

TECHNICAL PAPER 27

HOT-MIXED LIME MORTARS
MICROSTRUCTURE AND FUNCTIONAL PERFORMANCE



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Cover image: Scanning electron microscope (SEM) image of hot-mix mortar showing intimacy of bond between binder and aggregate in historic lime mortar; Kilmahew Castle, Strathclyde.

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HISTORIC ENVIRONMENT SCOTLAND TECHNICAL PAPER 27

HOT-MIXED LIME MORTARS

MICROSTRUCTURE AND FUNCTIONAL PERFORMANCE

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PREFACE BY HISTORIC ENVIRONMENT SCOTLAND

Hot-mixed mortars have a long history of use in Scotland, with evidence visible throughout the country on traditional buildings and structures. Since the mid-1990s however, their preparation and use has been largely superseded by dry-bagged natural hydraulic limes (NHLs) that have very different properties to their historic predecessors. The conservation sector's renewed focus on traditional materials and questions about the compatibility and authenticity of modern lime mortars on traditional masonry structures has encouraged a revival of interest in the use of hot-mixed mortars for repair and conservation. This report forms part of a series of Historic Environment Scotland Technical Papers that aim to improve understanding of hot-mixed mortars, and demonstrate why these materials are still relevant. These contribute to an evidence base which serves as a starting point for discussion on the revival of traditional mortars in Scotland and how they fit into the wider suite of mortar repairs for traditional buildings.

Hot-mixed mortars are prepared by mixing quicklime with aggregate and water, generating heat and producing a sticky, lime-rich mix. The benefits of hot-mixed mortars are known by practitioners and craftspeople, and have been documented in historic and recent texts on traditional building and conservation. They are favoured by many practitioners for their workability and early stiffening, allowing efficient building and economy of materials. But their ease of use is just one element; from a technical perspective lime-rich non- or feebly-hydraulic mortars offer protection to stone buildings by adhering tenaciously to the masonry and actively drawing moisture away from the stone. Modern practice has tended towards higher strength mortars to increase frost resistance and durability. However a balance must be struck in the conservation of traditional masonry, since increasing the strength of the mortar to resist freeze/thaw action compromises the mortar's ability to draw moisture and salts from the walls and preserve the masonry units. An increase in strength comes with a reduction in sacrificial behaviour. Traditional lime mortars can offer durability (without compressive strength), whilst maintaining breathability and capillarity. These qualities must be seen in the context of good building detailing and maintenance, without which defects and failures will inevitably occur.

This paper examines the micro-structural evidence for the benefits of hot-mixed mortars. Other papers in the series put the material in a wider context, including evidence from more recent lime applications in Scotland. It is hoped that a greater understanding of the performance characteristics of hot-mixed mortars will result in better quality and more appropriate specifications for traditional lime mortar repairs in Scotland.

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EXECUTIVE SUMMARY

This paper presents technical evidence for the use of hot-mixed lime mortars in the conservation of masonry structures. It begins by examining how historic lime mortars function in practice: why are they durable and how do they protect the masonry? These questions are answered by examination of microstructures of historic lime mortar samples, and reviewed against the relevant physical principles concerning the decay and preservation of traditional masonry materials.

Compatibility of historic lime mortar with masonry is quantitatively examined on a functional basis. The causality behind the developed microstructure (which imparts behavioural function) of historic lime mortar is considered, and this leads to a specification context: the specification of new lime mortars should be aimed at replicating this preservation process.

The paper then examines historic lime mortars on the basis of known credentials, relates the constituent ingredients and preparation method to the microstructure, and considers its functional behaviour in the active preservation of traditional masonry.

Hot-mixed lime mortars are identified as the optimal means of replicating the functional behaviour demonstrated by the historic examples. The paper does not start with the assumption that historic lime mortar is always hot-mixed; rather it starts with the known credentials of historic limes, of binder richness and lime richness, and examines how these can be best replicated in repair mortars.

Key characteristics of hot-mixed lime mortars are highlighted, with considerations of durability and active preservation function. This paper considers the difference between historic lime mortar and modern Natural Hydraulic Lime (NHL) based mortars, in terms of microstructural and functional characteristics. NHL mortars are shown to have lower free lime content than historic examples, and used at leaner mix proportions. In addition to the discord in composition and microstructure, NHL mortars are typically stronger and less deformable than historic lime mortars. This leads to inefficiency in drying masonry out and limited potential to actively preserve masonry units.

By contrast, this paper shows how hot-mixed lime mortars represent the optimal means for replicating the microstructure, and therefore functional behaviour, of historic lime mortars. The historic precedent for the preparation method is cross-referenced to other Historic Environment Scotland (HES) Technical Papers in the series and other research.

I. INTRODUCTION

The need for mortar to be compatible with its substrate is evidenced by the many examples of damage inflicted upon traditional masonry by inappropriate cement mortars in the last century. The 'lime revival' of the 1980s to 1990s arose in direct response to this situation and offered a modern solution with apparently clear historical precedent. However, early difficulties were encountered with attempts to use putty limes for external work in Scotland, as these often performed poorly in the harsh, wet climate. Reference can be made to Henry et al. (2012) for a detailed account of the history of the lime revival, examination of the chemistry, technology and practice of application of traditional lime mortars, and as a central point of reference to the widely published works on the subject.

The commercial arrival of NHL-based lime mortars has largely dominated building conservation in recent decades, thanks to their relative robustness and quick setting when compared with putty mortars. The design of repair mortars for traditional masonry has frequently been undertaken based on mortar analysis of surviving original samples; a large database of mortar samples is held by the Scottish Lime Centre Trust and has been analysed by HES (Schmidt 2017). Despite this, it is often the case that whilst original lime mortars tend to exhibit pronounced lime richness (typically with only feebly hydraulic character), the specified NHL repair binders (being mainly hydraulic in nature and of comparatively low free lime content) often bear little resemblance to the original.

There appears to be little historic precedent for the use of eminently or even moderately hydraulic mortars above ground level in masonry buildings. The traditional qualifying designation 'water' lime suggests their intended context of application, historically confined largely to foundations, civil engineering structures and water/maritime works.

The preservation function of mortar

Recent advancements in the understanding of historic lime mortar have led to compatibility being appraised in terms of functional performance requirements. Contemporary NHL mortars tend to fall short of the functional example of historic lime mortars, which have a role in the active preservation of the masonry units, and effectively draw the water out of the masonry fabric through their pronounced capillarity to keep the building dry (Wiggins 2015). Modern NHL mortars do not seem able to perform this function effectively on damp masonry walls; although the mortar can often appear

dry, the masonry or interior may remain damp, suggesting impaired capillary suction capabilities of the repointing mortar.

The key factor in the transport of water is the capillary porosity of the lime binder, dictated by the lime-richness of the original mortar composition (Wiggins 2015). By contrast, the limited drying ability of modern mortar mixes is related to the relatively low free lime content of NHL binders (St Astier, 2015; Hughes and Swann, 1998). This, coupled with the lean mix proportions and comparative high strength of NHL mortars means that modern NHLs differ in composition and function relative to the historic examples.

It appears that sight has been lost of a primary function of the mortar in traditional masonry. A mortar is a load-bearing, weather-proofing filler to keep the masonry units apart and at the same time draw the water out of the fabric. Traditional masonry structures work in compression, with no flexural resistance. The mechanical role of the mortar does not lie in strength *per se*, but in deformability and intimate adhesion with the masonry units throughout the fabric. Stability of the structural form relies on principles similar to dry-stone construction. The mechanical functions of the mortar are intimately entwined with its moisture-regulating/weather-proofing role, which may be considered as the principal role of the mortar.

Mortar durability tables have been imported from modern cementitious masonry design (Allen et al. 2003). These tables ignore the context in which the mortar must function, and simply state the response of the mortar in isolation to a standard suite of traditional durability tests. This is inappropriate for building conservation, where the focus is on the preservation of the masonry units, not the mortar. Such tables indicate that those with the highest degrees of hydraulicity (Ordinary Portland Cement (OPC) mortars) are the most durable, whereas they judge lime-rich mortars as non-durable (Allen et al. 2003). This is not the case when the context in which the mortar must function is considered: the lime-rich mortars of the past offer the optimal longevity to the masonry fabric. Surviving external and internal finishes which are now in external conditions (e.g. in masonry ruins) defy the 'mortar durability' tables which render them non-durable (Meek and Addyman 2018). Figure 1 records an internal lime plaster finish at Auchindoun Castle, which has survived hundreds of years in exposed external conditions.



