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# THE RUDIMENTS OF TRADITIONAL MORTAR PREPARATION AND USE

## ABSTRACT

*This paper seeks to summarise recent major shifts in the understanding of the nature and provenance of traditional mortars, the nature of the lime most used for the preparation of these mortars, as well as the methodology of the crafts in their preparation. It draws upon the author's experience of designing and using such mortars over a 20-year period, but also upon extensive research into old texts about lime and mortars written over the last 2,000 years, as well as upon extensive analysis of primary building accounts from England and elsewhere. It also references an expanding body of academic research in the characterisation of composition, as well as of the performance of such mortars, itself a significant shift in focus and understanding. It will set out the primacy of the quicklime slaking method in the delivery of successful mortar performance, optimal in the context of traditional building technology, and will reiterate the absolute importance of observing traditional lime choices, slaking method, rules and mortar proportion in the achievement of durable mortars of optimal performance for the like-for-like and compatible repair of traditional buildings of all kinds and status.*

**KEYWORDS: QUICKLIME, LIME MORTAR, EARTH-LIME MORTAR, HOT-MIXING METHOD, LIME SLAKING, POZZOLANS, MORTAR PROPORTION.**

## INTRODUCTION

As it becomes increasingly understood that most historic mortars were hot mixed with quicklime, and as increasing numbers of craftspeople around the world are rediscovering and routinely using such mortars in the care and repair of traditional buildings, it is important to set out the fundamental principles of lime slaking and mortar making methodologies, drawing upon the extensive historic texts on the subject of building, as well as upon building accounts and material science, with a view to avoiding simple mistakes with less than simple consequences. Much detail remains to be discovered, not only by the crafts themselves, but by professionals, researchers and academics in the field – intellectually as well as, crucially, by practical experience and observation. The author has worked with traditional earth-lime and hot mixed lime mortars for 20 years as a stonemason and building conservator and has conducted an extensive review of historic texts and archived building accounts ranging over the last 2,000 years. The story that these tell is generally consistent over this period - and is consistent with the experience of those using hot mixes again today - but is a very different story from that told, even by advocates for the use of lime mortar, over the last 50 years (Copsey 2019 a & b).

## HOW DO WE CHARACTERISE HOT MIXED LIME OR EARTH-LIME MORTARS?

After many years of confusion within academic circles and beyond, it is now beyond dispute that, in most cases, the presence of residual inclu-

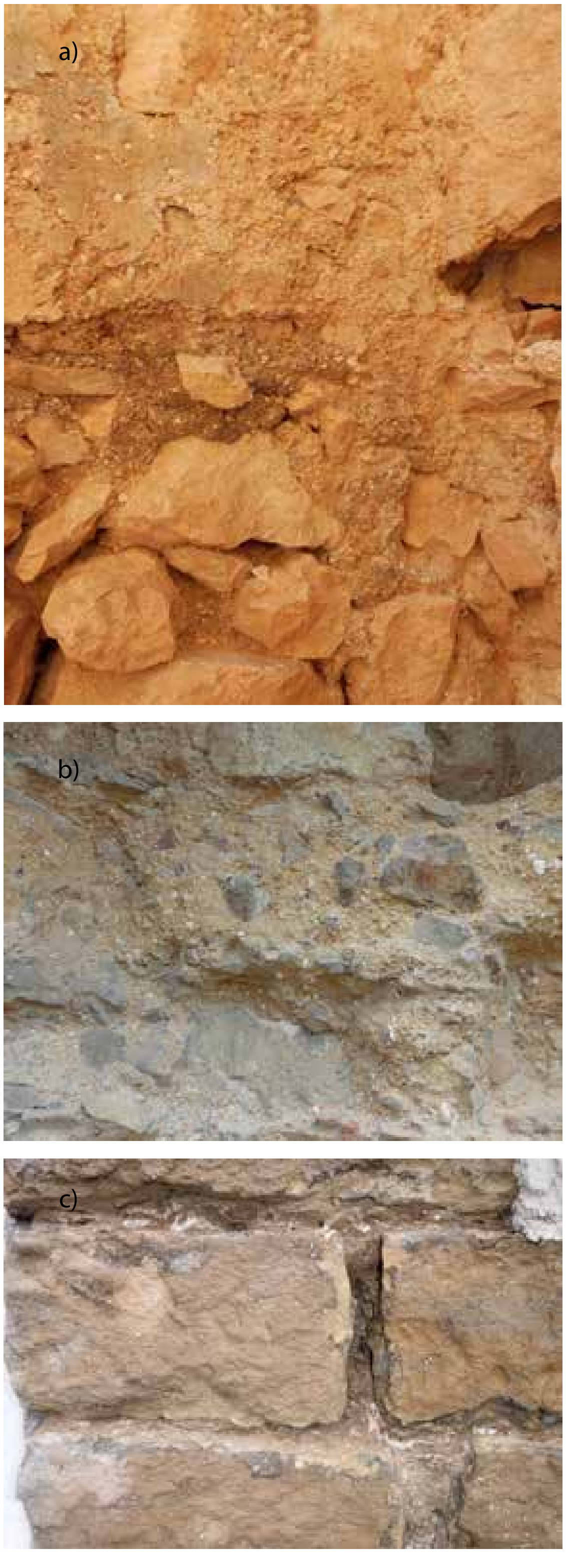

Fig. 1. The presence of residual lime lumps in earth-lime mortars from different periods and geographies: a. Masada, Israel, 2,000 years old; b. Rievaulx Abbey Cloister, North Yorkshire, 12th century; c. bedding mortar in the wall of calcareous sandstone, Wrench Green, North Yorkshire, 19th century (all photos by N. Copsey; c. from Copsey 2019c).

Fig. 2. Earth-lime mortar and remnants of pure lime basecoat plaster, medieval dovecot, Calvados, Normandy (photo by N. Copsey).

sions of lime – sometimes underburned quicklime, sometimes over-burned, sometimes simply slaked, unmixed and subsequently carbonated lumps, of variable dimension, but typically angular – indicates the preparation of the mortar to have been performed using a hot mixed method (Hughes, Leslie, Callebaut 2001), which is to say, that quicklime is slaked and mixed with intended aggregates as soon as the slaking is substantially complete, the quicklime remaining hot from the slake. When powdered or pulverized quicklime was used, the quicklime and sand would be mixed prior to or during the slaking of the quicklime, without generally leaving lime lumps in the mortar, but typically rich in lime (Revie 2019a). Figures 1a – 1c illustrate the presence of residual lime lumps in three earth-lime mortars from different periods and geographies, demonstrating not only their essential commonality, but also their dura-

Fig. 3. Hot mixed lime mortar with basalt beach sand, Vancouver Island, British Columbia, 1864 (photo by N. Copsey).

bility in significantly different climates. Figure 2 illustrates earth-lime mortar and remnants of pure lime basecoat plaster, in Normandy, while Figure 3 illustrates a typical hot mixed lime-sand mortar, in this case in British Columbia.

Callebaut (2000) was the first in a laboratory context to make a connection already made by numerous craftspeople such as Patrick McAfee (1997; 1999), disproving previous opinions (Bakolas et al 1995) that residual lumps were comprised of the thin, soft calcite crust that would form upon the surface of laid down lime putty, incorporated when this putty was mixed with aggregates to form a mortar. How such low volumes of soft calcite crust might account for such high volumes of hard residual lime lumps in actual mortars was seemingly not considered.

