Traditional lime mortars and masonry preservation

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Why use lime mortar? For many it has become synonymous with weakness, perceived as expensive, difficult to use and prone to failure. Cement mortars are easy to use: they are strong and will set with virtually no aftercare in harsh environments. Surely then, cement has closed the book on successful mortar design? But a quick reflection on the lime revival serves as a reminder that the resurgence started in direct response to the use of cement mortars on traditional masonry substrates. The cements caused extensive damage in a very short timeframe when compared with the prior lengthy existence of these historic buildings (see Figure 1).

Fig. 1 (Right) The barracks at Fort George, where the damage to stonework was caused by cement mortar. The cement on this elevation was left in place by Historic Scotland to demonstrate to visitors the damage caused by cement mortar on traditional masonry.

Fig. 2 (Above) The barracks at Fort George, where an area of well-conserved original stone masonry shows the healthy function and preservation capabilities of traditional lime mortar.

Against the backdrop of the centuries-old track record held by traditional lime mortars, why did the cement mortars cause the damage they did? Equally, what is it about traditional lime mortars that preserved the buildings so well in healthy operational service? (see Figure 2)

Common negative perceptions associated with lime mortars specifically pertain to the 'modern' usage of lime mortars during the lime revival of the past few decades. This initially focused on putty limes for external masonry work, sometimes in situations where it was an uphill struggle to get them to set. Paradoxically, 'traditional' lime mortars were the building mortar of choice for many applications, even when cements first became available. Masons of a century ago recognised good quality mortar and favoured fat lime (high-calcium, non- to feebly hydraulic in nature, which readily slaked to produce a sticky workable mortar with a high affinity for sand) for the overwhelming majority of super-structural work. But why did they use this mortar and what did they see in it?

Recent advancements in the lime revival have rediscovered hot-mixed lime mortars: traditional lime mortars, prepared in the traditional way. This in turn has led to greater understanding of the 'active ingredient', which made traditional lime mortars robust, durable, economical and a pleasure to use.

On review, the question 'why use lime mortar?' is not one of nostalgia, nor is it one of aesthetics or authenticity: in and of themselves, these aspects neither preserve the masonry nor induce its decay. The issue is one of functional behaviour. Traditional lime mortars should be used for the care and repair of traditional masonry because they are objectively the right material for the job.

Water: the engine of decay

Water is widely known as the engine of decay of masonry because it mobilises the agents of decay. In UK and Irish masonries, these are frost attack and salt attack. Both are important, but salt attack is the principal agent of decay.[1] Mobilised by wetting and drying cycles, it presents a continual threat to porous masonry. Even a casual inspection of the wind-driven rain index for the UK and Ireland brings into focus the aggressiveness of the environment.[2]

Effective roof detailing and well-maintained rainwater goods address the vertical fall of rain, but in areas exposed to high wind speeds (such as the west coast of the UK and Ireland, and in particular the west coast of Scotland, which experiences the highest wind speeds in Europe) a heavy water load can be driven horizontally onto the masonry fabric. Rising damp and internally released moisture add to the volume of water ready to attack the masonry.[3] And yet, the UK and Ireland boast a rich masonry heritage, which is proof of an historic resilient response to the engine of decay. A technical understanding of how traditional lime mortars have enabled the masonry to survive is imperative.

Functional behaviour of traditional lime mortars

Frost resilience

Traditional lime mortars, of largely aerial/feebly hydraulic set, are not frost 'resistant'. A quick glance at laboratory freeze-thaw tests indicates complete failure after a few cycles,[4] which seems to contradict the centuries-old track record of the survival of traditional lime mortars in harsh environments. This paradox reveals two things: firstly, traditional lime mortars are not frost resistant in the strict sense of the word. The term confers a mechanical strength of the binder to resist the applied stresses from the freezing process, which traditional lime mortars are known not to possess (the pore matrix in lime mortars is located in the size range most prone to freeze-thaw damage).[5,6,7] Secondly, it informs that the laboratory freeze-thaw resistance test is manifestly unrepresentative of real-life conditions. In practice, it is clear that traditional lime mortars somehow avoid the effect of freezing water rather than withstanding it: traditional lime mortars are frost 'resilient'.