Figure 1: Surviving lime plaster in very exposed conditions at Auchindoun Castle, Grampian.

Such durability seems difficult to replicate in new lime work. This paper seeks to unpack the underlying reasons behind the longevity of historic mortars, and apply the findings to a specification context for new work.

The need for masonry to breathe

In addition to the misconception of durability, the original principle of the need for masonry to ‘breathe’ as first described by the Society for the Protection of Ancient Buildings (SPAB 1979; Hughes 1986) has sometimes been misconstrued by practitioners. Focus has been directed largely at vapour-phase moisture permeability, at the expense of liquid-phase egress capability. Of the two mechanisms, it is liquid-phase egress which has direct bearing on the preservation or decay of the masonry fabric. Many proprietary ‘lime’ mortars and pre-mixed ‘restoration mortars’ adopt this vapour-only approach, and advertise high vapour permeability alongside low capillarity. These are two incongruous characteristics of normal porous materials unless chemically modified with water repelling agents. Critically appraised in terms of function, these materials diverge further from the historic lime mortar examples. They can lead to accelerated decay of the masonry or entrapment of water within the masonry fabric, thereby compromising the serviceability of the building. In view of this situation, there has been renewed interest from the conservation sector in the historic mix specifications and preparation methods.

2. WATER MANAGEMENT AND MASONRY CONSERVATION

Water and traditional masonry

Water is considered the 'engine of decay' in traditional masonry as it mobilises the agents of decay (Maxwell 1995). Scotland has a high wind-driven rain (WDR) index; it has amongst the highest wind speeds and annual rainfall in Europe, resulting in a heavy water load on its masonry heritage (Stirling 2002; Forster and Carter 2011). Effective roof detailing, rainwater management and routine maintenance address the brunt of the total precipitation amount, the majority of which falls vertically. However, the horizontal component in WDR, coupled with penetrating or rising damp and internally released vapour mean that moisture is often available to mobilise the agents of decay in the masonry fabric.

Whilst the water load on Scotland's masonry heritage is high, the wind speeds mean that it can readily dry out, thus establishing a wetting/drying cycle. It is necessary for the preservation and healthy function of traditional masonry that this water load be handled and discharged into the outer environment as efficiently and harmlessly as possible.

Agents of decay in traditional masonry

The two central agents of decay in masonry are frost attack and the precipitation of soluble salts. Of the two, it is salts, from flue gases and external sources, which presents the continuous, year-round threat. Therefore it is acknowledged as the principal agent of decay in walls of masonry buildings in the UK (Price 1975; Price and Doehne, 2010). Nevertheless, both are mobilised by water and both are exacerbated by poor management of moisture. Water retention within the building fabric promotes the absorption of salts from the atmosphere (Woolfitt 2000), and also lengthens the 'at-risk' window of frost susceptibility.

Susceptibility to frost damage in porous masonry is governed by the material's pore size distribution which dictates stress dispersal within the solid matrix. Water freezing in pores creates damage in a twofold process; crystalline needles of ice pierce the solid matrix, and the dispersed water exerts a hydraulic pressure against the pore walls (Everett and Hynes 1965). The phase change from water to ice is virtually instantaneous, and therefore the 'crystalline needle' aspect of frost attack is inevitable (Klemm and Klemm 1997b). Water increases in volume by some 9% upon freezing, and adjacent unfrozen water is dispersed accordingly within the porous matrix. Providing the pore structure can accommodate this expansion, no stress is exerted.

Where there is insufficient capacity for expansion, the water is compressed and exerts hydraulic pressure against the ice and against the pore walls of the solid matrix.

Engineering freeze-thaw resistance through air-entrainment is based on this premise; it targets the 'liquid dispersal' aspect of frost attack by providing the volume increase required. Its effectiveness is then governed by the interconnectivity and dispersal of those large pores (Klemm and Klemm, 1997a). Engineering the microstructure (e.g. air-entraining) against frost attack was also an ancient practice, through the incorporation of additives such as blood, beer, fats etc. (Carran et al. 2011).

An inherent limitation on the frost resistance of the mortar (to be distinguished from the durability of the masonry collectively) is the comparatively low strength of the binder. Higher strength binders such as hydraulic lime/OPC are able to sustain higher stresses induced by freeze/thaw (F/T) cycles. However, a compromise has to be made in the conservation of traditional masonry: increasing the strength of the mortar so as to resist F/T is to lose sight of the real task of the mortar, which is to dry out the walls and preserve the masonry units. An increase in strength is coupled with a reduction in the mortar's ability to preserve the masonry unit. Consequently, the only option to mitigate the effects of frost attack is to refine the microstructure of the material, accommodating unrestricted water dispersion, as demonstrated by historic lime mortars.

Salt weathering is similar in mechanism to the damage caused by ice formation in pores; the pore walls are stressed by salt nucleation and growth within the physical constrictions of the solid matrix. As with frost attack, resistance of the porous material is governed by the microstructure (Åkesson et al. 2007; Pavia, 1999). The number of crystallisation cycles is the prevailing aspect, therefore salt attack takes precedent over frost since it is a year-round threat, mobilised by each wetting-and-drying cycle.

The resistance of masonry to salt attack has historically been achieved by the traditional lime mortar, which has been found to draw the salt contaminants away from the more valuable masonry unit and into the sacrificial lime mortar (Klemm and Wiggins 2015a). Repointing was part of general building maintenance. It is now widely understood that traditional masonry owes much of its longevity to this sacrificial function of the lime mortar. In 1979 the SPAB observed an important moisture movement pattern in traditional masonry structures as they dried after periods of driving rain. They reported that the lime mortar joint appeared to draw the water out of the masonry units towards the face of the building, where it then evaporated (SPAB 1979; Hughes 1985).

The ramifications for the preservation of the masonry units this research uncovers are profound. Salts when in solution are by and large harmless to the masonry. However, when the water in which they are dissolved evaporates, the salts are forced to precipitate and the damage occurs (Torraca 1982; Klemm and Wiggins 2015a). The point of evaporation dictates where the salts induce damage. Therefore if the point of evaporation can be controlled and forced away from the valuable masonry units, then the damage can also be moderated. Historic lime mortar has done precisely this for centuries.

The resilience of historic lime mortar to decay processes

The reasons behind the SPAB's observations on the drying patterns around the masonry unit/lime mortar interface are explained by examining the microstructure of the masonry unit, relative to that of the lime mortar (Wiggins 2015).

Sedimentary building stones and historic bricks tend to be coarse-pored (or at least have an abundance of coarse pores). A typical sandstone, for example, has a predominant pore size of some 10,000nm. By contrast, historic lime mortar (drawing on c. 50 samples from some 20 heritage structures under the care of Historic Environment Scotland) tends to be fine-pored, typically exhibiting a predominant pore size of around 1,000nm. This is a distinct factor of ten smaller than that of the masonry unit (Klemm and Wiggins 2015b; Wiggins 2015).

With these two porous materials of distinctly different pore sizes laid together in the context of masonry joints, and the addition of water (e.g. from wind driven rain, rising damp, condensation or building defects) a poulticing interaction is induced.¹

Narrow pores have a greater capillary draw than broad ones, and so the fine pores of lime mortar draw the water away from the coarse pores of the masonry unit. In doing so, the salt ions held in solution are transported in the body of moving water in a process known as advection (Pel et al. 2010). The lime mortar pointing exploits a capillary drying regime whereby the evaporation front is formed at the surface of the pointing nib, and the evaporative loss is compensated by capillary flow from the body of the wall (Figure 2) (Coussot 2000). The point of evaporation dictates where the salt then precipitates, concentrated in the lime mortar pointing.

¹ See work by Hall & Hoff 2002; Pel et al. 1996; Sophocleous 2010; Torraca 1982 for a detailed examination of moisture transport principles in porous materials.