The possibility of hot mixing was long ignored in favour of a long-standing cognitive bias that held that most mortars historically had been made using matured lime putty, which the technical evidence, as well as the evidence of most historic literature and material science, indicates that they were not. Lime putty was always made, of course, although the period of repose would vary from days to weeks to months and even years, but for very specific purposes and for uses that made the continued presence of residual lime lumps problematic – such as fine plaster and stucco finish coats and the finest brick or stone ashlar jointed bedding mortars, within which lime putty was used as the mortar itself, on its own, and without the typical addition of sand or other aggregates (Langley 1750; Millar 1898). For more than these particular uses, lime putty was generally distrusted and considered to be lacking in binding qualities, compared to those that existed in a hot mixed lime mortar, which is not to say that it was never used in combination with aggregates, of course, depending upon practical circumstance. Beyond this, the preparation, storage, and later use of lime putty required much more handling and labour, reducing its efficiency when compared to a mortar that might be mixed and used immediately, even when that mortar might itself be laid down for a week or two, or sometimes longer, to allow for late-slaking to occur before a plaster was laid upon a wall (Higgins 1780; Millar 1898), although even this was not as common as many suppose (Langley 1750, Pasley 1826, Lazell 1915). A properly slaked lime putty ('just sufficient' water added to effect the slake, before some further water addition once the slake was complete, and whilst the heat of the slake endured) produced a material universally described in the past as having been of 'bread-dough' consistency, and of much greater immediate and subsequent density (and lower water content) than most commercially produced 'lime putties' available today. Lime putty so-slaked was a mouldable, plastic material (that resembled linseed oil window putty in character) that enjoyed excellent internal bonds and into which water was typically 'locked' and effectively invisible and unavailable to promote the 'swimming' of stones laid upon it, for example, or the staining of masonry substrates during use – much like a hot mixed lime: an aggregate mortar, in fact.

At Viminacium in modern-day Serbia, the former capital of Upper Moesia, the vast majority of Roman mortars so far revealed, whether pure, feebly hydraulic, or more hydraulic mortars according to purpose, retain lime lump inclusions consistent with the mortars having been hot mixed from quicklime, in the author's observation (Nikolic & Rogić 2018), as were the vast majority of sampled and analysed mortars from Roman Britain (Vindolanda mortar analysis in Revie 2019b; www.hotmixedmortars.com). Ottoman Empire mortars in Serbia and elsewhere were similarly processed in the author's observation and assessment. In the lands of modern-day Israel, mortars of all kinds (including earth-lime mortars) from every period – from as early as 10,000 BC, where hot mixed earth-lime and lime mortars were deployed as grave covers, as well as wall plasters– were hot mixed from quicklime and are considered to display a sophistication in processing that might indicate an already mature technological understanding during the Pre-Pottery Palaeolithic Era (Friesem et al 2019). In Greece, analysis of 1,300 mortars used during at least the last 2,000 years, offers a very similar picture, with the overwhelming majority of Hellenistic, Roman, Byzantine, Ottoman and medieval mortars, as well as those still used during the earlier 20th century, displaying residual lime lumps consistent with their having been hot mixed directly from quicklime (Stefanidou and Pappyianni 2011).

A similar picture may be seen in the British Isles, as in most places across the world. Lime putty formed the binder in a small minority of over 4,000 mortars analysed by the Scottish Lime Centre Trust (Historic Environment Scotland 2020), (Fig. 4), and even this may represent a misinterpretation, given that the not uncommon use of powdered quicklime historically would leave no residual lime lumps in the mortar. A long laid down hot mixed plastering mortar, knocked up before use, might display very few residual lime lumps.

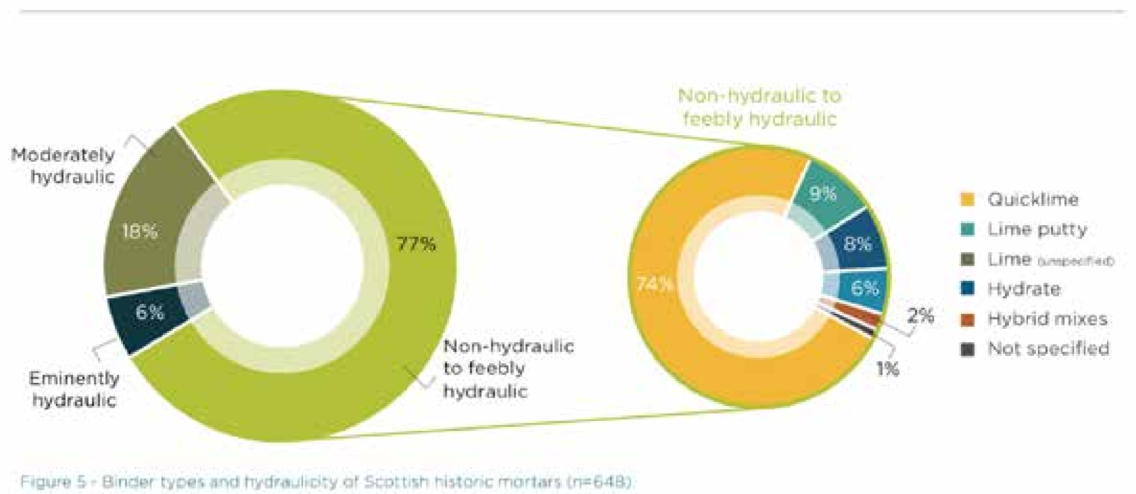

Fig. 4. Collated analyses of over 4,000 samples held by the Scottish Lime Centre. (Historic Environment Scotland Technical Paper 32, 2020).

## HOT MIXING METHODS

The precise hot mixing method might vary between dry-slaking (common for plastering mortars, the larger unslaked lumps sieved out- along with larger aggregate inclusions – after mixing with sand, or immediately after slaking and immediately prior to mixing with aggregates, if not used on its own after sieving and mixing with water, and with fibres added to control shrinkage) – or wet slaking, straight through to a useable mortar.

These mortars might be used whilst still hot, which offered significant advantages to the crafts in terms of initial shrinkage behaviour and general efficiency, as well as – recent research would suggest (Koeberle 2020) - forming a stronger immediate bond with substrates and delivering early stiffening in situ due to the immediate and rapid evolution of Portlandite crystal structures within the mortar, as well as offering greater durability over 'cold-mixed' alternatives.

Alternatively, hot mixed mortars might be laid down after mixing, subsequently used whilst cold – although there was a broad consensus historically that the majority of mortars, for the majority of purposes, should be used within a week of preparation; this consensus only becoming less firm as the 20th century wore on, and during which same period, lime putty came to be used much more as a binder, often in association with low level Portland cement addition to otherwise air lime mortars, uniquely delivering a mortar of similar workability to a traditional hot mixed mortar (Totten 1842, Geeson 1952, Copsey 2019 a & b). The lime putty typically 'matured' for days (plasterer Ray Warley, pers. comm.) or for several weeks, or sometimes only a week (Nicholson 1841, Millar 1897).

The particle size and character of a dry-slaked lime differs somewhat from a wet-slaked lime paste, as well as from that of a lime putty; this was known intuitively by the crafts, so that the slaking method was often determined by the intended purpose. Dry slaked lime forms an irreversible crystalline (and larger) particle, whereas wet slaked lime (or lime putty) forms a platelet structure with a finer particle size and significantly greater surface area (Rodriguez-Navarro et al 2005). The smaller and more malleable the particle size, the greater the likely bond with aggregates will be. This difference affects their workability and behaviour in use. A plaster mortar made with a dry slaked lime – even of similar lime-to-aggregate proportion – will typically shrink less than a wet-slaked or lime putty mortar, although it will also be typically less workable, of lesser adhesiveness and cohesiveness., in use. Before the 20th century, dry-slaked lime would be produced on site. Vicat (1837) discusses the immediate placement of such lime into barrels for storage. However, in most cases, prompt, if not immediate, use will have been the norm.