Although it may be possible to force traditional lime mortars to pass the freeze-thaw test, through the use of additives/admixtures intended to improve frost resistance, it is better to understand the lime's intrinsic response. A study of the material microstructure of traditional lime mortars informs how the water is managed. Microstructure (the arrangement of porosity within the material, i.e. the pore size distribution and interconnectivity) imparts functional behaviour with respect to moisture movement in porous materials.[8] Through the examination of the microstructure of traditional lime mortars, information about the root of their resilient response to frost can be gleaned.

Fig. 3 (Below)
A visual manifestation of traditional lime mortar's sacrificial functional behaviour at work. Underlying processes are examined in Figures 4 and 5.

Salt resilience

The Society for the Protection of Ancient Buildings (SPAB) examined how traditional lime mortars respond to salt attack. In 1979 it published its findings on observations of masonry structures as they dried after periods of wind-driven rain.[9,10] SPAB noted that the lime mortar appeared to draw the water out of the masonry units, transport it along the joints and confine the bulk of evaporation to the mortar pointing nib. As the point of evaporation dictates where soluble salts (which are harmless in solution) then precipitate and cause damage, it was observed that the bulk of the salt damage was confined to the mortar pointing – the sacrificial material – rather than the masonry units.

This fundamental masonry preservation process was dubbed 'sacrificial weathering' and is characteristic of traditional lime mortars (see Figure 3). A technical understanding of how it works is imperative to unlocking the secrets of lime mortar functionality and, in turn, informing the design of compatible repair.

Like frost resilience, salt resilience is an outworking of the microstructure-induced water management within the masonry fabric. In practice, the durability of lime relies on how it deals with the engine of decay (water), rather than the agents of decay (frost and salt). This leads to a durable mortar, but the real value is its functionality in preserving the masonry around it.[11]

Microstructure and poultice mechanics

Figure 4 shows a pore-size distribution of traditional lime mortar and a typical coarse-pored masonry unit (e.g. a sedimentary building stone or brick), idealised for clarity. The area under the curve represents the pore volume (the material's porosity), but the position of the curve on the size spectrum is important.

In this example, the masonry unit's predominant pore size is 10,000nm. By contrast, the predominant pore size of traditional lime mortar is smaller, around 1,000nm. When two porous materials of distinctly different pore size are laid together (e.g. in the context of a mortar joint in masonry) and water is added, a poulticing interaction is established. Water is preferentially drawn out of coarse pores into fine pores by capillary mechanics.[12,13,14] This is a function of pore size, interconnectivity and surface chemistry of the capillary/solid matrix.

The moving water drawn from the masonry unit into the mortar transports with it soluble salts, which were dissolved in the body of the water, in a process known as advection. Salts in masonry are typically absorbed over time from the environment, from the air and drawn up from the ground; some masonries may also have a salt

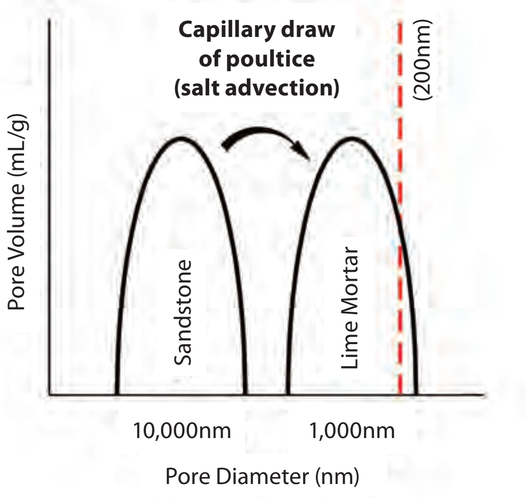


Fig. 4 (Left) Idealised relative pore-size distributions of a coarse-pored masonry unit and traditional lime mortar.

load built in at the time of construction.[15] Advection is a very effective desalination technique.[16] This continuous poulticing interaction, in which the lime mortar draws salts away from the masonry units – repeated over the lengthy lifetimes of masonry buildings – leads to an incredibly pronounced masonry preservation process: the heart of sacrificial weathering.[17]

SPAB's observations of lime mortar functional behaviour (1979) can therefore be explained through poultice mechanics, dependent on the relative material microstructures of stone and mortar (see Figure 5). It is important to remember that the moisture movement that SPAB observed was in both vapour and liquid phases: the latter, it seems, has been forgotten in recent references to 'breathability'.[18]

