly caustic material produced by burning limestone. Quicklime is slaked with water to produce lime for building works.

Relative bulk density: a method of comparing the weight of different materials for a given volume. A material with a low rbd will weigh less per given volume than a material with a high rbd.

Rubble: masonry using irregular and variable sized pieces of stone to create a strong construction. Walls vary in appearance depending on the builder and the nature of the building stone. Contrary to popular belief the wall is usually built in courses, not random.

Salt efflorescence: the crystallisation from solution of soluble salts from within a structure. Normally associated with the drying out of wet walls.

Silt: finely divided mineral particles, usually less than 75µ dia. Smallest sizes (below 2µ) will stay in suspension in a liquid.

Slaking: the controlled process of combining quicklime with water to form slaked lime in the form of lime putty or dry hydrate.

Slurry: a thick, but fluid, mixture (eg of a dry powder gauging material in water).

Spalling: the degradation of masonry or lime materials through loss of surface parts or layers.

Suction: the characteristic by which a wet bond is created between lime, and other, mortars and porous masonry surfaces.

Tampers: tools of various shapes for pushing mortar into joints.

Water limes: hydraulic limes, so called because they will set in wet locations.

Whin: traditional but informal name for hard dark grey rocks (usually basalt or andesites).

APPENDIX F
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BS/EN459-2:1995 *Building lime. Test methods*

BS890:995 *Specification for building limes.* (This will be withdrawn when EN459 is formally incorporated into British Standards)

BS882:1992 *Aggregates from natural sources for concrete.*

BS1199/1200:1976 rev 1986 *Building sands from natural sources*

BS8000-3:2001 *Workmanship on building sites. Code of practice for masonry.* (Clauses relating to standards of workmanship and site practice are generally applicable to work with traditional lime mortars.)

BS8000-10:1995 *Workmanship on building sites. Code of practice for plastering and rendering.*

BS5628-1:1992 *Code of practice for masonry - Part 1: Structural use of unreinforced masonry.* (Includes specifications and strength requirements for various classes of cementitious mortars not generally applicable to traditional masonry buildings.)

BS5628-3:2001 *Code of practice for masonry - Part 3: Materials and components, design and workmanship.*

BS8221-1:2000 *Code of practice for the cleaning and surface repair of buildings. Cleaning natural stone, brick, terracotta and concrete.*

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APPENDIX G
USEFUL ADDRESSES
(as at February 2003)

Specialist services and materials are currently available in Scotland as noted below. Similar services and materials are also available from a range of sources in England. This information is provided in good faith but the inclusion of any particular firm, individual or product does not imply endorsement by Historic Scotland.

Advice on conservators, craftsmen, conservation contractors and architects: -

The Scottish Conservation Bureau, Longmore House, Salisbury Place, Edinburgh EH9 1SH.
Telephone 0131 668 8668

Practical hands-on training and specialist advice on lime based materials: -

Scottish Lime Centre Trust, The Schoolhouse, Rocks Road, Charlestown, Fife KY11 3EN.
Telephone 01383 872722
Email slct@scotlime.org

Other one-off short courses are provided by various individuals and organisations from time to time.

Traditional lime based materials, including associated specialist materials: -

The suppliers marked * produce a limited range of materials.

*Cumming & Co, 8 Whitefriars Street, Perth PH1 1PP. Telephone 01738 567899.
Email office@cummingltd.com

*Leonard Grandison & Son, Innerleithen Road, Peebles EH45 8BA. Telephone 01721 720212.)

*Becky Little, Earth and Lime Construction, Ash Cottage, Monimail, Cupar, Fife, KY15 7RJ. Telephone 01337 810323
Mobile 07968 494063.
Email becky@becky.little.co.uk

Masons Mortar, 77 Salamander Street, Leith, Edinburgh EH6 7JZ. Telephone 0131 555 0503.
Email quickline@btclick.com
(Lime mortars & plasters, lime putty, hydraulic limes, limewash, aggregates & sands, crushed brick and soft-fired brick dust, hair, pigment and other specialist products)

*Tim Meek Associates, Unit 3, Whitedykes Industrial Estate, Bayview Crescent, Cromarty, Ross-shire IV11 8XN.
Telephone 01463 250433
Email tim.meek@btopenworld.com

*The Plaster Restoration Company, 1 Beresford Terrace, Edinburgh EH5 3HR.
Telephone 0131 552 5363
www.plasterrestoration.co.uk