## LIME PURITY

Contrary to many prevailing narratives today, and since the widespread promotion and use of initially Portland cement and, more recently, natural hydraulic lime, (usually coupled with a dismissal of the value and usefulness of fat limes for any purpose), the quicklime that was preferred, in all periods and in all regions of the world, was as pure as might be found. 'Pure or nearly pure' would be the most accurate description. This understanding, made evident in all reviewed texts about lime and craft practice historically (see Copsey 2019b, Appendix 10), runs contrary to recent narratives concerning the historic use of natural hydraulic limes, which were, in fact, rarely used for much beyond the making of concretes, lest, like the Blue Lias lime used in the UK, (Smeaton 1791; Taylor & Levon 2021) they were of unusually high free lime content, offering more workability, when they might be used for waterworks, although always with the addition of pozzolan to consume the excess of free lime, consistent with their purpose. In Scotland, where far fewer pure limestone deposits were available, and where natural hydraulic limestones were more common, the desired pure lime was derived from sea-shells, abundant along an extensive coastline, or were imported by sea and river from Northumbria or from Cumbria, across the border in England, whilst indigenous sources of pure or feebly hydraulic lime were exploited wherever they existed, as is evidenced by the building accounts of the Royal Works before the 1709 union with England (Accounts of the Masters of Works Vols 1 & 2 1957). This picture is demonstrated in Fig. 4, above. Even in the first recorded use of lime mortars, by the Natufian culture in the Palaeolithic Era, at the excavated burial site of NEG II, the immediate geology was of dolomitic limestone and the mortars were made with a high calcium lime carried from further afield for the purpose (Freisem et al 2019). The Romans were aware of impure limestones that delivered strongly hydraulic mortars – Pliny (2015) calls it 'silex' – but preferred to use hot mixed pure lime and pozzolan mortars for waterworks and in other inherently wet situations. The most hydraulic pozzolanic mortar, which would ultimately consume all free air lime, offered a workability in use – delivered by the free lime before its consumption to form (primarily) di-calcium silicate, otherwise known as belite - that was little different than that of a pure lime and sand mortar; it enjoyed excellent initial water retentivity, contributing to optimal bond formation (Boynton & Gutschick 1964) and was, anyway, considered more reliable and more stable during its life-time, when compared to a mortar made from natural hydraulic lime (Totten 1842). Indeed, masons would frequently reject NHLs (Biston 1828), in favour of fat lime mortars that offered a workability that NHL mortars did not and which did not dry too quickly (the countering of which demanded significant on-going hydration, which fat limes did not, and significantly more time-consuming aftercare, as well as the extensive wetting of building units). Vicat (1837) says that these must be saturated and kept that way for a long period prior to use, compromising the necessary bond formation and promoting the swimming of newly laid building units, thereby hampering building progress. When using a fat lime mortar, only the initial rate of suction (Hall & Hoff 2009) needed to be satisfied to prevent over-rapid drying of the mortars. This allowed for immediate and sufficient bond, as well as the full extent, of durable bond and it was generally enough to dip a brick or stone in water immediately prior to bedding it, or to splash an existing mortar joint before pointing it, after which no more on-going hydration would generally be required. Fat limes need to lose their excess of water to begin to set, but will lose this slowly and steadily; NHLs need water to set, but will lose what water they contain very quickly in the absence of long-term and on-going hydration.

Pure or nearly pure lime was predictable and of generally similar behaviour and performance wherever it was found. Many limes contained small volumes of clay or other impurities, and these may or may not have been reactive silicas or aluminas. Even if they were, in small volumes, these might have made a mortar feebly hydraulic, but their slaking behaviour and ultimate strength would have been only marginally different from a pure lime, and might, in fact, ultimately have delivered a slightly weaker mortar than their pure lime equivalents (Dibdin 1911). Any advantage that there was, was in the initial shrinkage behaviour, it being significantly reduced. This same advantage could be won by the addition of small volumes of brick or of wood ash, or another pozzolan, to an otherwise pure lime mortar. Such additions were common at the craft level in all periods and places, particularly, perhaps, for pointing mortars. The addition of even 10% pozzolanic material (as a proportion of the slaked lime) would leave 80% of the binder as pure lime, continuing to offer high – if not quite optimal – effective porosity. Most often, around 5% pozzolanic addition is found in analysis. (Revie 2019b; www.hotmixedmortars.com). After the laboratory research of Roman mortars in Serbia, there is an ongoing study into the possibility of using natural pozzolanic materials and lime with hydraulic properties at the provincial sites of the Roman Empire - Viminacium and Lederata, for the mortar production (researcher Emilija Nikolić, pers. comm). Romans at Viminacium abundantly used brick in mortars in humid and water environments, and there is also an indication that some red fragments in mortars were actually 'natural brick' formed by the spontaneous combustion of shallow coal-seams that lay beneath the clay soil in the nearby hill, since the laboratory research confirmed its pozzolanic features (Nikolić, Tapavićki-Ilić, Delić-Nikolić 2022). In Israel, brick, cocciopesto and wood ash were used for a similar purpose, the routine use of wood ash as a pozzolan arriving in the region with the Romans (Van Zuiden & Asscher 2021) and this, along with other Roman practices were swiftly adopted by King Herod. Hydraulic quicklime and wood ash mortars, as well as hot mixed cocciopesto mortars, used to plaster water cisterns in Masada remain intact today, 2,000 years after placement, in the author's observation, and as assessed by Tal Hayut, the lead conservator at the site. A recently excavated lime kiln at Masada (Figs. 5 and 6), built to a typical Roman pattern, which contained in situ air-slaked and carbonated lime, as well as unburned limestone, would indicate not only chemical purity but also the burning of limestone from without the local geology, suggesting its careful selection and carriage. Analyses of both are currently underway

Figs. 5 and 6. Masada lime kiln and associated lime slaking area just below, where the slaked lime was discovered (photos by N. Copsey).

Natural hydraulic limes are eminently variable (and unpredictable) materials (Figueiredo 2018; Seo Jun 2020), not only between sources, but within the same source (Fig. 7). Boynton (1980) saw this as the primary obstacle to the use of NHLs for building, although as early as 1777 Le Sage, in France, had called for the prohibition of NHLs for general building purposes for the same reason (Vicat 1837). Their initial setting times vary significantly from one batch to the next, and this would always have alarmed the building crafts (as it still does today). It may be considered a basic principle of building that the mortars of construction should be of the same strength and character throughout the build, and certainly above ground. NHLs do not deliver this certainty whilst, at the same time, they have been shown to continue to gain strength over an unknown, but possibly indef-

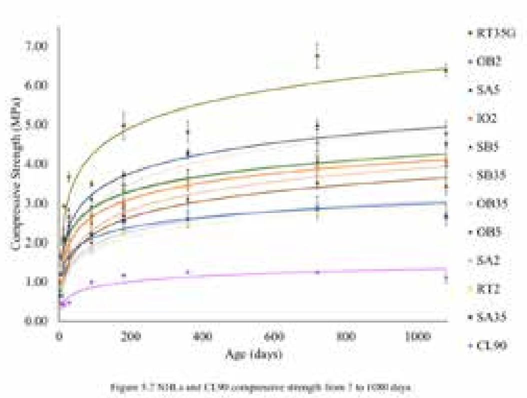

Fig. 7. NHLs and CL90 compressive strength from 7 to 1,080 days (Figueiredo 2018).

inite, period after placement, each gain in strength indicating an increase in density and an associated diminution in an already low effective porosity. This, with the ongoing hydration necessary for them to set properly. In the absence of such ongoing hydration, over a period that might need to be 6 months – their period of maximum strength-gain – they are unlikely to set properly, remaining (behind an apparently set and hardened face) as a mush or as a powder within a masonry joint, in the authors' observation, as well as that of others (Roger Curtis, Historic Environment Scotland, Technical Research team, pers. comm.). This latter behaviour is commonly seen in the UK, where many give little to no hydration after placement, leaving the mortars to rely upon received rainfall and frequently high relative humidity only. At the same time, NHL-pointed traditional buildings in the UK and elsewhere tend to display permanently elevated moisture levels in their fabric, which will peak during the winter months, but only slightly diminish during the summer, once more, in the author's observation.

In contrast, traditional buildings that retain their original pointing mortars, or which have been repointed with non-hydraulic hot mixed lime mortars (often after years of suffocation by sand: cement or NHL mortars) quickly dry after wetting and remain perennially dry in their fabric in all seasons. (Figs. 8-12)

Effective porosity – like appropriate and useful workability – is primarily delivered by a high free/air lime content (Wiggins, in Copsey a 2019). A mortar that enjoys a high level of air lime will possess a high proportion of capillary-active pores held within an inter-connected pore structure. Whilst the fundamental laws of physics indicate that the penetration of received water will be but

Figs. 8 and 9. Marske Hall; porous Jurassic sandstone' Repointed with NHL. Winter and summer, the latter image taken after five months without significant rainfall (photo by N. Copsey).