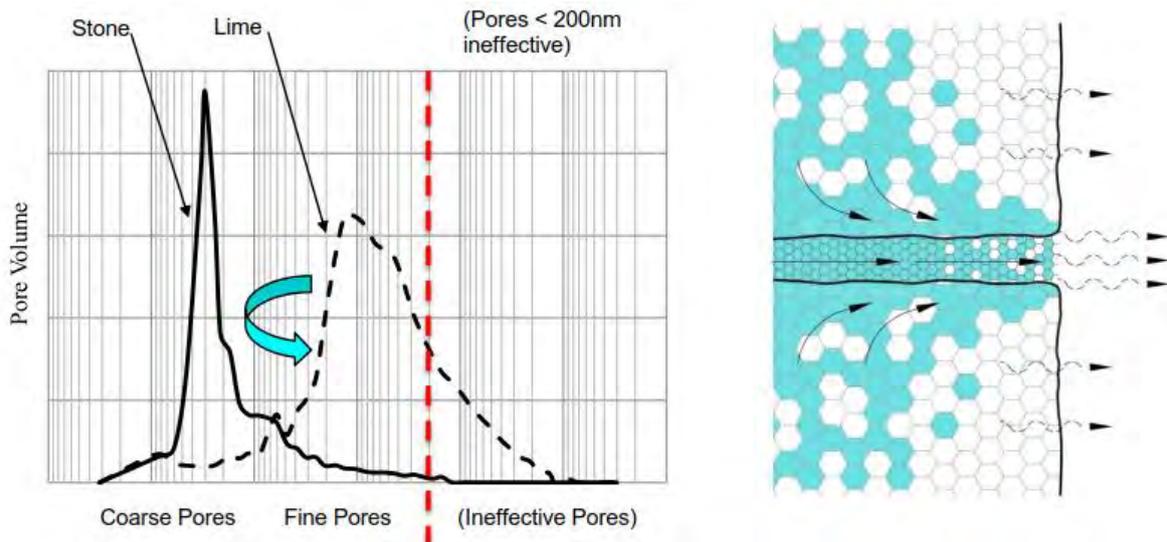


Figure 2: Poultrice mechanics (log scale) and as applied to a 2-D cross-section through a mortar bed joint with inferred water movement pattern (salt advection) (Wiggins 2015).

This interaction is mobilised year round every time the building dries after periods of wind-driven rain. Over the lengthy lifetimes of masonry structures, the mortar acts as a poultrice, offering a pronounced preservation-enhancing function (Figure 3).



Figure 3: Sacrificial protection in practice - precipitation of soluble salts in mortar joints at Aydon Castle, Northumberland (18th century agricultural buildings).

Due to the poultice function of the lime mortar, the micro-scale water management within the masonry also leads to benefits in resilience to frost attacks on the masonry. Since the lime mortar handles the water preferentially over the masonry unit, it adopts frost susceptibility over the masonry unit, again behaving sacrificially.

Lime harling exploits the active drying-out, active preservation-enhancing function of historic lime mortar leading to the survival of traditional masonry. A demonstration of poultice mechanics and the capillary drying regime, the harling actively wicks the water out of the joints and out of the face of the stone. It magnifies the evaporation area whilst sustaining capillary suction with the fabric behind to compensate the accelerated evaporative flux. The key contribution of lime harling to the durability of the masonry fabric is not only that it accelerates drying out, but that it forces the evaporation front away from the face of the masonry. This moves the 'damage zone' whereby soluble salts can precipitate outwards into the harling, itself a sacrificial medium (Torraca 1982; Wiggins 2017).

3. MICROSTRUCTURAL CHARACTERISTICS AND DURABILITY OF HISTORIC LIME MORTARS

Within this paper an effort has been made to refer to 'historic' or 'traditional' lime mortars. This is to distinguish them from currently available NHL-based lime mortars. The latter, which are frequently specified, fall short of the example set down by historic lime mortars in terms of their microstructures and therefore their performance in use (Wiggins 2015; Klemm and Wiggins 2015b; Grilo et al. 2014; Adamski et al. 2010; Alvarez et al. 2004).

Moisture-handling characteristics of historic mortars

This section presents representative data of historic lime microstructures (from Wiggins 2015). Lime is a variable material, but distinct traits can be observed (Figure 4).

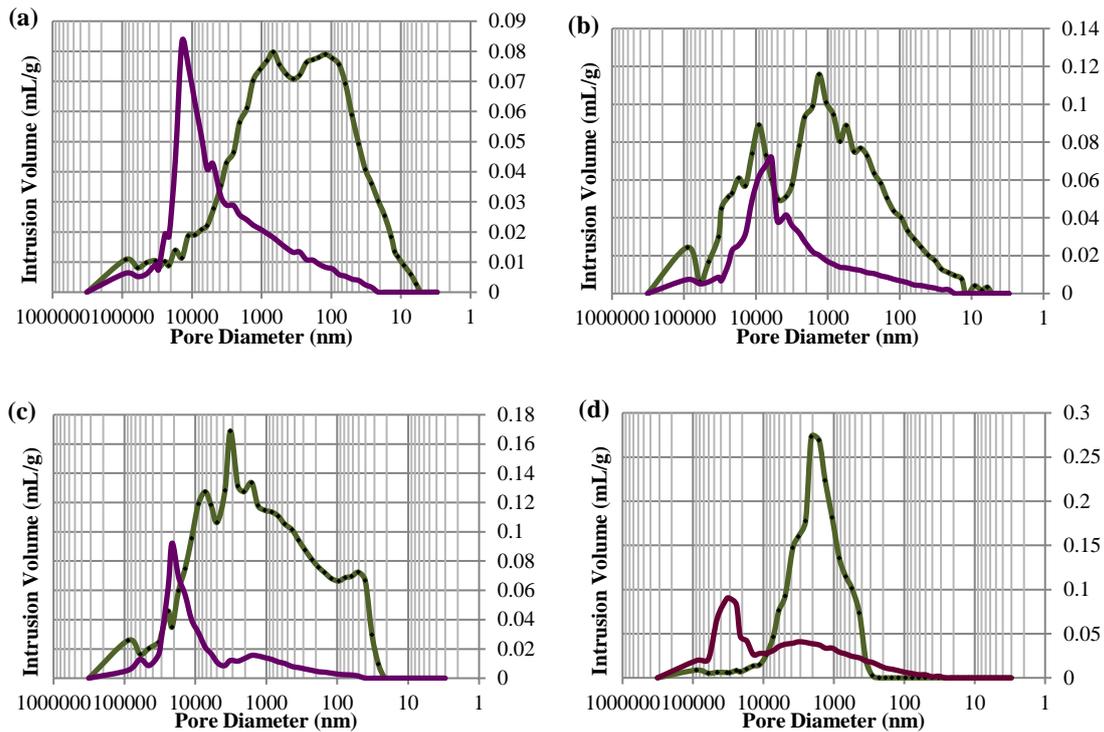


Figure 4: Data pore size distributions of sandstone and lime mortar. (a) Bothwell Castle, South Lanarkshire; (b) Melrose Abbey, Roxburghshire; (c) Newark Castle, Port Glasgow; (d) Saltmarket Tenements, Glasgow. The purple line represents stone, the green line represents lime mortar (Wiggins 2015).

The sandstones in Figure 4 exhibit relatively monomodal pore size distributions with predominant pore size of around 10,000nm and porosities ranging from some 15-25%. The historic lime mortars are substantially higher in porosity than the sandstone; porosities range from some 30-40%. This porosity is well interconnected. The lime mortars exhibit broader pore size distributions than the stone, encompassing both large pores and small pores. Notably, however, a distinct trend throughout is a predominant pore size of around 1,000nm in diameter. This capillary porosity is located within the pore size range attributable to calcitic development i.e. carbonated free lime. Due to the relationship between the predominant pore sizes of the two respective materials, when set together in the context of a mortar joint, pointing, or surface coating (harling), water is wicked away from the coarse-pored stone into the fine-pored lime mortar. This leads to the enhanced preservation offered by lime mortar to the masonry units (e.g. Figure 3).

The above 'historic example' microstructure set down by traditional lime mortars in Scotland demonstrate high porosity and high capillary porosity.² This important capillary porosity is formed through calcitic development, (Wiggins 2015). It is evident from the pronounced degree to which this is observed that the original mortar mix was often very lime-rich, around 1:1.5 binder to aggregate, or even greater.

The preservation-enhancing function of traditional lime mortar is most pronounced when viewed against a backdrop of a vulnerable masonry unit. Porous, sedimentary building stones are typically susceptible to water (the 'engine of decay') which then mobilises the agents of frost and salt attack, as discussed previously. By contrast, the 'non-porous' masonry counterparts such as igneous and metamorphic stones are exceptionally durable, owing to their general insusceptibility to water penetration.