Figure 5 pertains to fabric preservation.[19] Lime mortar water-management functionality goes further: it actively dries out the masonry. A masonry wall built with traditional lime mortar, a highly capillary-active material, will dry out far more efficiently under the same environmental conditions than the same wall built with a denser mortar of lesser capillary activity. This is because the former exploits the capillary drying regime, which can readily supply the evaporation front at the surface with water to compensate for the evaporative flux. The denser material, of impaired capillary activity, supplies the evaporation front at a slower rate and retards the evaporative flux, thus making inefficient use of favourable evaporation conditions.[20]

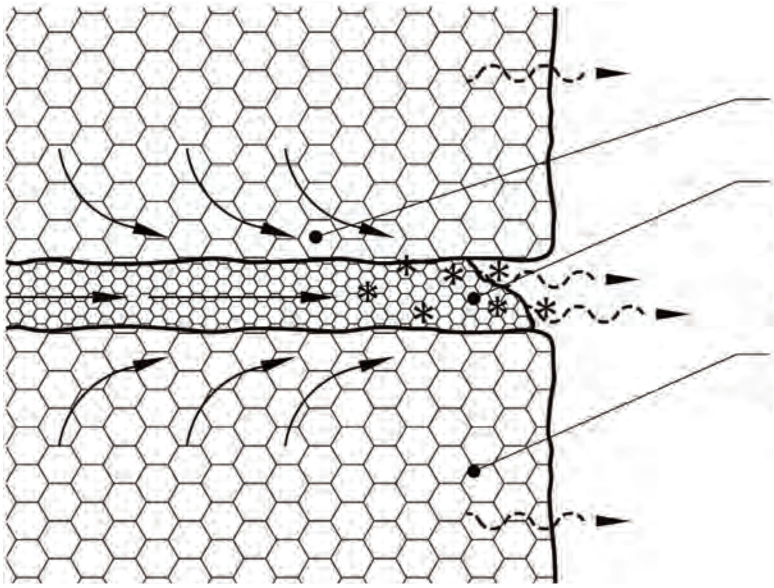
The poulticing function of traditional lime mortars is important not only in the context of the mortar joints but also in lime harling. Harling extrapolates the poulticing process over the full surface of the fabric, and is unrivalled in its ability to actively dry out the fabric (its primary historic purpose).[21] It also lessens the absorbed water load on the wall by preferentially holding water close to the evaporation surface, and its capillary activity makes it difficult for a coarse-pored masonry substrate to become wet (as it must compete against the capillary suction of the harling in order to do so). Furthermore, harling moves the harmful evaporation front away from the valuable masonry units, thereby actively preserving the substrate.

Functionally, traditional lime mortars grapple with the engine of decay by actively drying out the fabric, while washing it free of salt contaminants. Dry masonry cannot freeze and is, therefore, frost resilient. Salt precipitates in the sacrificial lime pointing and the masonry is, therefore, salt resilient. The real significance of a traditional lime mortar is not the material itself but its effect on the masonry around it.

Microstructure and macrostructure

Effective water management in masonry is undoubtedly of prime significance for the preservation of the fabric in the long term. More acute in the short term is its effect on the healthy operation of a building. Damp masonry markedly impairs the thermal performance

Fig. 5 (Below) Bed joint cross-section, showing sacrificial weathering of traditional lime mortar in action.



Migration and evaporation of water through the lime mortar joint.

Concentration of soluble salt precipitation, manifesting in the sacrificial weathering of lime mortar. When exhausted, the mortar becomes friable and is then raked out and replaced, refreshing the protection for the next service life.

Typical coarse-pored sedimentary building stone, notably sandstone and limestone. Historic bricks similar.

of masonry walls. It propagates mould growth and can affect the health of the building's inhabitants.[22,23]

Masonry walls typically enjoy significant structural restraint from built-in structural timbers, including floors and roofs.[24,25] Where the masonry is unable to dry out, the necessary local environmental conditions for rot to occur can be established, leading to the failure of these essential structural members and compromising the stability of the masonry walls. A wall will become a pile of rubble far quicker if it suddenly collapses than if the fabric of the standing structure slowly decays. From a structural engineer's perspective, the threat to the continued stability of masonry structures posed by the water retentivity of the fabric cannot be overemphasised.