Fig. 10. A humbler building of similar geology, pointed with hot mixed air lime mortars, Pockley, North Yorkshire (photo by N. Copsey from Copsey 2019c).

minimally absorbed into an essentially dry capillary-active material (Pender 2012) – a behaviour known to all masons who work on old buildings, who might soak existing traditional mortars before repointing, to find that this water has been absorbed to a very shallow depth, in fact. This received water, as well as that which might be generated by interstitial condensation, and by moisture generated within a building interior, or from the ground, will be quickly released into the atmosphere due to wind or air movement powered capillary activity, so that a fabric that retains its original or otherwise air lime-rich mortars will tend to be perennially dry and resistant to water penetration – all the more so because a mortar rich in air lime will have retained enough water during and immediately subsequent to its application for optimal bond formation with the substrates or the masonry units, thus offering high resistance to water penetration (ASTM 2007; Johnson 1926). In addition, such bonds will be durable – they will not be disrupted by expansion and contraction during wetting and drying, or during thermal cycles (Palmer 1931 - US Bureau of Standards Research Paper 321). Hydraulic mortars are not stable in such cycles and this characteristic will compromise the bond has been formed in mortars lacking in water retentivity, such as sand and cement, and natural hydraulic lime mortars without any, or much reduced, free air lime content (Johnson 1926).

Beyond this, and as demonstrated by the US Bureau of Standards (Palmer 1931 - Research Paper 321) as long as 100 years ago, the initial shrinkage of a fat lime mortar happens at a moment when the mortars remain plastic, allowing easy closure of such shrinkage, this being the only shrinkage such a mortar will exhibit in its lifetime. The Bureau further demonstrated that, although hydraulic mortars exhibit much less, or no apparent initial shrinkage, they will shrink by up to four times the extent of the initial shrinkage in a fat lime mortar in their life-span, but only after they have set hard. Even unclosed initial shrinkage in a fat lime mortar (the leaving of which was not unusual in craft practice at a time when most buildings were routinely limewashed upon completion and throughout their life-time) will not present a structural or performance issue – received moisture will quickly evaporate away. Shrinkage in a much less effectively porous hydraulic mortar will always be a problem, allowing the ingress of re-

Fig. 11. Archbald Moffat House, Moffat, two years after repointing with NHL 5.0 mortar (photo by N. Copsey from Copsey 2019a).

Fig. 12. Archbald Moffat House, Moffat, two weeks after repointing with a hot mixed air lime mortar and after 12 hours of rainfall (lean-to on the right still retains NHL pointing) (photo by N. Copsey).

ceived water that will find its egress much less immediate or straightforward, leading to cumulative dampness.

In this context, the addition of relatively small volumes of air lime to a clay-bearing subsoil, was sufficient to counteract the swelling of clay particles upon wetting (and their subsequent shrinkage upon drying), enhancing the durability of their bond to the substrates as well. The addition of 10 or 20% of pure lime was the norm, not only for plasters and bedding mortars, but for solid-wall earth construction also (Vegas et al 2014), in very many cases. Sometimes more lime than this was added, depending upon the situation and purpose. At the Atlit Crusader fortress near Akko, in modern-day Israel, earth-lime mortars are found below the water-line, in excellent condition and still fit for purpose (Eli Sklar, pers. comm.), exploiting the feebly hydraulic reactions that can occur between the lime and clay components (Boynton 1980).

Experience and observation in the UK (as well as in Israel, where similar NHL mortars have been used over the same 25-year period for routine conservation and repair) has shown that most masonry buildings repointed or otherwise repaired with NHL mortars quickly become wet in their fabric, and that this wetness tends to become cumulative – very similarly, in fact, to that which occurs when sand and cement mortars are used. (Figs. 8-12). Over 20-year time spans (and frequently sooner), such mortars tend not to behave sacrificially in the presence of salts or other decay mechanisms, and the stones or bricks decay exponentially. (Figs. 13-15).

Ongoing wetness of the fabric has also promoted frost damage – at Lincoln Castle, for example, where limestone faces regularly fall off during winter months (the specifying architect, pers. comm.). The pore size distribution of NHL mortars is similar, in tests, to that of cement and sand mortars, and both mortars (Wiggins 2019), which are of similar overall porosity, are low in capillary-active pore sizes, meaning that received water is slow to be removed from the fabric, as well as being encouraged to combine with already present water molecules, to penetrate and to linger. In Israel, the low effective porosity of pointing mortars has facilitated significant decay of masonry units in the presence of salts, in the author's observation, whilst the NHL mortars remain largely intact (Figs. 13-14). A similar situation is increasingly observed in the UK (Fig. 15) – much as Smeaton observed about the use of NHLs in association with Bath stone, as long ago as 1756:

Figs. 13 and 14. Akko, Israel. Exponentially decaying calcareous sandstone after repointing with NHL pre-mixed mortar (photo by N. Copsey).

"The Bath freestone is of the pure calcareous kind, and it is remarked that when it is walled with this kind of mortar (*blue lias NHL, with high free lime content*), which is *frequently,* if not generally, used for the purpose, the joints are more permanent, and resist the weather better, than the stone itself…" (Smeaton, account of Edystone etc p115 1791)

In Israel, as in most parts of the world, including North America, per the author's understanding, only naturally feebly hydraulic limestones exist (and existed) in an accessible form – their routine use has never been and cannot be a like-for-like response to the care and repair of traditional buildings, even had NHLs been extensively used in those regions with the limestones that might deliver them hydraulicity, which they

Fig. 15. Pennine sandstone, 20 years after repointing with St Astier 3.5 mortar. Salt-induced decay of the sandstone; no sacrificial behaviour in the mortars, Studley Royal, North Yorkshire (photo by S. Baxter from Copsey 2019a and 2019c).

were not. For building above ground, NHLs may be seen as generally defective in their behaviour, character and performance and, in their low capillarity and high strength (by comparison with traditional mortars), generally incompatible with the porous construction mortars and especially incompatible with porous stone or brick, and with earth construction generally.

By contrast, in my own (and other practitioners') experience and observation, hot mixes made with pure or nearly pure; pure or feebly hydraulic quicklimes, and made to historic lime: sand proportions are efficient and economical to produce. They offer mortars of eminent workability, encouraging good and efficient workmanship. They also offer optimal water retentivity and excellent bond strength as well as a consistent, full extent of the bond. Additionally, they demand much less after-care than other forms of lime. They are tenacious and they offer appropriate durability. As long as traditional building details are respected and maintained, may can be expected to last indefinitely. The addition of small (or even large) volumes of pozzolan enhances the tenacity and speed of the initial set without compromising workability, water retentivity or other essential mortar characteristics. They offer highly effective porosity, keeping the building fabric dry and thermally efficient and reducing the need for repair or replacement of building elements.

## WORKABILITY

As is evident in innumerable historic texts (Copsey 2019b, Appendices 4, 10 & 11), workability was the standard, historically. If a mortar was workable, it was considered fit for purpose. This essential mortar property was substantially forgotten during the 20th century, as less than workable mortars – specified by individuals who did not themselves use them, their design frequently driven by abstract laboratory testing - have come to dominate building practice, encouraging the addition of chemical additives, such as air entrainment, in pursuit of a semblance of workability. These additions will often serve to eliminate the necessary capillarity.

Surprisingly, perhaps, although due, one might suggest, to the legacy of extensive research into mortars carried out by the US Bureau of Standards during the 1920s and 1930s, and to the work of Robert Boynton in the USA more recently (1964; 1980), historic understandings are perfectly expressed in the modern ASTM guidance:

"X1.5.1 *Workability* – Workability is the most important property of plastic mortar. Workable mortars can be spread easily with the trowel into the separations and crevices of the masonry unit. Workable mortar also supports the weight of the masonry units when placed and facilitates alignment. It adheres to vertical masonry surfaces and readily extrudes from the mortar joints when the mason applies pressure to bring the unit into alignment. Workability is a combination of several properties, including plasticity, consistency, cohesion, and adhesion, which have defied exact laboratory measurement. The mason can best assess workability by observing the response of the mortar to the trowel. …Good workability is essential for maximum bond with masonry units…. (p6)**"** *(*ASTM International C270-07. 2007).

This bonding characteristic is due to workability's indication of excellent water retentivity (Boynton & Gutschick 1964)).