However, lime mortar has a centuries-proven track record of use in masonry which is essentially non-porous (e.g. whinstones and granites), and is known to perform well in this context. The issues which have occurred when non-porous masonry has received cementitious coatings/interventions, demonstrate the optimal function of lime mortar. With masonry of non-porous stone, the only water egress route through the structure is the lime joints. If this egress route is impaired (e.g. by incompatible repointing), the wall core can saturate and create a damp interior environment. Hence, whilst the decay of the valuable masonry unit is less of a threat in igneous or metamorphic stone (where they are insusceptible to water-mobilised agents of decay), the building pathology can still be markedly affected by compatible/incompatible mortars. Water retention in masonry structures can lead to damp and poorly performing buildings and structural failure by various mechanisms (Beckmann and Bowles 2004). Such mechanisms may include the separation of the formal masonry outer 'leaves' relative to the rubble core, leading to bulging, bowing or leaning of the debonded 'leaves'; or indeed displacement of the masonry units through mortar disaggregation due to excessive leaching (Forster 2007).

Structural integrity can become compromised through water entrapment when this leads to the decay of built-in timbers (e.g. beams, floors and roofs) that provide restraint and stability to the stone walls. Water retention is a prevalent structural threat to both porous and non-porous masonry. The durability and healthy function of non-porous masonry relies on the mechanical compatibility-related characteristics of traditional lime mortar.

² For a detailed examination of pore interconnectivity reference should be made to Klemm and Wiggins, 2015b.

Failures in masonry of this form are commonly observed where water is poorly handled, especially where the water load is high.

Mechanical compatibility-related characteristics of historic mortars

Lime mortar sacrificially yields to protect the masonry unit, as demonstrated by the mechanical role of the mortar. On a small scale, the joint serves to keep the masonry units apart, evening out localised crushing stresses arising from an imperfectly flat cut face of the masonry unit. On a large scale, the joint(s) should deform to accommodate small structural movements without cracking. The mortar should be of low enough strength that the masonry units do not overstress and crack; the mortar should be plastic enough to deform without cracking itself.

The ability of the mortar to deform without crushing to the point of failure (e.g. complete disaggregation) is described by the material's elasticity modulus, a function of stress against strain. The lower the material's modulus, the greater its ability to deform; this is generally a favourable characteristic in traditional masonry, which works in compression. Typically, an increase in mortar strength is associated with a decrease in deformability (higher strengths lead to brittle mortars).

Historic lime mortars are known to possess this deformability characteristic. Data of historic lime moduli is scarce and more research is needed, but a study was made to examine the difference in deformability between an air-lime which may be fairly representative of a typical historic lime, and an NHL-based modern lime (Drougkas, et al. 2016). Both mortars were mixed to 1:3 proportions, the air-lime being a CL90 putty and the NHL being of 3.5N/mm² strength class. The air-lime mortar was twice as deformable (it had half the modulus) of the NHL. From this relationship, the effect of compressive strength can be appreciated as an indicator of the likely deformability function. Historically, the lime mortar strength scarcely exceeded some 10% of the crushing strength of the stone, and indeed compressive stress in heritage structures was typically limited by design to this 10% value (Heyman 1996).

Deformability and intimacy of bond are also important characteristics of historic lime mortars in the context of non-porous masonry. For example, in a mortar bond with granite, the stone has no capillary porosity to draw across the soluble binder when the mortar is fresh, and no mineral 'adherence extension' can be established. The adhesive bond has to rely wholly on chemical and intermolecular bonding (van-der-Waals' forces) between the binder particles and those of the masonry unit (Nogami et al. 2015). This is dependent on the binder particle size and dispersal that control

the surface area of point-contacts between binder and substrate, which is generally finer (leading to a larger area) for any hydraulic phases formed. This makes the adhesive bond strength between, for instance, lime mortar and granite even more remarkable.³

There is scarce literature on the mortar bond interface with non-porous stones and it warrants further research (Moropoulou et al. 1997; Moropoulou et al. 2000; Nogami et al. 2015). However, there is empirical evidence of the tenacious bond between historic lime mortar and non-porous masonry units, including slate, whin and granite, many examples of which are to be found in Scotland and elsewhere (Meek and Addyman 2018).

Interdependency between moisture and mechanical related characteristics

The mechanical characteristics of historic lime mortar are intimately linked to its ability to function as a moisture-handling weather-proofing medium (Wiggins and Klemm 2014). Deformability is important in order to sustain intimacy of bond. The bond intimacy at the masonry unit-to-mortar interface is complex; it is affected by the characteristics of the mortar, the characteristic and surface texture of the masonry unit, curing environment and workmanship. Three configurations of bond intimacy vs. hydraulic/capillary continuity across mortar/masonry-unit interfaces have been distinguished (Figure 5), and the capillary flow of each proposed. (Abrantes et al. 1996).

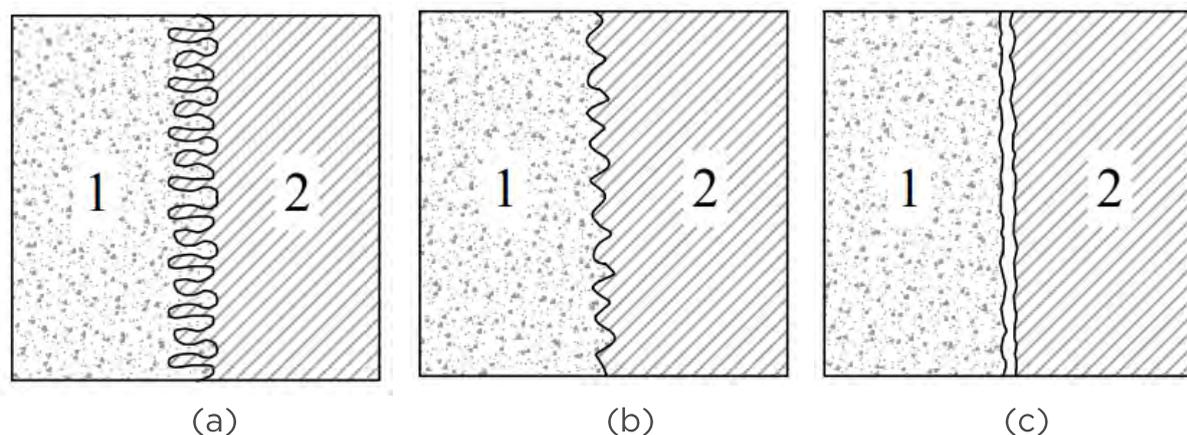


Figure 5: Theoretical variations of bond intimacy and their effect on capillary flow. From left to right: (a) represents hydraulic continuity; (b) represents natural contact; (c) represents an air space formed by shearing of the interface manifesting in interruption to fluid phase movement (Wiggins 2015).

³ See Moropoulou et al. 1996, for a pozzolan-gauged hot-mixed mortar.

Variation (a) shows 'full hydraulic continuity,' an ideal that is seldom realised in practice. Variation (b) demonstrates the bond between the mortar and masonry unit where there is 'natural contact', despite a demonstrable adherence extension of mineral binder interlinking the pores between mortar and masonry. The pronounced disruption to moisture transport caused by even a small air gap is demonstrated in variation (c) (Haghighat et al. 2003).

Historic lime mortars possess intimate bond capabilities, both with masonry units on the macro-scale, and with the sand aggregate on the micro-scale (Goodwin and West 1980; Bakolas et al. 2000). The intimacy of bond and associated adhesive strength is typically related to the area of surface contact between the binding matrix and the aggregate or substrate. Where binder particles are small and closely arranged, an intimate and strong bond is formed. For a historic lime mortar, known to be binder-rich, an intimate bond can be discerned (Figure 6).