Poultice mechanics govern water movement from masonry unit to mortar joint, but they are only realised in the context of porous masonry units. The decay of masonry units tends not to be an issue where non-porous stones are used; however, the shorter term water management issues for the wall or building as a whole are more significant. In masonries of non-porous stone, the only escape route for water is through the mortar joints; it cannot, for example, evaporate through the stone as it might in a sandstone wall.

Examples of the structural failure of non-porous granite walls that have been pointed or rendered in cement, thus saturating the walls and leading to the failure of the timber restraints, core slump and bulging/leaf separation etc., emphasise this point. Indeed, many structural deterioration mechanisms are triggered by badly managed water in traditional masonries.[26] Clearly, the functional behaviour of traditional lime mortars in drying out the building is of engineering importance.

Mechanical function

As a load-bearing component in the masonry wall, the mortar needs sufficient strength to resist the applied compressive stress. Historic masonry structures usually exhibit high load, but with low stress, owing to the typically massive section thickness of the structural element in question. Traditional lime mortars tend to have compressive strength between *c.* 1N/mm^2 and 2N/mm^2, typically around one-tenth the compressive strength of the masonry unit, and it is rare for compressive stress to exceed this value.[27]

The apparently low strength of the mortar allows it to yield sacrificially under load, to regulate and limit local compressive stresses (compression force over contact area) on the masonry units, which again hold significant heritage value in historic masonry.[28,29] Strength is not the issue with modern high-strength mortars on traditional masonry: it is their material brittleness and dense microstructure that present the problems. In order to regulate the stress, the mortar needs to be able to squash slightly. The ability for mortar to deform without cracking and crushing to failure is described by the Young's modulus (also known as the 'deformability modulus') and is a function of compressive stress over strain (the amount of deformation under load relative to its original form). Lime-rich mortars exhibit a significant plastic deformation zone under stress/strain profiles, thus demonstrating this behaviour.[30]

This mechanical behaviour of traditional lime mortars is closely related to their ability to realise their water management functionality. In order for the mortars to realise this function behind frost and salt resilience, a good degree of capillary continuity between mortar and masonry unit is required. Real structures routinely undergo minor movements as a matter of course. The response of traditional lime mortars has been to deform plastically while sustaining intimate contact with the masonry units, thereby maintaining the ability to draw water across the bond.

Evaluation of modern mortars

With a clear understanding of the functional role of lime mortars in traditional masonry structures (in terms of water management and load-bearing deformable filler), modern mortars can be evaluated objectively, using the historic example as a measure against which to appraise technical compatibility in terms of function. Water management function is inferred by the material microstructure, and mechanical function can be determined from physical properties; both are outworkings of the mineral ingredients in a mortar.

Cement

It is widely known that cement mortars accelerate the decay of traditional masonry substrates. But what is it specifically about cement that causes the damage? Figure 6 presents a pore-size distribution of samples of sandstone, lime mortar and modern gun-applied cement pointing (pressure pointing) taken from Glasgow Cathedral.[31]

As with Figure 4, the sandstone is coarse-pored, with a predominant pore size in excess of 10,000nm. The traditional lime mortar bed joint exhibits a pore size of 1,000nm and is clearly a very effective poultice, able to draw the water out of the stone and wash away soluble salts in the process. However, the pore size of the cement grout is a further factor of ten smaller; its entire pore volume is below 100nm in pore size.

Capillary mechanics only occur in pore diameters down to *c.* 200nm. Below this size, water movement becomes markedly impaired.[32] Although the cement mortar sample has half the porosity of the lime mortar sample, porosity in and of itself reveals nothing of the material's response to water. The microstructure