Furthermore, C270-07 emphasises the importance of lime for the formation of durable bonds that will most effectively resist water penetration, as well as removing excess moisture that might promote frost damage. “X1.6.4 *Durability*….The coupling of mortars with certain masonry units, and design without exposure considerations, can lead to unit or mortar durability problems. It is generally conceded that masonry walls, heated on one side, will stand many years before requiring maintenance…Parapets, masonry paving, retaining walls, and other masonry exposed to freezing whilst saturated represent extreme exposures and thus require a more durable mortar. (p7)…. A wall containing [a straight Portland cement and sand mortar] would be strong but vulnerable to cracking and rain penetration….A wall containing… [a straight sand-lime mortar] would have lower strength, particularly early strength, but greater resistance to cracking and rain penetration” (ASTM International C270-07. 2007).

According the author’s perception, and feedback from the crafts who recently re-embraced the use of traditional mortars, most masons and other building crafts throughout most of history would agree with the statements above. The question has only been which kind of mortar best meets these demands. Until very recently, there was no debate or discussion about this within the crafts. It was an earth-lime or a hot mixed fat or feebly hydraulic lime mortar, amended, according to exposure, by the addition, as necessary, of pozzolanic additives to the same.

As late as 1910, in France, Champly succinctly expressed the hierarchy of building mortars: “We differentiate mortars thus: fat lime, used for raising walls, hydraulic lime for foundations, substructures, basement and works meant to be immersed. Slow (Portland) or prompt (natural) cement for underwater works or in very humid places” (p.54)

There was no obsession about strength or, indeed, with drawing real-world conclusions about practice on site from generally unrepresentative laboratory experiments. Palmer and Parsons (1934) described typical laboratory freeze-thaw tests as ‘meaningless’ in the context of real buildings and their mortars in the 1930s. In the United Kingdom, there was no standard for the compressive strength of building mortars until 1938 (Stewart 1997). Before the ascendancy of modern, thin-wall construction technology, there had been no perceived need to know – traditional mortars routinely delivered between 1 and 2 MPa and recent research strongly indicates that a typical and properly proportioned hot mixed lime mortar will reliably achieve 2 MPa after 3 months (Truschik 2018), (See Fig. 16), and a typical earth-lime mortar, 1 MPa over a similar period (Rashmi et

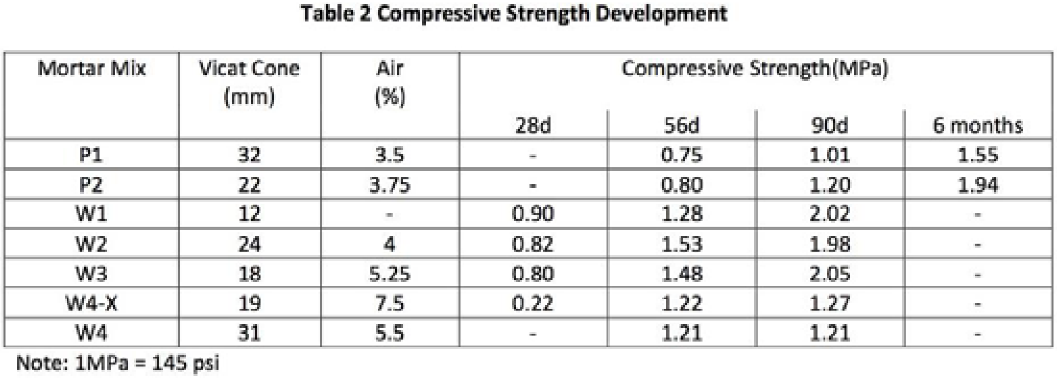

**Table 2 Compressive Strength Development**

| Mortar Mix | Vicat Cone (mm) | Air (%) | Compressive Strength(MPa) | | | |
|---|---|---|---|---|---|---|
| | | | 28d | 56d | 90d | 6 months |
| P1 | 32 | 3.5 | - | 0.75 | 1.01 | 1.55 |
| P2 | 22 | 3.75 | - | 0.80 | 1.20 | 1.94 |
| W1 | 12 | - | 0.90 | 1.28 | 2.02 | - |
| W2 | 24 | 4 | 0.82 | 1.53 | 1.98 | - |
| W3 | 18 | 5.25 | 0.80 | 1.48 | 2.05 | - |
| W4-X | 19 | 7.5 | 0.22 | 1.22 | 1.27 | - |
| W4 | 31 | 5.5 | - | 1.21 | 1.21 | - |

Note: 1MPa = 145 psi

W1 1:3 Graymont kibbled quicklime from Quebec: Nesbitt sand
W2 1:3 Graymont powdered quicklime ditto; Nesbitt sand
W3 1:3 Indiana limestone fired on site: Nesbitt sand.
P1 and P2, sand-slaked but not hot mixed.

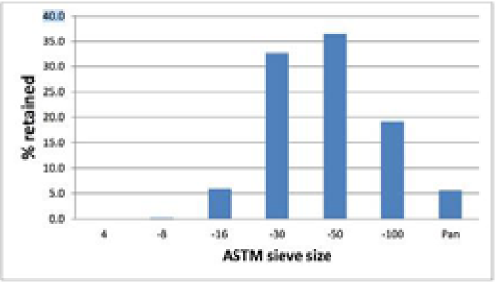

Fig. 16. Tested lime mortar samples. W1, 2 & 3 sampled whilst still hot (Truschik 2018).

al 2014). Both of these were more than sufficient to ensure the structural soundness and integrity of a traditional building of solid wall construction, and, indeed, included a generous redundancy to such mortars and structures. In 1911, Dibdin doubted the utility of laboratory testing of mortars, suggesting that experienced observation and the inability to crush a small sample of original mortar between thumb and forefinger would be sufficient to demonstrate its fitness for purpose (Dibdin 1911).

Over the last eight years, there has been a major revival in the routine use of hot mixed pure and feebly hydraulic limes (Henry 2018), as well as – to a somewhat lesser, but also growing extent, the use of earth-lime mortars - in the UK and Ireland, across Scandinavia and in parts of central Europe, as evidenced by the Gatherings of the Building Limes Forums in these regions. This revival continues to grow and to expand into North America, Australasia and, most recently, across Israel, where the Antiquities Authority has initiated seven major research streams into all aspects of traditional mortars and their use (Carmel Y, presentation to the Building Limes Forum Ireland, 4th September, 2022), whilst the conservation crafts themselves have begun to explore and to deploy like-for-like mortars for perhaps the first time. This change has been substantially driven by the crafts, assisted by some more enlightened structural engineers and other professionals, as well as by the research teams of Historic England and Historic Environment Scotland, the latter of which have commissioned and published seven Technical Papers (numbers 25 – 33) dealing with different aspects of traditional mortar preparation, use and performance. As has become clear during numerous conversations with the author in recent years, many craftspeople had become frustrated by the widespread commercially driven use of natural hydraulic lime mortars, and associated pre-mixes, which their own experience suggested were inappropriate, unpredictable and potentially damaging to traditional buildings not at all built or, until recently, repaired with more than feebly hydraulic mortars. This renewed embrace of substantially like-for-like materials – the existence and nature of which had been largely forgotten by the building trades and substantially ignored until recently by the conservation community internationally, as well as by academics and professionals working within this community – has been met with resistance from vested interest, both commercial and intellectual, but has gained a seemingly unstoppable momentum. For all of us craftspeople, it has been, and continues to be, a steep but deeply satisfying and empowering re-learning curve, after years of focus on materials that were not so much used for the purposes to which we have sought to put them – particularly lime putty (frequently improperly slaked) and natural hydraulic limes. The best teacher of all, of course, has been, and will always be, the material itself and the methodology by which it should be processed.