*William McVey, Hawkhill Cottage, Stevenston, Ayrshire, KA20 4LF. Telephone 01294 603033.
Email bill@cornice.co.uk

Sources and suppliers of natural hydraulic limes: -

UK-produced materials

Product name	***hl2* Blue Lias Hydraulic Lime**
ENV class	NHL3.5
Producer	Hydraulic Lias Limes Limited Tout Quarry, Charlton Adam, Somerton, Somerset TA11 7AN
Supplier	Available to order from the producer. Telephone 01458 223179 Email hl2@limesolve.demon.co.uk

French-produced materials

Product name	**St Astier NHL2 NHL3.5 NHL5**
ENV class	NHL2 NHL3.5 NHL5
Producer	UCDC Chaux et Enduits de Saint Astier
Importer	Setra Marketing Ltd
Supplier	Masons Mortar, 77 Salamander Street, Leith, Edinburgh EH6 4JZ. Telephone 0131 555 0503 Email quickline@btclick.com

Product name	**Castle Natural Hydraulic Lime**
ENV class	NHL3.5
Producer	SOCLI, Izaourt, in SW France
Importer	Castle Cement Ltd, Park Square, 3160 Solihull Parkway, Birmingham B37 7YN
Supplier	Castle Cement, contact Paul Livesey. Telephone 01200 422401 Email paul.livesey@castlecement.com

Product name	**Chaux de Pavier**
ENV class	NHL3.5 NHL5
Importer	Cathedral Works Organisation, Terminus Road, Chichester, Sussex PO19 2TZ
Supplier	Cathedral Works Organisation. Telephone 01243 784225 Email c.w.o@osborne.co.uk

Italian-produced materials

Product name	**Unilit Natural Hydraulic Lime**
ENV class	NHL3.5 / NHL5
Producer	Tassullo
Importer	Telling Lime Products, Primrose Ave, Fordhouses, Wolverhampton WV10 8AW Telephone 01902 789777 Email info@telling.co.uk
Supplier	Telling Lime Products, as above

Swiss-produced materials

Product name	**JuraKalk**
ENV class	NHL5 (at stronger end of the NHL5 class)
Producer	Jura Ciment Fabriken, CH-5103 Wildegg, Switzerland
Supplier	Masons Mortar, as above

Mortar mixers: -

A range of mixing machinery suitable for site production, gauging and knocking up traditional lime mortars is available from suppliers, including those below. Machines may be available in a choice of capacity and include:

- *Roll pan mixers.* These are of the traditional mortar mill design, usually incorporating two heavy rollers which mix and compress the mortar.
- *Paddle mixers.* These incorporate paddles rotating within a vertical drum and operate by beating the mortar.
- *Forced action paddle mixers (screed mixers).* Similar to paddle mixers but with an action which contributes to air entraining in the mortar. These normally take a full bag (25kg) of lime hydrate.
- *Full capacity concrete mixers.* These are heavy duty rotary drum mixers (as used on commercial bricklaying sites) and will take a full bag (25kg) of lime hydrate.
- *Heavy duty hand held mortar whisks.* These can be used for mixing small quantities of mortar from dry hydrates and sand.

Imer Direct GB Ltd, Unit 10, Echo Way, Lanesfield Drive, Wolverhampton WV4 6UB.
Telephone 01902 353252

Linco Sales Ltd, Crews Hole Road, St George, Bristol BS5 8AY.
Telephone 0117 955 520.

Liner Manufacturing Ltd, Monckton Road Industrial Estate, Wakefield WF2 7AL.
Telephone 01924 290231

Masons Mortar, 77 Salamander Street, Leith, Edinburgh EH6 7JZ. Telephone 0131 555 0503

Refina Ltd, Unit 15, Ventura Place, Factory Road, Upton Place, Poole BH16 5SW.
Telephone 01202 632270

Specialist analysis of original materials: -

The Scottish Lime Centre Trust, The Schoolhouse, Rocks Road, Charlestown, Fife KY11 3EN.
Telephone 01383 872722
Email slct@scotlime.org
(Mortar characterisation, specialist thin section analysis and simple chemical analysis)

CMC Ltd, Wallace House, Whitehouse Road, Stirling FK7 7TA. Telephone 01786 434708.
Email bill@cmcstirling.co.uk
(Chemical and X-ray analysis)

THE HOUSE 3/03 PRODUCED ON SUSTAINABLE MATERIAL