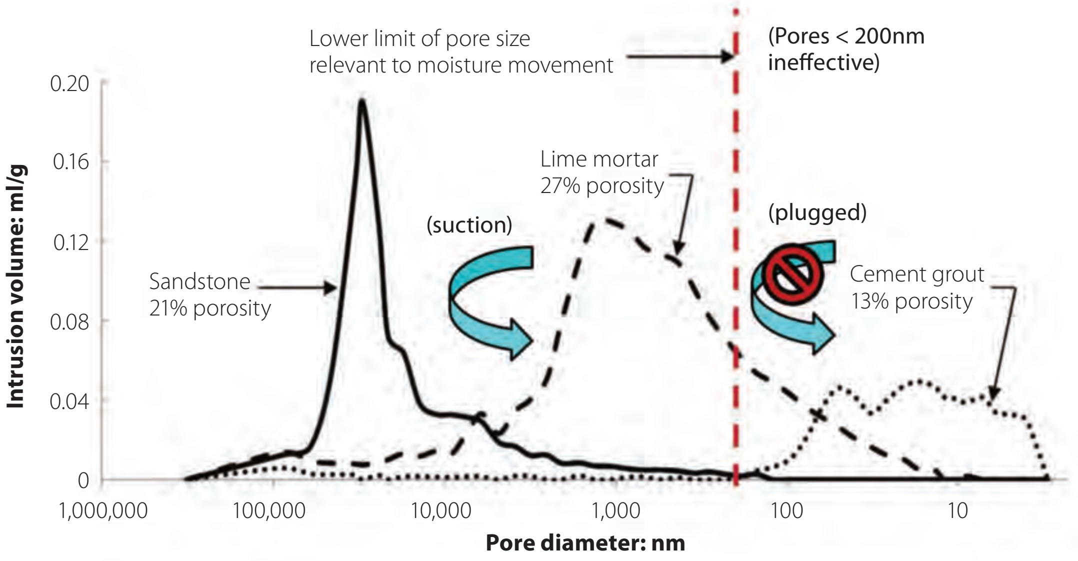


Fig. 6 (Left) Relative pore-size distributions of sandstone, traditional lime mortar and modern cement grout pressure pointing interacting in a bed joint at Glasgow Cathedral.

Fig. 7 (Left) A reminder of the physical outworkings of displaced water evaporating through the stone arrises (this is the local context at Glasgow Cathedral sampled to produce Figure 6).

as presented in Figure 6 demonstrates that the entire pore volume of the cement grout, regardless of its porosity, is ineffective for capillary flow processes (on the basis of its small pore size), hence the pronounced plugging effects to the mortar joint. The accelerated decay around the arrises of the stone is an outworking of the displaced evaporation front by this surface plug (see Figures 7 and 8).

As shown left and below, cement mortars fail the traditional lime mortars on water management grounds. They also fail on mechanical grounds. With their higher strengths come higher Young's moduli: cements are significantly more brittle than traditional lime mortars.[33] They exhibit brittle failure and do not plastically deform, which leads to an inability to accommodate minor movements in the masonry. This often results in cracking (a key water ingress route) or debonding from the masonry substrate, severing what tenuous capillary continuity they may once have possessed and exacerbating water management issues – in short, creating an inability to dry out. The higher strengths also transfer stress to the masonry units themselves, which can damage the more fragile masonries of historic buildings.