“In all the regions of France and Italy I have travelled to study the way of building, I questioned workers, the ones who seemed the smartest. I found that their knowledge came, from a practical side, from use and experience. There are many differences in materials; it is not possible to prescribe specific methods, because every rule requires uniform qualities and properties in the materials, which does not happen. A worker of long experience knows how to judge if the mortar is fat enough, beaten enough, if it has the right consistency - he almost never makes a mistake; he crushes and mixes the different materials until it feels right. This is why it is not enough to propose methods, we need to train workers to understand and modify them on account of the materials and buildings intended to be built. There is an infinity of things that cannot be said nor prescribed in advance. We can only indicate the general precautions to take for the most important operations, which are the methods of slaking lime and the methods of mixing it with sand and cement *(pozzolan)* to make a good mortar.” (Rondelet 1803 p.301)

It is essential to the successful performance and anticipated longevity of traditional mortars, whether used in the context of repair of existing buildings and fabric, or in the context of new build (and this, not only in the context of the inherent good sense and fitness for purpose of traditional building technology, but of its essentially sustainable nature in the context of mounting climate chaos), that historic methods of preparation and historic binder to aggregate proportions are observed. These rules and prescriptions were consistent for thousands of years, the condensed wisdom and experience of craft practice over millennia. They have been substantially departed from, in terms of preferred binders and binder to aggregate proportions, for not much more than 120 years in some parts of the world, and for fewer years than this in other parts. Indeed, in some parts of the world, less touched by the constrictive tentacles of global capitalism, it is likely that the knowledge and practice of hot mixing has never been lost.

## MORTAR PROPORTION

During the 20th century, typical mortar proportions changed significantly, lime mortars becoming leaner in binder content than at any time before. In the cement-lime mortars that dominated mid-20th century practice (a compromise between traditional mortars and modern, thin-wall building methods, as well as the growing rate of exploitation of the building crafts and the demand for rapid construction (Searle 1935, Powell 1980), after the realisation that cement and sand mortars led to leaky building fabric and to the accelerated decay of masonry units) the typical binder to aggregate proportion was 1:3. The binder might comprise 1 part Portland cement to 3 parts air lime (which might be industrially hydrated air lime or, if an especially workable version was demanded, lime putty or quicklime) to 12 parts aggregate. It might be 1:2:9 or, for especially exposed situations, 1:1:6. (Mitchell 1947). Common to all of these (and many other local variations) was a 1:3 binder to aggregate proportion. In this case, this reflected the increased power of Portland cement, as well as a saving in cost. In the observation of the author and as has been researched by Yotam Carmel and Eli Sklar, conservators, the majority of buildings of Tel Aviv were built with such mortars, as were very many brick and stone buildings across the UK and North America. The vast majority remain in a sound and healthy condition, although this can quickly unravel when such fabric is repaired with sand and cement or, indeed, NHL mortars. A lime rich cement-lime mortar offered a good and durable bond, as well as good functional performance and such mortars tend to behave sacrificially when required. The free lime content of even a 1:1:6 exceeds that of most currently available NHLs, many of which also exhibit tri-calcium silicate (alite) content, unlike historic NHLs, which were burned to deliver only belite into their composition (Davy 1802, Eckel 1922, Figueiredo 2018).

The 'Lime Revival', which originated in Sweden (Holmstrom 1996) and very soon afterwards began in the UK, continued this 1:3 proportion, typically using lime putty, a significant volume of which was water, not lime, potentially increasing the already unprecedented leanness of such mortars dramatically, unless this was accounted for in the gauging (which it frequently was not). Around 30% of the volume of even a properly slaked, dense lime putty, will be water, not lime. (Boynton 1980). The failure in situ of many (although not all) lime-lean lime putties across the UK in the early years of the 'Lime Revival' unquestionably led to the overly eager and unresearched embrace of NHLs in the UK, following the clear encouragement of its use by English Heritage after 1997 (Ashurst 1997). NHLs, too, were mixed at 1:3, with little attention paid to the variable bulk density of these materials between and within brands (Figueiredo 2018), or to traditional mixing proportions for such binders.

In both cases, such mortars, whether NHL or lime putty, were mixed at a significantly lower lime content than their historic equivalents, when such were used, and most certainly with at least half the lime content of the leanest hot mixed lime mortar in the past.

If a traditional, hot mixed lime mortar as lean as 1 part lime to 3 parts aggregate exists, it has yet to be discovered and analysed. The leanest ratio at which such mortars were mixed, as evidenced by innumerable mortar analyses across the world, (Revie, material scientist, pers. comm. and example mortar analyses Revie 2019b) and of mortars from every period, was 1 part quicklime to 3 parts aggregate, when fat limes were used. A pure or nearly pure quicklime will typically at least double in volume during slaking, delivering a binder to aggregate proportion of at least 2 parts lime to 3 parts aggregate, although some of this lime content will be in the form of residual lumps, and be aggregate, not binder. A ratio of 1 part lime to 1 part aggregate (made by mixing 1 part quicklime with 2 parts aggregate) is as commonly found. Many lime mortars historically were even richer in lime than this. Typical lime pointing over earth-lime building mortars in North Yorkshire were hot mixed but were 2 parts lime to 1 part aggregate (in this case, finely sieved limestone aggregate) ('Stonehouse' mortar analysis in Revie 2019b) (Fig. 17). Such mortars have been shown to have lasted 400 years or more. In 18th century London, bricklaying mortars might have been hot mixed at 2 parts quicklime to 1 part sand, delivering a mortar that was 4 parts lime to 1 part sand (Langley 1750). It was in response to such apparent profligacy with the most expensive ingredient (the lime), that Charles Pasley was prompted, in 1826, to set parameters on the essential lime to aggregate proportion (Pasley 1826). He concluded that 1 part quicklime to 3 parts sand was the most sand that might be carried without compromising either workability or performance, and that the most lime-rich mortar that might be generally required was made with 1 part quicklime to 2 parts sand. He considered any more lime than this to be wasteful (he was a military engineer keen to control Government expenditure) and a reflection of the desire of the crafts for the stickiest, most cohesive and adhesive mortar they could get. That said, the most commonly found lime to aggregate proportions on analysis, from the Roman period onwards, has been 2:3 or 1:1.

Fig. 17. Dry hot mix pointed building, "Stonehouse", Thornton-le-Dale (subject of a referenced mortar analysis by Revie) (photo by N. Copsey).

NHLs, when used, were also made from quicklime (at least until 1896, when Lafarge in France began to produce slaked, dry hydrated NHL lime (Gillmore 1871)). These expanded less on slaking, the less so, the greater their hydraulicity, and were mixed at 1:2 or 1:1, quicklime to aggregate.

When already slaked lime was used or specified, this was never leaner than 1:2 (Vicat 1837, Pasley1826), except in the case of concretes, when the quicklime to aggregate proportion could be as lean as 1:7 (when NHL was initially displaced as a binder for concrete, the proportion was often 1: 8). (McKay 1938; Mitchel 1912)

A further error of the 'Lime Revival' was to condemn the use of dry hydrated lime, a form of slaked lime that had a much longer historically pedigree as a binder than had lime putty. Lime sieves (indicating dry slaking of quicklime) appear routinely in building accounts in the UK in all periods (Copsey 2019b). Dry slaking allowed for the screening of mortars after mixing, removing larger lumps of unslaked lime, as well as of aggregate. It was less cohesive and adhesive than a wet-slaked mortar, but still more adhesive than most modern mortars. It tended to promote less initial shrinkage on application as a plaster, and tended to be richer in residual lime lumps than a wet slaked equivalent, which may or may not be significant.

## SLAKING

The temperature of the slake is the single most important aspect of the hot mix method, as it is of all kinds of lime production. Simply put, the temperature of the slake needs to reach at least 100 °C (Hassibi 2011). This temperature inevitably produces steam and, in most hot mixing methods, this steam will slake at least some of the lime, in tandem with liquid water. The significance and effect of this is currently being researched at Northumbria University (Pesce 2021). In the commercial lime industry, dry hydrated lime is typically produced by the steam slaking of powdered quicklime, and a slaking temperature of between 100 and 120 °C is demanded (Lafarge-Tarmac, Buxton, pers. comm.).

Historically, it is said repeatedly, by numerous authors, that lime which slakes the fastest and the hottest is the best. Moxon (1703) and others stress the need to 'keep the steam' in, as well as the, perhaps more mystical, 'spirit of the lime'. Both requirements indicate that temperature and steam were essential parts of the equation. The purer a quicklime is, the more quickly will its slake begin, on receipt of the necessary water, and the more rapidly will its slake complete.

