What is hot mixing? The Importance of the Slake.

Whilst not all traditional mortars were hot mixed, although very many were, the methods by which such mortars were made, or manipulated, was generally somewhat different to that which has been common during the 'lime revival', as well as to many of the methods that evolved during the 20thC. Most of these differences attach to the method of slaking and to the binder to aggregate proportions. Hot mixing was simply the most effective and efficient way of both slaking the quicklime at the necessary temperature at the same time as making a workable mortar for either immediate or prompt use, whilst at the same time, it would appear, producing mortars of optimum workability and appropriate durability and structural performance.

Hot mixing is a method by which lime and sand or other aggregates are incorporated to produce a workable mortar for building purposes. It is a method, not a product, and all manner of mortars for all sorts of purposes may be made by hot mixing. Mortars might be non-hydraulic, made with pure or very nearly pure high calcium lime; they might be feebly hydraulic (called semi-hydraulic in the 20thC), made with lime produced from a limestone with less than 5 or 6% clay content or else – if a 'lean' or 'meagre' lime with 20 or even 30% clay content most of which will remain insoluble and not combine with the lime to form dicalcium silicate or aluminate; they might be moderately or eminently hydraulic, made with a limestone with a clay content of 10% or more, most of which is soluble and amenable to combination with lime. All such limes will slake in the presence of water – high calcium and feebly hydraulic limes will slake vigorously and rapidly either immediately or very soon after the addition of water, with a great deal of heat; lean and more than feebly hydraulic limes will slake more slowly and the heat generated will diminish somewhat the more hydraulic the lime. Slaking will only occur when free lime (free quicklime, calcium oxide) remains – natural cement, first discovered in 1796, is an eminently hydraulic lime but no free lime survives the burning process and must be mechanically ground to a very fine powder before water is added to initiate the set. So long as 25% free lime remains, the slaking of this will be normally sufficient to break the lump lime to a fine powder by slaking with water, avoiding the necessity for grinding (Eckel 1922).

The temperature at which slaking occurs is critical to the performance of the lime, whether it is used alone or as the primary binder of a mortar. In order to maximise the porosity and the surface area of the resultant lime, the temperature of the slake should exceed 100 degrees Centigrade. If too much water is added to the lime, this temperature may not be attained and the lime will be lacking in binding qualities (Vicat, Wright, others). For this reason, running lime to 'putty' or to a thin paste during slaking was generally avoided and counselled against in the past. Lime would be slaked initially either to a dry hydrate or to a thick, dough-like paste to be subsequently mixed with the sand or other aggregate. This mixing might be done immediately the slake was complete, taking advantage of the 'flowability' of hot lime, or once the slaked lime had cooled. Alternatively, and very commonly in craft practice, the lime might be pulverised before slaking and mixed with the sand before any water other than that already in the sand was added and slaking would proceed with the sand and slaking lime in the most intimate of association. This latter method was generally considered to deliver a 'stronger', more tenacious mortar which was eminently workable, cohesive and adhesive. Similar properties might be enjoyed when the just slaked and still partially slaking lime is mixed with the sand, the initial slake having broken down the lump lime sufficiently to facilitate this. Once mortar machines were introduced on a wide scale, and if these included rollers, the lump lime was crushed in these before the addition of aggregate and water and the slake proceeded with all ingredients together.
Quicklime generally arrived on site as lump. In the burning of the limestone, the stone was broken into lumps before loading into the kiln. These were typically around the size of a fist, but might be larger if the limestone was particularly pure, or sometimes smaller. The quicklime would emerge from the kiln very similar in appearance but some 40% lighter and extremely porous, all water and carbon dioxide ('carbonic acid' in old texts) having been