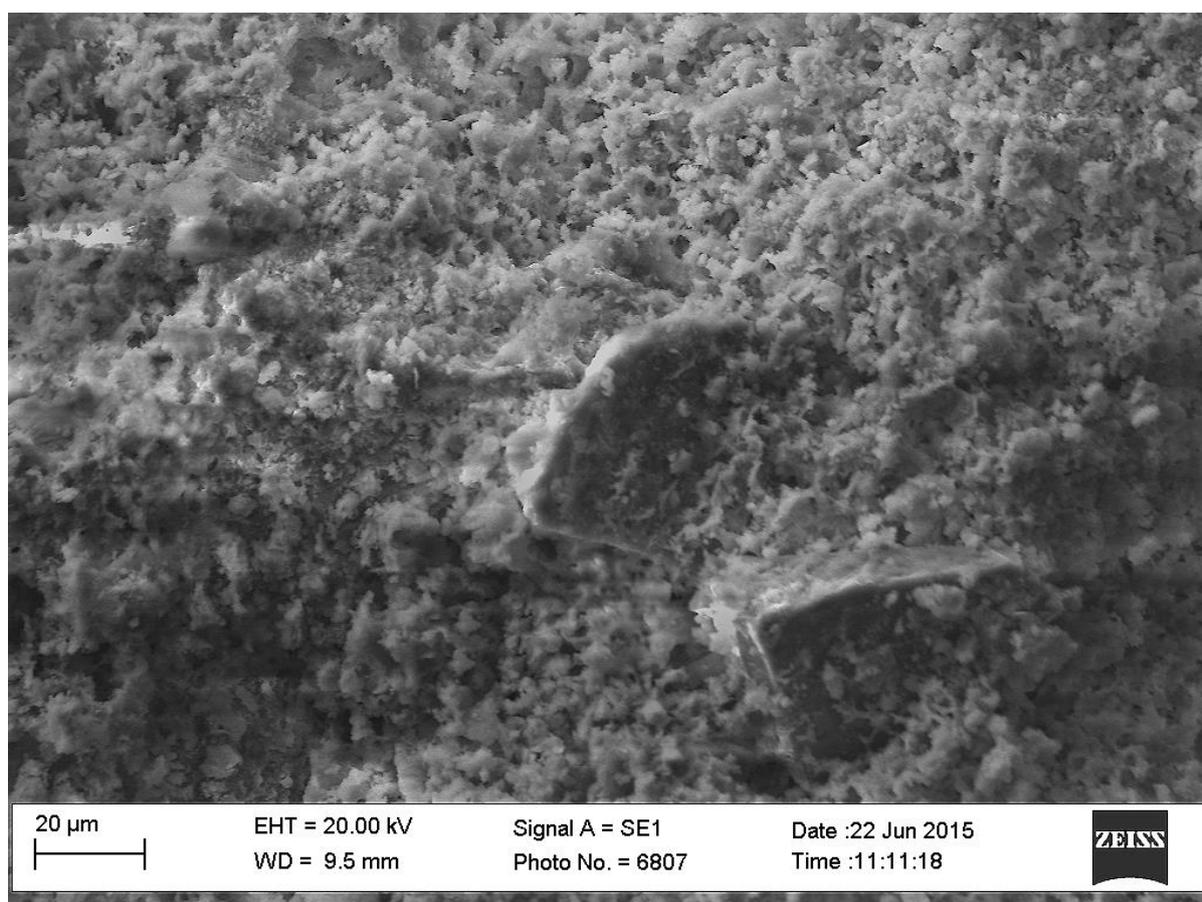


Figure 6: Scanning electron microscope (SEM) image showing microporous nature of binder and intimacy of bond with aggregate in historic lime mortar. Kilmahew Castle, Strathclyde c.1500-1700. Quartz aggregate, binder is calcite rich. Note the scale bar and size of the pores ca. 1 μ m (Wiggins 2015).

Mechanical deformability is not only relevant for the bond interface between mortar and masonry unit, but holds importance within the body of mortar itself. Autogenous (or 'self-') healing observed in historic lime mortars may restore intimacy of bond and promote transport across cracks or the bond interface, recovering a degree of capillary continuity (Joos and Reinhardt 2003).

The 'historic example' mechanical characteristics set down by traditional lime mortars in Scotland have demonstrated the credentials of deformability and bond intimacy.

Causality of the historic lime mortar microstructure

The preservation-enhancing characteristics of historic lime mortar (its micro-management of water, etc.) are due to its microstructure. How that unique microstructure was developed requires examination of the mortar ingredients and preparation method.

Indigenous Scottish limestones are typically impure, leading to a degree of hydraulicity in the lime mortars then produced (Holmes 2003). However, analysis of historic Scottish lime mortars (Schmidt 2017) reveals that they are typically feebly hydraulic (Frew 2015), and that the major binding compound is lime (calcite). This pronounced extent of calcite in the mortars tells of an original mix which was high in free lime proportion of the binder, coupled with a high total content of the binder in the mix (i.e. a binder-rich mix proportion).

The free lime proportion of the binder is a product of the limestone mineralogy and the calcination process. Historically, limes were burnt at low temperatures when compared with contemporary NHL or cement binder production. The general consensus is that the optimal burning temperature for maximum free lime proportion in the quicklime produced is around 900°C (Aggelakopoulou et al. 2001; Weber et al. 2007). This is both in terms of free lime proportion produced, and in terms of quicklime reactivity (Livesey 2011).

The historical mix proportions were very binder-rich, a typical lime:aggregate proportion of the resulting mortar produced would usually be around 1:1.5 (Frew 2015; Gibbons 2003).

The historic preparation method for mortar-making is known to be generally 'hot-mixed' (Copsey 2018; De Brito et al. 2011; BLFI 2014), which involves combining quicklime with the aggregate and the addition of water, described in detail elsewhere (Gibbons 2003). The microstructural

implications of the preparation method will be examined in Section 5 of this report.

Preservation-enhancing characteristics of historic lime mortar microstructure

Historic lime mortars are frost resilient due to their microstructure, which is interconnected, allowing 'escape pathways' for the water displaced by the ice to move through the pore network. This relieves the hydraulic pressure which would have otherwise stressed the pore walls.

Historic lime mortars make the masonry resilient to salt attack. This resilience is achieved by actively preserving the masonry units by poulticing the water out of the coarse-pored stone, and with the water, the salt contaminants are washed out. Over the lengthy lifetimes of masonry structures, this leads to a pronounced preservation function of the historic lime mortar and its host masonry. The necessary credentials for this function are the interconnected capillary porosity and high total porosity in this relevant pore size. This relevant capillary porosity has been demonstrated to be created by calcite: carbonated free lime in the mortar. This is thanks to the lime richness of historic mortars. Calcite is in the frost-susceptible pore range. However, this capillary porosity enables the mortar to act as a poultice to draw out the water from the wall and protect the masonry units, sparing the masonry units from frost damage.

The standard 'durability tests' for F/T resistance of the mortar in isolation is misleading, as they render the lime-rich mortars non-durable and yet endorse highly hydraulic or cementitious mortars. This misses entirely the context in which the mortar must function. Historic mortars, known to be lime-rich, have a centuries-proven track record of actively preserving the masonry units. In a conservation context it is inappropriate to increase the strength of the mortar when this moves the risk of decay to the masonry unit.

Historic lime mortar readily dries the masonry out thanks to its optimal microstructure, and the mortar itself also readily dries. This makes it inherently frost resilient, as it discharges the water necessary for the attack to take place. In summary, historic lime mortar avoids attack, rather than resists it.

4. OBSERVATIONS ON MODERN LIMES

Natural Hydraulic Limes

Natural Hydraulic Lime (NHL) mortars have been increasingly used for the majority of lime-related repair and conservation work since the lime revival. This is particularly true in Scotland where putty-based lime mortars are unfavourable for external building work due to environmental conditions. NHLs are dry-hydrate hydraulic lime binders derived from limestone. They are protected by the qualifying 'Natural' designation under BS EN 459 against the inclusion of additives during calcination, and in general artificial manufacture. This guarantees that the binder produced has only natural constituents from the original limestone.

However, it has often been reported by practitioners and researchers that the NHL-based limes can bear little resemblance to historic lime mortars. Indeed, there is little historic precedent for the use of limes whose set is strongly hydraulic for anything other than civil engineering work (such hydraulic limes were known as 'water limes') (Hurst 1996; Copsey 2018). Historic Scottish building limes were typically feebly hydraulic, with the major binding product being calcite (Schmidt 2017).

NHLs are generally known to have a lower porosity than historic lime mortar; for a typical 1:2.5 mix ratio an NHL 3.5 may have a porosity of some 25% (Grilo et al. 2014). A dense microstructure is characteristic of NHL mortars when compared to the historic limes. Where the major binding compound is hydraulic, this is reflected in the resulting microstructure of the set material; the 10-200nm porosity fraction is attributable to hydraulic phases (Arizzi and Cultrone 2012).

Where the major set in NHL mortars is hydraulic, the minor long-term set arises from the carbonation of the residual free lime proportion of the binder, set down in BS EN 459.

| Lime Mortar | Free Lime (Ca(OH) ₂) Content According to Manufacturer (St Astier, 2006) (%) | Free Lime (Ca(OH) ₂) Content of St Astier Lime as Evaluated by (Hughes, D. and Swann, S. 1998) (%) | Minimum Conformity Criteria for Free Lime (Ca(OH) ₂) Content to BS EN 459-1:2010 (BSI 2010) (%) |
|-------------|--|--|---|
| CL 90 | - | - | ≥ 80 |
| NHL 2 | ≥ 50 | 43 | ≥ 35 |
| NHL 3.5 | 24-26 | 36 | ≥ 25 |
| NHL 5 | 15-20 | 23 | ≥ 15 |

Table 1: Free lime proportion relative to total binder amount, with conformity criteria to BS EN 459 (Wiggins 2015).