According to the author's experience, and the consensus of numerous texts (Copsey 2019b, Appendix 11), if too much slaking water was used, the lime might be 'drowned', which is to say, that it would not reach a temperature during the slake of 100 °C or more. Whilst the quicklime would typically turn to a paste even so, it would not acquire the necessary tenacity in use; it might be weak, particularly in its bonds, both within the mortar and on building substrates. In the case of a limewash, it might disaggregate on contact, dusting off to the touch. In the author's experience, hot limewash, slaked at the necessary temperature, does not dust off, and may be applied at a greater thickness without crazing and cracking than one made from diluted lime putty, especially if this lime putty has itself been drowned during slaking. The superior behaviour of a limewash made from quicklime, in terms of thicker coats, minimal crazing after application, better bond and greater durability (Koeberle 2019), comes, to some extent, from typically having been applied whilst still hot, but also from the simple fact of having been slaked at the correct minimum temperature. Experiments by the author would indicate that the advantageous properties remain, even after a hot limewash has cooled, indicating that the advantage is delivered by the slaking method itself, as is the tenacity of a properly hot mixed mortar. "Aggregated limewashes", more usually described as sheltercoats are similarly superior when made from quicklime and applied whilst still hot (Figs. 18a and 18b).

Historically, writers about lime stressed the need to slake the quicklime with 'just sufficient' water. Once slaking was complete, then more water could be added according to the intended purpose, but the 'short-cut' of adding all the necessary water at the onset was condemned. It was an 'iron rule' that water should always be added to the quicklime, and that quicklime should not be added to water. The 'Lime Revival' inverted this rule, although by the mid-20th century, the addition of quicklime to water had become the norm, perhaps in response to the high reactivity of 'scientifically' burned quicklime. The slaking water to quicklime ratio, however, remained the same (British Standard Code of Practice 1951).

Figs. 18a. and 18b. Hot lime sheltercoat to a 12th century doorway (with recycled Roman columns), St Michael's Church, Foston, near York (photos by N. Copsey from Copsey 2019a).

How much water is 'just sufficient'? It was not until the late 19th century that precise volumes of slaking water were explicitly articulated (Richardson 1897). This knowledge was very much held by the crafts before then, consistent with Campbell's assertion in 1747 (Campbell 1747) that central to the stonemason's craft was that he was 'the Judge of all Kind of Cements, and the Secret of preparing them for Use' (The London Tradesman, 158), a situation that had been increasingly eroded during the second half of the 19th century in the UK and

North America, mortar design being increasingly co-opted by architects, surveyors or, indeed, others, unfamiliar with using the materials themselves (Powell 1980), (Clarke L 2012).

Limestone fired in a kiln will lose between 30 – 40% of its weight during firing. This equates to an enforced and unnatural loss of 'molecular' water and carbon dioxide. Quicklime desperately wants back the water it has artificially lost, so much so that it will begin to slake in moist air; it will re-absorb carbon dioxide much more slowly after application. It was a common demand historically that quicklime should be slaked as soon as possible after burning.

If a dry-slaked lime is required, then the quicklime will require around 1/3 of its weight in water to slake (Richardson 1897). This typically equates to an equal volume of water to that of the lime. If the intention is to make a mortar immediately, and to 'wet-slake,' then between 2 and 3 volumes of water to the volume of the quicklime will be added. Any more than this will suppress the temperature of the slake (as will the addition of more than 3 parts of sand to a powdered quicklime, many modern pre-mixed hot mixes being mixed at 1 part quicklime to 5 or 6 parts sand, also suppressing temperature, when the powdered quicklime is mixed directly with this sand before slaking). If boiling water is used to slake the quicklime, then greater volumes of slaking water will have no ill-effect (Miller 1960). If too little water is added in the first instance, then the temperature of the slake may quickly exceed 400 or 500 °C, it will be 'burned', in traditional parlance. In and of itself, this is not as problematic as it may sound, except that the addition of the necessary water (usually cold water) to an only partially slaked quicklime will 'chill' it. The consequence of burning, followed by chilling, will be the arresting of any further slaking and the delivery of a 'short' and lime-lean mortar. Generally, however, it is important to note that the residual lime lumps in traditional mortars are not a consequence of this.

## SLAKING AND MIXING METHODS

In most parts of the world, the most common method, using lump quicklime, was to form a 'basin' with the sand or other aggregate into which the lump lime was placed. This was the same for both dry and wet slaking. Necessary volumes of slaking water were then poured onto the quicklime all in one go. The slaking quicklime was immediately banked over with sand, to retain heat and steam. As the quicklime expanded in volume, the sand covering would crack and open up. These cracks would be closed down, again to retain as much heat as possible. The slaking of a pure quicklime takes as little as two minutes; a feebly hydraulic (or old) quicklime might take five or six minutes (Miller 1960). This progress might be considered substantially complete once expansion and cracking of the sand cover ceases. At this point, the sand and the hot lime would be mixed and beaten together to form a mortar. (Figs. 19-22). More water might be required, although the more vigorous the beating, the less this might be necessary to achieve a similar workability, and the less water that is added at this stage, the lesser might be initial shrinkage in use. Beating of a freshly made mortar was a common requirement historically. Extensive beating will certainly improve the workability of an initially dry-slaked mortar. In all parts of the world, this method was called the 'ordinary' or the 'common' method, indicating its ubiquity (Copsey 2019b Appendix 11) Its primary practical purpose was to reduce lump quicklime to a size that might be readily incorporated with the sand.

This early incorporation of the hot lime with the sand or other aggregate may also be considered essential to hot mixing. Quicklime slaked but left to cool before mixing with the sand will offer a mortar of significantly different character, one that would be somewhat less workable, although extensive beating would improve this, whilst requiring more labour.

Lump quicklime might alternatively be slaked alone in a box or a pit, with similar slaking water volumes, before either sieving or, more commonly, being slaked to a thick paste, before being promptly mixed with sand in the same or another box or pit.

Dry hydrated lime might alternatively be slaked alone, by immersion in water whilst inside a basket, held beneath the water until it has absorbed all of the water it can, before being tipped out into a pile to slake (or into a barrel, as Vicat (1856) describes, to 'cook') and to fall to a powder. This might be sieved before mixing with sand, although it might be mixed without sieving, or it

Figs. 19 - 22. The Ordinary Method (all photos by N. Copsey, photos left and top right from Copsey 2019a).

might be used on its own. In a variation on this, the quicklime might be laid out on the ground and water poured from a watering can over the whole, after which it, too, would fall to a powder.

All of these methods guaranteed the minimum necessary temperature of the slake and, therefore, maximised the potential of the material.

One possible reason for the common distrust of lime putty was the suspicion that too much slaking water would be used. Vicat (1837) and other engineers expressed this anxiety. However, the procedure for making lime putty in the past was not so different from the procedures set out above. Lump lime would be given between two or three volumes of water in one tank or basin, the slake allowed to substantially complete, before more water might be added to allow the lime putty to pass from an upper tank into a lower tank. (Biston 1828). Between the two tanks there would be a grill to remove larger unslaked lime, or lumps of under- or over-burned quicklime. Lime putty could be stored in the lower tank (or in a pit in the ground, as Vitruvius (2015) De L'Orme (1567) and others describe), or it could be immediately mixed with sand, in which case, this method would be simply another hot mixing method.

De L'Orme (1567), and others describe the slaking of lime to a thick paste in a pit, beneath a covering of sand, typically for storage. The sand was laid on to preserve the lime in an 'unctuous' condition (De L'Orme 1567) after water had been poured through the sand covering to effect its slake. The sand may, or may not, have been mixed with the lime at a later time. The lime may have been used on its own for plastering or it may have been mixed with sand to form a mortar. Ware (1756) describes a similar procedure in England. Hassenfratz (1825) also makes clear that the sand and the lime were kept separate and were not necessarily subsequently mixed together, indicating that woven wattle hurdles separated the two. The sand (or earth) was to keep the lime from drying out and to maintain it in a fresh, cohesive and adhesive state.