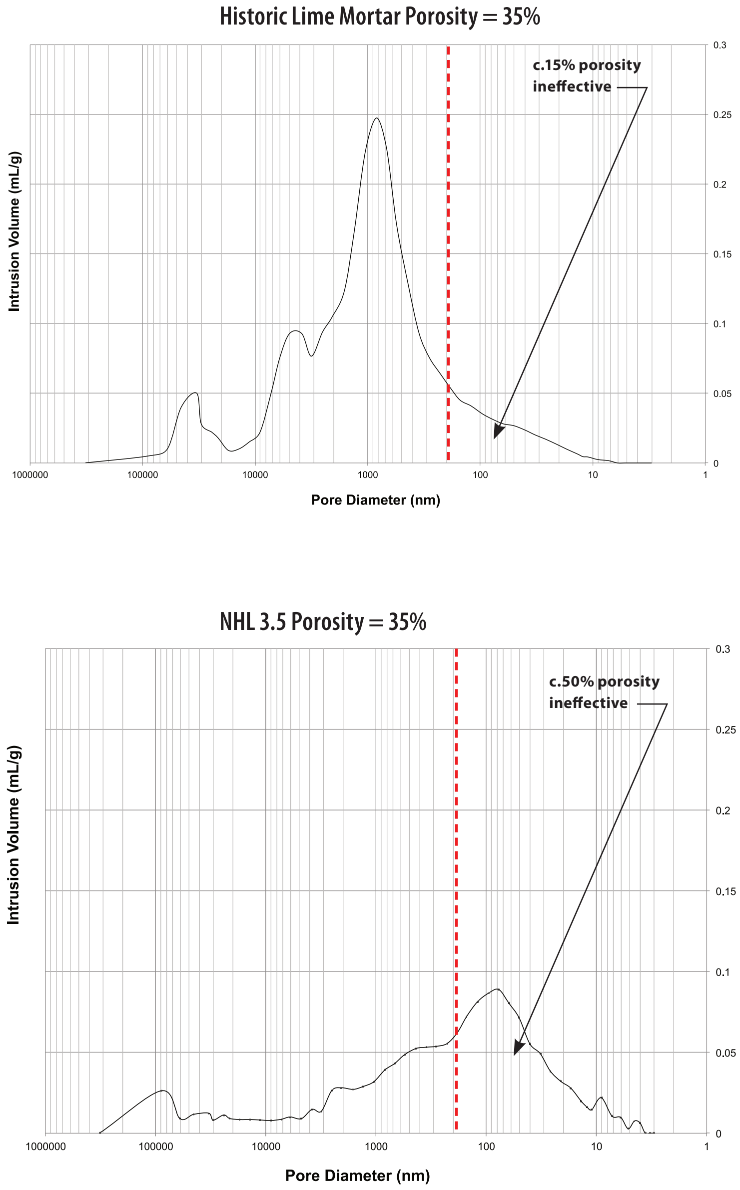
Fig. 8 (Below) A visual manifestation of the damage of cement at work: the ramifications of forcing evaporation and hence salt precipitation to occur in the arrises of the stone, displaced around the mortar joint (rather than through it, as in Figure 3).

Natural hydraulic limes

Natural hydraulic limes (NHLs) were hailed as the answer to the problems of lime putty for building work. However, it has been appreciated for some time that the NHLs of the past decade or so do not function like the historic example, set down by most traditional lime mortars, that they are supposed to replicate: they bear little resemblance in physical, chemical or mechanical senses. Figure 9 presents the microstructures of a sample of traditional lime mortar and the developed microstructure of an NHL after two years' field curing.

A marked difference in the microstructures of the two materials is evident. Given that microstructure imparts functionality in porous materials, differences in behaviour can be inferred. More than 85 per cent of the traditional lime mortar's porosity consists of pores greater than 200nm and is therefore effective for capillary flow processes (responsible for drying out the fabric and preserving the masonry in doing so), but only 50 per cent of the NHL's porosity is effective. Half of its pore volume is located in the dense nanopore size region (formed by the hydraulic set), and is essentially 'plugged' as far as capillary flow capability is concerned.

Fig. 9 (Below) Relative microstructures of traditional lime mortar (above) and modern NHL-based mortar (below).[34]



The 'active ingredient' responsible for the developed microstructure of traditional lime mortars is calcite: carbonated free lime in the original mortar mix, produced by the carbonation of calcium hydroxide. This forms the porosity fraction, which centres around 1,000nm.[35,36,37] A porosity fraction below *c.* 200nm is developed via a hydraulic set of reactive minerals, either included naturally in the lime (in NHLs) or added to the lime (pozzolans). In the UK and Ireland, the historic limes of masonry buildings are known to be fat limes of typically feeble hydraulicity.[38,39] Therefore, the binder is very lime-rich, in broad terms something close to the CL90 currently available today but perhaps a little less pure. The mix proportions of historic limes are known to be very binder-rich, typically around 1:1.5 binder: aggregate. In addition, the active ingredient contributes significantly to the low modulus and comparatively low strength of traditional lime mortars. The binder richness in lime-rich mortars does not lead to a disproportionate increase in brittleness: good deformability is an inherent property of the calcitic set in traditional lime mortars.

Given that the microstructure in mortars is generally due to the binder (a quartz sand is non-porous), the highly porous, pronounced pore-size distribution – centring around 1,000nm – characteristic of traditional lime mortars is developed as an outworking of the active ingredient (the binder 'type'), combined with its mix proportions (the binder 'amount'). This distinctive microstructure imparts the functionality exhibited by traditional lime mortars. If functional behaviour is to be replicated in a repair mortar, which technical compatibility requires, the causal agents behind it (binder type and amount) need to be replicated.