Table 1 highlights the low free lime proportion of NHL binders, confirming that the capillary porosity fraction which is attributable to carbonation set will be correspondingly small relative to the overall porosity. NHL production is based on cement phase chemistry, with minimum conformity criteria to meet, leading to a low free lime proportion in NHLs. With the same control feedstock (the raw limestone), the calcination process can be adjusted to change the resulting composition of the quicklime produced. From the same limestone origin, the full spectrum of NHL 2, 3.5 and 5 binders can be manufactured.

Mix proportions

Examination of current mix proportions highlights that NHL-based mortars are 'lean-mix', of low overall binder proportion in the mix, typically 1:2.5 / 1:3. The low free lime proportion in the binder, coupled with the low total binder amount, together lead to a mortar with low capillary porosity and low total porosity. This explains the discord between the microstructures of NHLs and historic lime mortars (Figure 7). The practical significance of this microstructural difference is manifested in the difference in liquid-phase and vapour-phase breathability between NHLs and historic lime mortars (Klemm and Wiggins 2015b; Wiggins 2015).

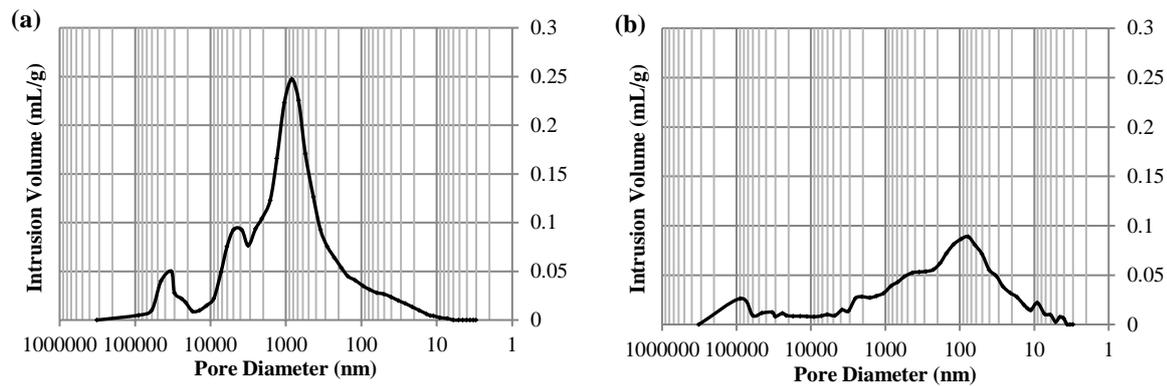


Figure 7: Pore size distributions of (a) historic lime mortar from Balvenie Castle; (b) modern NHL-based lime mortar in use at Urquhart Castle after 2-yr field curing. Note the distinct discord in predominant pore size in addition to the discord in overall porosity (the area under the curve) (Wiggins 2015).

In terms of total porosity and pore size distribution alone, there is little material difference between an NHL mortar of 3.5/5N strength class and a general purpose CEM-II cement mortar at comparable mix ratios of 1:3. Modern cements, however, contain other ingredients which adversely affect performance characteristics and compatibility with traditional masonry.

The issue of low free lime proportion in NHLs is difficult to address. Objective selection between competing manufacturers is not readily achievable, as they are under no obligation to disclose the data, only to meet the minimum conformity criteria under BS EN 459. This standard would need to be revised. One possible way of increasing the free lime in an NHL mortar is by content, not proportion. Increasing the binder richness of the total mix, to replicate those of the historic example, e.g. from 1:3 to 1:1.5, doubles the available free lime content in the mortar to carbonate.

Caution must be exercised, however, to ensure that the mortar does not become too strong to satisfy the sacrificial mechanical compatibility criteria for traditional masonry. The microstructure, whilst a vital causal agent to the moisture-movement compatibility characteristics through capillary activity, is nevertheless interlinked and interdependent on the physical and mechanical characteristics of the mortar. As a general rule, an increase in compressive strength leads to an increase in modulus, i.e. a decrease in deformability. Whilst the hydraulic phases in the NHL should lead to intimacy of bond, the higher strength mortars have a greater propensity to crack, interrupting the capillary flow mechanisms necessary for effective drying out and poultice action. Cracks present key routes for rainwater ingress, resulting in increased water absorption of the masonry fabric.

Formulated limes

A market of proprietary lime-based mortars has emerged using the NHL binder as a base, to create what is known as 'Formulated Limes'. These proprietary materials are pre-mixed, pre-bagged 'lime' mortars which state the NHL binder class and the aggregate mix ratio. This circumnavigates the BS EN 459-protected 'Natural' designation, as this relates only to the binder. Admixtures are then included which can profoundly alter the working and final characteristics of the mortar (Torney et al. 2015; Klemm and Wiggins 2015b).

Some of these materials are known to comprise hydrophobic surface chemistries which disrupt moisture movement and preclude poultice/wick action, preventing the capillary draw of water from the masonry units and rubble core. The hydrophobicity may be a result of the inclusion of a water-repellent, or a consequence of other additives (such as air entrainers, water retainers, etc.). These materials often boast high vapour permeability alongside low capillarity (liquid phase permeability), two normally incongruous characteristics which betray undisclosed additives. Hydrophobic mortars are generally inappropriate for lime-based repair and conservation work, as they can accelerate salt attack in the valuable masonry substrate (Klemm and Wiggins 2015).

5. MICROSTRUCTURAL CHARACTERISTICS OF MODERN HOT-MXED LIME MORTARS

There are few published studies on modern hot-mixed lime mortar microstructures with quantitative data. Further research is required to examine the microstructural development of hot-mixed lime mortars, with and without gauging (e.g. pure or gauged with pozzolans/NHLs). This paper does not start with the assumption that historic lime mortar by definition is hot-mixed, although other works demonstrate that this is usually the case (Copsey 2018; Schmidt 2017). Rather, this paper starts with the known credentials of historic limes, and examines how these can be replicated/arrived at. Broadly, the historic example can be replicated if:

- a) The constituent ingredients are the same;
- b) The mix proportions are the same;
- c) The preparation method is the same.

Starting with what is known of historic limes, the key characteristics are that they are binder-rich in mix proportion, around 1:1.5 lime:aggregate, and that

they are lime rich (Klemm and Wiggins 2015). These composition-related credentials can be matched through the correct specification of new lime mortars to develop the right microstructure. Remembering that the microstructure leads to function, where the ‘microstructural’ example can be replicated, the mortar will therefore function in a similar way to the historic limes. The historically adopted preparation method of hot mixing is today well documented (Copsey 2018).

Replicating the example of historic lime mortars

Theoretically, an NHL 2 binder mixed to a historic mortar proportion of 1:1.5, having a free lime proportion of some 50%, would only reach perhaps half the total lime content found in the historic example. According to St Astier’s data, this is close to the mortar mix ratio of 1:1.3 used in lab tests to BS EN 459 (St Astier 2015). The compressive strength for this mix exceeds a guaranteed minimum of 2N/mm^2 at 28 days, with potential overlap to reach 5N/mm^2 strength. The mortar would strengthen further over its lengthy development period. The NHL 2 mortar, to reach the target lime content of the historic example, would need to be mixed at richer than 1:1, leading to a mortar which is several times the strength of the historic example.

Given that historic lime mortars rarely exceed compressive strengths over 2N/mm^2 , an upper boundary in terms of compatibility is needed. Aiming for a mortar with high lime and high binder content, without a disproportionate increase in strength and stiffness (modulus), effectively rules out mortars based solely on NHL binders.