A common variation on the ordinary method as described above, and which was common, perhaps more so in Central Europe and the Balkans in more recent history (Koeberle 2019), would be to lay the lump quicklime onto a bed of some of the sand to be mixed with it. The quicklime would then itself be covered with the remainder of the aggregate. Slaking water, in similar proportions to those above, would then be poured – or drizzled – through the sand covering to unite with and slake the quicklime, either to a dry hydrate or to a wetter paste, or, indeed, to a mixture of the two. A heap of material treated in this way could then be cut away incrementally to be mixed together in an accurate lime to aggregate proportion. This (as above methods) might only be defined as hot mixing if the sand and slaked lime are mixed together immediately. If the lime is left in situ to cool before mixing, then the method should properly be termed 'sand-slaking' and would deliver a mortar of somewhat different character. The 'ordinary method' may be reproduced in modern pan mixers, quicklime is evenly spread over a bed of part of the aggregate within a stationary mixer. Necessary volumes of water are then be poured over the quicklime and the mixer covered to retain steam. Once slaking is substantially complete, the mixer is set in motion and the remainder of the aggregate added, more water is added as mixing proceeds, according to the intended purpose.

Although frequently seen today as being a 'modern' and somehow 'inauthentic' form of quicklime, powdered or pulverised quicklime was used historically. When roller mills were used, which they were from an early period, built into the ground before free-standing machines became the norm, the lump quicklime would be thrown into the mixer and crushed, before slaking water was added, followed by the sand or other aggregate (Wright 1845). Performed manually, pulverisation inevitably involved additional labour, but was considered to deliver the 'strongest' mortar of all (Dossie 1771), as well as the most adhesive and cohesive (De la Faye 1777). The perception of greater strength was probably due to the absence of residual lime lumps; the total volume of the quicklime being binder after its slaking, although Dossie's assertion might usefully be tested. Dossie indicates that powdered quicklime should be mixed with the aggregate before the incremental addition of water, the mix being kneaded as each increment of slaking water is added. He suggests the mixing of small batches, with a trowel, and indicates that this should be done whilst still hot. Powdered quicklime is currently the most commonly used form of quicklime today and has been the most commonly used form during the recent revival in hot mixing. It being the most readily available in the UK has been the primary reason for this, although for those new to the material, its method of preparation – whether mixed by shovels, or mechanically – is little different from the mixing of dry hydrated binders of all kinds, although it remains essential to observe the initial slaking water to quicklime volumes. The use of powdered quicklime avoids any risk of late-slaking, removing anxiety about hot use, especially for plastering. Elsewhere in Europe and across the world, although they are scarce, small-scale traditional lime burners remain and traditional lump lime is more readily available, in the author's observation.

The initial pulverisation of natural hydraulic limes, when these were used, was common in the UK during the late 18th and 19th centuries. This accelerated what could otherwise be a very slow slake (sometimes up to 12 hours), as did the use of hot slaking water. Pasley (1826) states that whilst such powdering of the quicklime was routine for Blue Lias NHL (used for concretes and for some water works), it was also, at that time, becoming increasingly common for fat quicklimes as well. It is possible, if not likely, that many of the mortars interpreted as having been made with lime putty – due to the general absence of residual lime lumps – were, in fact made with powdered quicklime. For all that, these still represent a relatively small minority of analysed mortars. (HES Technical Paper 32). Plaster mortars can be similarly interpreted, where a hot mixed plaster has been laid down to allow for late slaking to occur, and knocked up immediately before application. That said, the author has seen very few historic plasters the mortars of which were not hot mixed, and which do not display a multitude of residual lime inclusions; lime putty being reserved for the fine finish coats

Fig 23. Hot limewashed exterior, reinstating original coating and pigment (iron sulphate). Bishop Burton Old Hall. Limewash offers moisture buffering and capillary activity across the whole surface area of building elevations (photo by N. Copsey).

over these hot mixed backing coats, whether these coats were of earth-lime or of lime and sand.

Earth-lime mortars would have been generally prepared using the ordinary method. Although the quicklime proportion tended to be less, it remained important that the lime was slaked at the necessary temperature prior to mixing with the clay-bearing subsoil or loam.

Limewashes (and grouts) would have been prepared similarly to lime putty, as described above, the former diluted somewhat after initial slaking and poured through a sieve to remove unslaked lumps prior to application whilst still hot. Such sieving was also common for the making of lime putty for bricklaying (when the joints were very fine); the lime putty pressed through a hair sieve and used as a bedding mortar whilst still hot (Langley 1750, Pasley 1826). This avoided the need to lay the lime putty down and allowed for hot use, when the lime putty remained 'flowing' and very straightforward to use. Hot limewash takes similar advantage of the easy flow of lime when it remains hot, and before it thickens on cooling (See Fig. 23).

## CONCLUSIONS

Pure and nearly pure lime mortars and earth-lime mortars were essential elements – perhaps the *most* essential elements – of building technology and construction over many thousands of years. As a system, traditional building technology was relatively simple and straightforward, generally sustainable and made good and sensible use of locally available natural materials, and these were often processed and altered, typically by the use of fire. Mortars were critical to the success and longevity of such systems and were generally porous, as were most other building materials. Most were built by practical men and women drawing upon centuries and more of learning and experience. That hot mixed lime and earth-lime mortars were the ubiquitous mortars of construction for so long as humanity built structures at all is, quite simply, because they were the fittest materials for purpose and delivered dwellings and other structures that were healthy in themselves and healthy for those who occupied them. As modern craftspeople around the world are increasingly coming to understand, they remain the mortars most fit for purpose, for new builds, so long as the buildings themselves are designed within similar parameters and to similar principles as traditionally, and for the conservation and repair of existing structures applying rational principles of 'like-for like' and compatibility.

*"The technical evidence does not point to short cuts in the achievement of good building; it points consistently to the discovery by scientific means of the rationale of established building traditions, which should be altered only with the full knowledge of the consequences…"* (RIBA 1946).

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## REZIME

## RUDIMENTI TRADICIONALNE PRIPREME I UPOTREBE MALTERA

**KLJUČNE REČI: ŽIVI KREČ, KREČNI MALTER, BLATNO-KREČNI MALTER, VRUĆI POSTUPAK, GAŠENJE KREČA, PUCOLANI, PROPORCIJE MALTERA.**

Zaključak koji se može dobiti iz zanatskog iskustva o kome svedoči mnoštvo postojećih konstrukcija, kao i međusobno doslednih tekstova o kreču i malteru pisanih tokom poslednjih 2.000 godina, a najmanje do 1925. godine, iz obilja arhiviranih građevinskih izveštaja i specifikacija tokom sličnog perioda, kao i iz savremene nauke o materijalima, je taj da je živi kreč sa visokim sadržajem kalcijuma bio osnova za većinu tradicionalnih maltera. Specifični agregati ovih maltera mogu varirati u zavisnosti od dostupnosti i geologije, kao i od predviđene namene, a metodologija i razumevanje načina njihove pripreme i upotrebe su bili izuzetno postojani od najmanje 10.000 pre nove ere, da bi bili prekinuti i obezvređeni tokom XX veka. U to vreme tradicionalna zanatska praksa i znanje postaju sve više izazvani i podriveni unutar građevinske industrije, a uspostavlja se nova i prethodno nepostojeća građevinska tehnologija, omogućena razvojem sve više globalizovanog industrijskog kapitalizma i uz promenljivu ravnotežu klasnih snaga unutar industrije. Ovo tradicionalno znanje i razumevanje je dodatno umanjeno i kompromitovano – iako sa najboljom namerom – greškama, nesporazumima i kognitivnim predrasudama u okviru različitih pokreta za ponovno uspostavljanje upotrebe krečnih maltera za očuvanje i sanaciju starih građevina, a nakon „preporoda kreča“ u Skandinaviji i Velikoj Britaniji posle 1975. godine. Tradicionalni malteri pripremljeni tradicionalnim metodama gašenja i uz tradicionalne proporcije, izuzetno su pogodni za ovu namenu. Optimalno su obradivi u upotrebi, nude odgovarajuću trajnu vezu i odličnu efektivnu poroznost, dok su slični i kompatibilni sa postojećim tkivom građevine, nudeći održivije opcije ne samo za sanaciju ovog tkiva, već i za nove konstrukcije. Iako nam ostaje još mnogo istraživanja o nijansama i detaljima tradicionalnih maltera, mora se reći da znamo da oni “funkcionišu”, kao što su to znali i u prošlosti, sve dok poštujemo i primenjujemo znanje i razumevanje o njima - onih koji su ovde bili pre nas, i sve dok priznajemo, pre svega, da stojimo na ramenima divova, od kojih su većina poznati samo po građevinama i strukturama koje su stvorili.

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