In broad terms, with a CL90 mortar, increasing the amount of binder in the mortar increases the poultice functionality, as there is more lime to carbonate and create the optimal microstructure observed in traditional lime mortars that in turn imparts behaviour. A CL90 mortar made at 1:1.5 mix proportions appears to be an excellent replication of the historic example, or at least a good starting point for the mortar design.

NHL mortars fall short of the historic example on the following grounds. In a typical NHL 3.5 at 1:3 mix proportions, the binder may have a free lime proportion of as little as 25 per cent,[40] meaning each unit of binder has only a quarter of the active ingredient relative to the historic example. It is clear then that there is a binder type issue with NHL-based mortars. Furthermore, contemporary NHL mortars are made at lean mix proportions, typically at half the binder richness of traditional lime mortars: the binder type issues are compounded by a binder amount issue. Consequently, an NHL 3.5 at 1:3 mix proportions may have only an eighth of the total free lime content available to carbonate and create the pore network responsible for the water management processes, when compared to the historic example.

NHL mortars also fall short of the historic example on mechanical grounds. In spite of their typically lean mix proportions, they exhibit far higher strengths than traditional lime mortars. Linked to this increase in strength is an increase in brittleness, which leads to a lesser ability to absorb structural movement and to sustain capillary conductivity with the masonry units.[41] Given the discord in water management and mechanical grounds, it stands to reason that the NHLs do not behave in practice much like the traditional lime mortars they are supposed to replicate.

A serious issue with many NHL mortars currently used is the pervasion of additives and admixtures into mortar design, which is especially prevalent in pre-mixed and proprietary mortars. This appears to be an attempt to force the mortar to pass the standard durability laboratory tests that are known to be unrepresentative of real-world conditions. The tests also seem to be designed to allow corners to be cut in preparation, application and aftercare. The outworking of the suite of admixtures often leads to water-repelling surface chemistry and compromised microstructure, which both impair or even preclude poultice/water management functionality.[42] Capillarity is fundamental to the mortar's ability to draw the water out of the wall and to preserve the fabric in the process. Where a hydrophobic mortar is used, the disruption to the water movement around the pointing is worse than where a cement mortar is used (see Figure 10, see also Figures 7 and 8).

Importing solutions from the cement and concretes industry and forcing them onto lime mortars and traditional buildings should be abandoned: the focus needs to be on examining how the historic example works, which should then become the basis for compatible mortar design. Above all, contemporary lime mortars should replicate the functional behaviour of traditional lime mortars.

Replicating the functional behaviour of traditional lime mortars

As previously stated, the active ingredient in traditional lime mortars that imparts poultice functionality, vapour permeability, intimacy of bond and deformability is calcite: carbonated free lime. A technical understanding of how and why traditional lime mortars function in the way they do enables new lime mortars to be specified that will perform in the same way.

With regard to the mix composition of traditional lime mortars (typically fat lime at 1:1.5 mix proportion), the specifier considers how such a lime-rich and binder-rich mortar might be made within the 'compatibility goalposts' set down by the functional behaviour of traditional limes. The answer is found in hot mixing, the only known viable way of making mortar with the historic ingredients at the historic proportions.[43]