Henry (2016) investigated ways of replicating the lime richness of historic mortars of predominantly aerial (carbonation) set, and established a target of producing an air lime (CL90) mortar of historic 1:1.5 mix ratio (2:3). This was attempted through pre-slaked methods using lime putty, and by hot-mixed methods. Theoretically, the free lime proportion of the binder and total lime content in the mortar would be the same, leading to comparable microstructures. It was observed that the hot-mixed preparation method was by far the most practical method of achieving this mortar of historic mix proportions. The lime putty mortar was unworkably wet and almost incapable of setting to be of any practical use. It ultimately required the aggregate to be pre-dried before it could be mixed to produce workable mortar (Henry 2016). Similar findings were observed in the hot-mixed vs. putty trials at Nidaros Cathedral, where the rich putty mix failed, compared with the hot-mixed mortar (Pennock 2017)

A CL90 dry-hydrate mortar could theoretically be used, instead of putty, to achieve the historic lime-rich mortar proportions. Valek and Matas (2012)

found that the as-hardened properties of laboratory-prepared/cured hot-mixed limes were similar to those of the hydrate or putty preparation method of the same mix proportions. The same chemical constituents led to similar set mortar characteristics once cured. This supports the view that the primary benefit of the hot-mixed preparation method is during the practical application stage (Valek and Matas2012). Air-lime hydrates need to be mixed with water and matured for several days, and do not have the benefit of the slake to drive out excess water. For all intents and purposes they are as wet to work with as the putty at such rich proportions (Henry 2016). Freshness of the hydrate is critical. Hydrates need to be measured by weight and are often used in erroneously lean mix proportions. These factors contributed to the conclusion of Historic Scotland Technical Advice Note 1 which states that dry hydrated lime mortar is not suitable for building mortar; its primary use is as a plasticiser for hydraulic mortars (Gibbons 2003).

By contrast, the quicklime binder in hot-mixed lime mortar allows binder-rich mix proportions, without the above-described drawbacks. Primarily produced for the steel-making industry, CL90 grade quicklime is reliable in quality, guarantees lime yield, and provides a fat, sticky, workable mortar. Therefore, it is suggested that the most practical and reliable way of replicating the historic lime composition without compromising the mechanical compatibility criteria is to employ the hot-mixed method of mortar preparation (the historically adopted method).

Hot-mixed lime mortars: key microstructural characteristics

Various qualities have been attributed to hot-mixed lime mortars, relative to their pre-slaked air lime counterparts, but there is a lack of objective research by way of validation. The following preparation-specific attributes are frequently stated of hot-mixed lime mortars:

- Forced pore interconnectivity arising from pathways of escaping steam during slaking;
- Air-entrained microstructure arising from the steam produced on slaking;
- Moisture displaced on slaking draws binder across interfaces with masonry unit and porous aggregate if present, enhancing adherence extension;
- Expansion against aggregate and masonry unit promotes intimacy of bond;
- Heat of slake enhances pozzolanic activity if present in binder or aggregate;

- Heat enhances caustic effects on aggregate potentially scarifying surfaces, promoting intimacy of adhesion.

The above possible attributes of hot-mixed limes are considered in turn by Forster (2004), and require further research to prove their contribution to the enhancement in mortar characteristics associated with hot-mixing over pre-slaked limes.

The present advantage hot-mixed lime mortars are known to possess, however, is not necessarily with the preparation method itself, but the fact that hot-mixing is the only practical way of replicating the historic mix constituents in the historic proportions. This is an important conclusion in its own right.

6. CONCLUSIONS

This Technical Paper examined the functional behaviour of historic lime mortar sampled from a number of heritage structures. The root of the preservation-enhancing behaviour found in these lime mortars lies in their microstructure. The causality behind the development of this function-imparting microstructure is due to the material composition; the key aspects are its lime richness and overall binder-richness.

Appraising modern NHL-based lime mortars in terms of microstructure, and hence behavioural function, against the historic examples, shows them to be outperformed by hot-mixed limes in meeting the functional performance requirements of historic masonry.

The composition of hot-mix lime mortars offer the best means of replicating the unique microstructure and function of historic lime mortars. If the function of the original material is the focus of replication in any compatible repair, hot-mixed mortars are the best practical means of replicating the historic mix constituents at the historic proportions. Together these characteristics impart function.

Further research is recommended into the following areas:

- Setting up a database:

A database reporting the physical, mechanical, microstructural and physico-chemical characteristics of a range of hot-mixed lime mortar specifications would be helpful for the conservation sector's reference and future research.

- Investigating the preparation method:

Investigation into the preparation method would confirm whether the major influence is composition, preparation method or if both have equal relevance. This could be done in a suite of tests by comparing hot-mixed lime against pre-slaked lime, both of control binder type and mix proportions.

- Investigating the hydraulic gauging of hot-mixed lime mortars:

This would confirm the effect of gauging on the mortar's microstructure and response to moisture. Pore size distributions and physical water absorption testing of control hot-mixed limes could be compared to samples prepared with hydraulic gauging through a range of gauging proportions.

REFERENCES

- ABRANTES, V., DE FREITAS, V. and CRAUSSE, P., 1996. Moisture Migration in Building Walls - Analysis of the Interface Phenomena. *Building and Environment*. 31(2), pp. 99-108.
- ADAMSKI, G., KLISIŃSKA-KOPACZA, A., KOZŁOWSKI, R. and TIŠLOVAB, R., 2010. Pore structure of historic and repair Roman cement mortars to establish their compatibility. *Journal of Cultural Heritage*. 11 pp. 404-410.
- AGGELAKOPOULOU, E., BAKOLAS, A. and MOROPOULOU, A., 2001. The effects of limestone characteristics and calcinations temperature to the reactivity of quicklime. *Cement and Concrete Research*. 31 pp. 633-639.
- ÅKESSON, U., LINDQVIST, J.E. and MALAGA, K., 2007. Microstructure and functional properties of rock materials. *Materials Characterization*. 58 pp. 1183-1188.
- ALLEN, G., et al., 2003. *Hydraulic Lime Mortars for Stone, Brick and Block Masonry*. Dorset: Donhead Publishing.
- ALVAREZ, J., BARNAL, J., BELLO, M. and LANAS, J., 2004. Mechanical properties of natural hydraulic lime-based mortars. *Cement and Concrete Research*. 34 pp. 2191-2201.
- ARIZZI, A. and CULTRONE, G., 2012. Aerial lime-based mortars blended with a pozzolanic additive and different admixtures: A mineralogical, textural and physical-chemical study. *Construction and Building Materials*. 31 pp. 135-143.
- BAKOLAS, K., BISBIKOU, A. and MOROPOULOU, A., 2000. Physico-chemical adhesion and cohesion bonds in joint mortars imparting durability to the historic structures. *Construction and Building Materials*. 14 pp. 35-46.
- BECKMANN, P. and BOWLES, R., 2004. *Structural aspects of building conservation*. 2nd ed. UK: McGraw-Hill International.
- BLFI, 2014. *Hot Lime Mortars. HLM Project: Technology Transfer & Applied Research*. Ireland: The Building Limes Forum Ireland.
- BROCKEN, H., KOPINGA, K. and PEL, L., 1996. Moisture transport in porous building materials. *Heron*. 41(2), pp. 95-105.
- BSI, 2010. *BS EN 459 Building lime Part 1: Definitions, specifications and conformity criteria*. UK: BSI.

CARRAN, D., HUGHES, J., KENNEDY, C. and LESLIE, A., 2011. A Short History of the Use of Lime as a Building Material Beyond Europe and North America. *International Journal of Architectural Heritage*. 6(2), pp. 117-146.

CARTER, K. and FORSTER, A.M., 2011. A framework for specifying natural hydraulic lime mortars for masonry construction. *Structural Survey*. 29(5), pp. 373-396.

CASSINELLO, M., 2006. Effect of mortar joint thickness on deformability in medieval stone walls. *Materiales De Construcción*. 56(284), pp. 69-80.

COPSEY, N (2018) *Technical Paper 25: Historic texts relating to hot-mix mortars in Europe 1400-1900*. Historic Environment Scotland (pending publication).

COUSSOT, P., 2000. Scaling approach of the convective drying of a porous medium. *The European Physical Journal B - Condensed Matter and Complex Systems*. 15(3), pp. 557-566.

DE BRITO, J., MARGARLHA, G., SILVA, A.S. and VEIGA, R., 2011. Traditional methods of mortar preparation: The hot lime mix method. *Cement & Concrete Composites*. 33 pp. 796-804.

DROUGKAS, A., ROCA, P. and MOLINS, C., 2016. Compressive strength and elasticity of pure lime mortar masonry. *Materials and Structures*. 49 pp. 983-999.

EVERETT, D.H. and HYNES, J.M., 1965. Capillary properties of some model pore systems with special reference to frost damage. *Rilem Bulletin*. 27 pp. 31-38.

FORSTER, A., 2004. Hot-Lime Mortars: A Current Perspective. *Journal of Architectural Conservation*. 10(3), pp. 7-27.

FORSTER, A.M., (2007) Binder loss in traditional mass masonry: a cause for concern? *Structural Survey* 25(2), 148-170.

FREW, C., 2015. Lime harling. *The Journal of the Building Limes Forum*. 22 pp. 25-31.