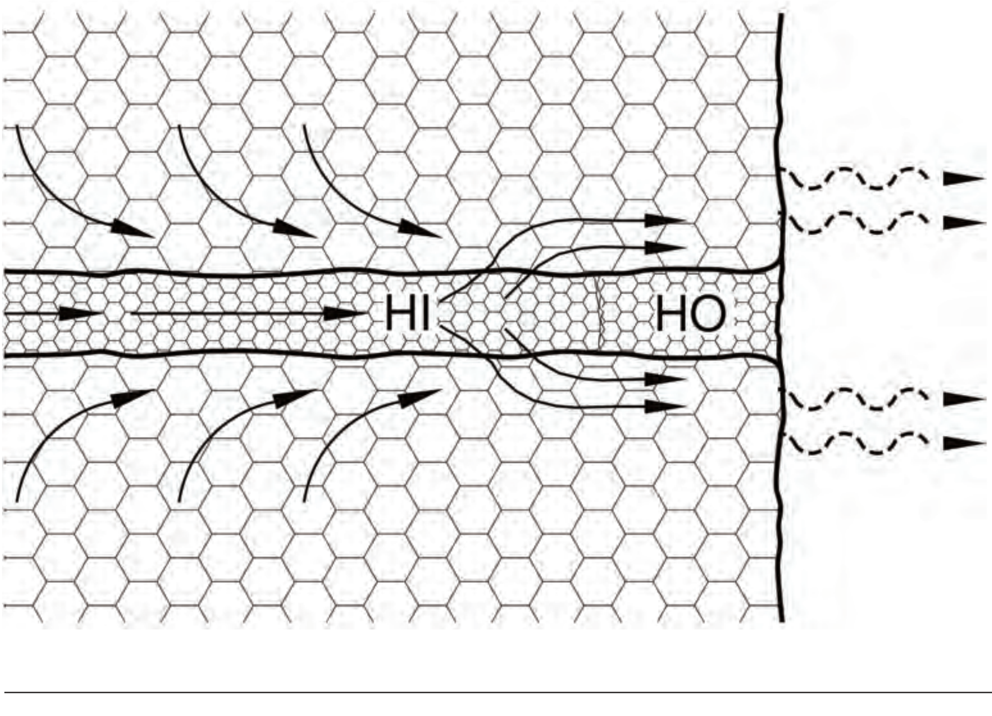


Fig. 10 (Left) Disruption to water movement and drying conditions caused by repointing with a mortar of water-repelling surface chemistry (HI: hydrophilic; HO: hydrophobic).

Given the lime richness observed in the historic example, the CL90 binder appears to be the best starting point. Such rich mix proportions using this binder type can only be achieved using the hot-mixed method (the traditional method of mortar preparation for many historic mortars).[44] As quicklime doubles in lime yield during slaking, the typical starting mix would be 1:3 quicklime: aggregate to replicate the 1:1.5 historic example.

In order to reproduce the required degree of hydraulicity of the original mortar and meet the environmental/service requirements of a particular context, the quicklime mortar can be gauged with a pozzolan or by partial binder replacement with NHL.

Pozzolans create a hydraulic set by consuming a proportion of the free lime in the mortar mix: the 'lime demand' of the respective pozzolan is described by its reactivity under the Chapelle test. Particularly reactive pozzolans, such as metakaolin, broadly consume their own weight in free lime. Research indicates that by keeping the pozzolan content to around 10 per cent of the weight of the lime binder, a microstructure very close to that of an aerial lime mortar can be produced – with all the practical benefits of a hydraulic set.[45,46,47] The pozzolan inclusion should be limited to 'just enough' according to its lime demand and the context in which the mortar is to be used.

Quicklime-NHL hybrid lime preparation is a very practical way of overcoming the markedly low free lime content in an otherwise NHL-only mortar. Recent work has demonstrated excellent replication of the original mortar's physical and chemical properties and the resulting functionality.[48] Work by the Building Limes Forum Ireland,[49] Historic Environment Scotland and Historic England demonstrates the opportunities presented by the traditional method of mortar preparation using a contemporary palette of materials. Masonry heritage testifies to the enduring reliability of the material and the method.

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Summary and conclusions

- Technical compatibility requires that the functional behaviour of traditional lime mortars be replicated by repair mortars.

- The functional behaviour of traditional lime mortars, water management and sacrificial weathering through poultice mechanics is due to the predominantly calcitic set. This establishes the optimal microstructure, which then imparts function.

- Modern NHL repair mortars fall short of the historic example. This is principally due to their lack of the calcitic set exhibited in traditional lime mortars. Instead, the NHL set is predominantly hydraulic, which leads to a denser microstructure that functions differently in practice.

- Admixtures and additives can profoundly alter the functional behaviour of the mortar, especially those that lead to water-repelling surface chemistries. They should not be used in repair/conservation mortars unless their effect on the final performance of the mortar can be demonstrated by test data, and justified. The unregulated widespread use of admixtures in pre-mixed NHLs presents a real threat to the continued preservation of heritage masonry.

The functional behaviour exhibited by traditional lime mortars is best replicated by hot-mixed lime mortars today. This is entirely unsurprising. The basic chemistry behind lime mortar is no different to that found in home baking: if the same recipe is followed, using the same ingredients and prepared in the same way, for all intents and purposes the same result can be expected. Hot-mixed lime mortars use the historic 'recipe', the right 'ingredients' and the traditional method of mortar preparation, thus ensuring the mortars are made in the same way.

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