FREW, C. and REVIE, W., 2018. *Review of Hot-mix Lime Work in Scotland 1990 - 2015*. Edinburgh: Historic Environment Scotland.

GAMEIRO, A., et al., 2014. Physical and chemical assessment of lime-metakaolin mortars: Influence of binder:aggregate ratio. *Cement & Concrete Composites*. 45 pp. 264-271.

GIBBONS, P., 2003. *Preparation and use of lime mortars*. Edinburgh: Historic Scotland.

GOODWIN, J. and WEST, H., 1980. *A review of the literature on brick/mortar bond*. UK: The British Ceramic Research Association.

GRILO, J., et al., 2014. New natural hydraulic lime mortars - Physical and microstructural properties in different curing conditions. *Construction and Building Materials*. 54 pp. 378-384.

HAGHIGHAT, F., KUMARAN, M. and QIU, X., 2003. Moisture transport across interfaces between autoclaved aerated concrete and mortar. *Journal of Thermal Envelope and Building Science*. 26(3), pp. 213-236.

HALL, C. and HOFF, W.D., 2002. *Water transport in brick, stone and concrete*. 1st ed. Oxford: Taylor & Francis.

HENRY, A., 2016. *NHL and Hot-Mixed Lime Mortars - Research Outcomes*. In: Anonymous *Building Limes Forum Hot-Mixed Lime Mortar Seminar and Workshop*. Coventry., 2016. UK: .

HENRY, A. and STEWART, J., 2012. *Mortars, Plaster & Renders*. English Heritage.

HEYMAN, J., 1996. *Arches, Vaults and Buttresses*. UK: Variorum.

HOLMES, S., 2003. *Evaluation of limestone and building limes in Scotland*. Edinburgh: Historic Scotland.

HUGHES, D. and SWANN, S., 1998. Hydraulic limes - a preliminary investigation. *Lime News*. 6 pp. 41-53.

HUGHES, P., 1986. *The need for old buildings to "breathe"*. London: SPAB News.

HURST, L., 2002. The properties and uses of Roman Cement. *Construction History*. 18 pp. 21-35.

HURST, L., 1996. Concrete and the structural use of cements in England before 1890. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*. 116(3), pp. 283-294.

JOOS, M. and REINHARDT, H.M., 2003. Permeability and self-healing of cracked concrete as a function of temperature and crack width. *Cement and Concrete Research*. 33 pp. 981-985.

KLEMM, A.J. and KLEMM, P., 1997a. The effects of the alternate freezing and thawing cycles on the pore structure of cementitious composites modified by MHEC and PVA. *Building and Environment*. 32(6), pp. 509-512.

KLEMM, A.J. and KLEMM, P., 1997b. Ice formation in pores in polymer modified concrete-II. The influence of the admixtures on the water to ice transition in cementitious composites subjected to freezing/thawing cycles. *Building and Environment*. 32(3), pp. 199-202.

KLEMM, A.J. and WIGGINS, D.E., 2015a. Lime mortar and sacrificial protection of heritage stonework. *Proceedings of the Institution of Civil Engineers: Engineering History and Heritage*. 168(EH4), pp. 167-176.

KLEMM, A.J. and WIGGINS, D.E., 2015b. Microstructural characteristics of modern repair materials vs. the performance requirements of historic lime mortar. In: BRANDT, A.M., ed. *11th International Symposium on Brittle Matrix Composites*. Warsaw., 2015. Poland: RILEM, pp.(In Print).

LIVESEY, P., 2011. Building limes in the United Kingdom. *Proceedings of the Institution of Civil Engineers Construction Materials*. 164(CM1), pp. 13-20.

MALINOWSKI, E.S. and HANSEN, T.S., 2012. Hot Lime Mortar in Conservation: Repair and Replastering of the Facades of Lacko Castle. In: BROCKLEBANK, I. ed., *Building Limes in Conservation UK*: Donhead, pp. 271-294.

MAXWELL, I., 1995. Introduction to lime in Scotland. In: DORRINGTON-WARD, J. and MAXWELL, I., eds. *The Historic Scotland International Lime Conference*. Edinburgh., 1995. Scotland: Historic Scotland; The Building Limes Forum, pp.5.

MEEK, T. and ADDYMAN, T., 2018. *Historic External Lime Finishes*. Edinburgh: Historic Environment Scotland (pending publication).

MOROPOULOU, A., BISCONTIN, G., BAKOLAS, A. and BISBIKOU, K., 1997. Technology and behaviour of rubble masonry mortars. *Construction and Building Materials*. 11(2), pp. 119-129.

MOROPOULOU, A., et al., 1996. Hot lime technology imparting high strength to historic mortars. *Construction and Building Materials*. 10(2), pp. 151-159.

NOGAMI, L., PARAGUASSU, A., RODRIGUES, J. and RIBEIRO, R., 2015. Adhesive mortars for stone plate bonding. *Bulletin of Engineering Geology and the Environment*. 74 pp. 1489-1497.

PAVIA, S., 1999. *Stone, brick and mortar: historical use, decay and conservation of buildings*. Ireland: Wordwell.

PEL, L., SAWDY, A. and VORONINA, V., 2010. Physical principles and efficiency of salt extraction by poulticing. *Journal of Cultural Heritage*. 11 pp. 59-67.

PENNOCK, C., 2017. Restoration Mortars at Nidaros Cathedral. *Journal of the Building Limes Forum*. 24 pp. 9-21.

PRICE, C., 1975. The decay and preservation of natural building stone. *Chemistry in Britain*. 11(10), pp. 350-353.

PRICE, C. and DOEHNE, E., 2010. *Stone Conservation: An Overview of Current Research*. 2nd ed. California: Getty Conservation Institute.

SCHMIDT, A., 2017. Insights from the Historic Mortars Database. In: Anonymous *Historic Environment Scotland Hot-Mixed Mortars Seminar*. Edinburgh., 2017. UK.: Historic Environment Scotland.

SELBY, A.R., 2001. The stability of slender masonry mullions. In: BREBBIA, C. ed., *Structural Studies, Repairs and Maintenance of Historical Buildings VII* UK: WIT Press, pp. 21-28.

SOPHOCLEOUS, M., 2010. Understanding and explaining surface tension and capillarity: an introduction to fundamental physics for water professionals. *Hydrogeology Journal*. 18 pp. 811-821.

SPAB, 1979. *Repointing stone and brick walling*. London: Pressworks.

ST ASTIER, 2015. *Physical & Mechanical Data St Astier*. [viewed 14/10/2015]. Available from: <http://www.stastier.co.uk/nhl/testres/physmech.htm>.

STIRLING, C., 2002. *Thermal insulation: avoiding risks*. UK: Construction Research Communications.

TORNEY, C., FORSTER, A.M., BANFILL P., and SZADURSKI, E., 2015. The effect of site modification on the physical properties of formulated restoration mortars. *Construction and Building Materials*. 75 pp. 359-367.

TORRACA, G., 1982. *Porous building materials: materials science for architectural conservation*. 2nd Ed. ed. Rome: ICCROM.

VALEK, J. and MATAS, T., 2012. Experimental Study of Hot-Mixed Mortars in Comparison with Lime Putty and Hydrate Mortars. In: VALEK, J., HUGHES, J.J. and GROOT, C. eds., *Historic Mortars: Characterisation, Assessment and Repair* London: RILEM Bookseries 7, pp. 269-282.

WEBER, J., et al., 2007. Microstructure and mineral composition of Roman cements produced at defined calcination conditions. *Materials Characterization*. 58 pp. 1217-1228.

WIGGINS, D.E., 2017. Traditional lime mortars and masonry preservation. *Journal of the Building Limes Forum*. 24 pp. 28-37.

WIGGINS, D.E., 2015. *Lime mortar and the sacrificial protection of heritage masonry*. PhD Thesis, Glasgow Caledonian University.

WIGGINS, D.E. and KLEMM, A.J., 2014. Compatible repairs to stonebuilt structures. *Proceedings of the Institution of Civil Engineers: Engineering History and Heritage*. 167(EH4), pp. 196-207.

WOOLFITT, C. 2000. Soluble salts in masonry. *The Building Conservation Directory*. Cathedral Communications Ltd, pp83-84.

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Our Short Guides are aimed at practitioners and professionals, but may also be of interest to contractors, home owners and students. The series provides advice on a range of topics relation to traditional buildings and skills.

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Historic Environment Scotland is the lead public body established to investigate, care for and promote Scotland's historic environment.

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