driven off. This typically occurred at around 900 – 1000 degrees C, the same temperature at which bricks were fired traditionally; the same temperature at which volcanic ash (a traditional pozzolan) is thrown into the air; the sort of temperature at which most fires would burn, producing ash from either coal or wood. Quicklime fresh from the kiln is desperate for the water it has lost – it will begin to slake in moist air – so that the use of quicklime 'fresh from the kiln' is a common prescription historically, and quicklime not slaked immediately must be stored in air-tight containers or packaging to avoid its premature slaking and degradation in quality. This is much easier today than it was in the past, when lime would be packaged for transport in barrels or sacks, or even transported loose on barges or carts. It was a common complaint in London that quicklime brought from Kent by river would be tipped on the quays and left for days before onward transport, promoting partial slaking or material that had already begun to slake in transit (Ref Davy 1839?). When some of the lime was already slaked, the masons on site would necessarily and inevitably add more lime to the mortar to achieve the necessary consistency and 'feel', explaining to some extent the lime richness of some traditional mortars on analysis, although masons and bricklayers are routinely accused in old texts of using too much lime if left to their own devices, in pursuit of workability and adhesiveness. It was not until the later 18thC and certainly into the 19thC that the 'most efficient' quicklime to sand proportions were established – which is to say, the maximum levels of sand (the cheaper item) that may be added to one part of quicklime without compromising either performance or workability was arrived at. This was 1 part of quicklime to either 2 or 3 sand, depending upon the purity of the lime. For more hydraulic limes, this proportion was 1:2 or 1:1 depending upon hydraulicity, except for concretes (which became common in the UK from the beginning of the 19thC for foundations), when the proportion was more typically 1:7). If the lime was already slaked when mixed, the proportion for the fatter limes was 1:2, for more hydraulic limes, 1:2 or 1:1.
Pure and feebly hydraulic quicklime will typically just more than double in volume as it slakes. If too much water is added in the first instance, this increase might be seen to be 3 times or even more, but the increase is not in lime, but water (Richardson 1897).

In order to reduce lump lime to a form that might be readily mixed with sand, the lumps had first to be broken down. If the lime was pure or nearly pure – as the limes preferred by craftspeople usually were (Smeaton, Hitchcock, Hassenfratz, Vicat, Schmidt, other), the most labour-efficient method of doing this was simply to add water in sufficient quantity to effect the slake.

The addition of one-third the weight of the lime in water is sufficient to slake a typical lime to a dry powder or lime hydrate. Somewhat more was usually added, but the lime would seem to be a dry hydrate. Quicklime might be hydrated on its own in a mortar box, or on a flat ground, before being sieved, to remove under-burned or over-burned lumps. It might then be mixed with sand or other aggregate immediately, whilst still very hot, or it might be formed into heaps or tipped into barrels to 'cook' and to allow for late-slaking, before being mixed with the sand when cold. The former would be a 'hot-mixing' method; the latter is not. Cold-mixed hydrate tends to deliver a 'shorter', less cohesive and less adhesive mortar. Throughout most of history, it is commonly asserted that lime and lime mortar should be used promptly, usually within a week, lest it was for plastering. Even the latter, however, was typically used within a few weeks, and material science and observation would indicate that in much of the UK, first and second plaster coats were applied either hot or very soon after hot mixing. The quality of the mortar was considered likely to diminish incrementally, once made, though there were always those who asserted the opposite – that lime mortar improved incrementally for being kept. On site, the impulse will always have been to make and use the mortar, where possible, and the clear practical advantages of hot mixing and of using mortars whilst still hot will have promoted such habits amongst most craftsmen. In reality, the means of storing slaked lime and mortar were inefficient in the past. Today, plastic tubs and plastic bags allow for the storage of not only slaked lime and pre-mixed mortars, but of quicklime as well, significantly reducing the hazard of premature carbonation as well as of premature air-slaking.

Slaking to a dry hydrate was an efficient method of ensuring the minimum necessary temperature of the slake, as well as allowing for the easy sieving of the lime, to remove larger unslaked lumps, some of which might later slake in the work. It was common – 'lime sieves' appear in building accounts from the medieval period onwards. The extending use of mortar mills in the 19thC made them less necessary, although their routine use in plastering continued unabated. Until the later 19thC, plasterers, if they did not hot mix their base-coats, would first slake their lime to a hydrate, achieving the necessary temperature in the slake, before sieving and then adding water to produce a 'lime paste' that could be readily mixed with sand. The quicklime might be slaked by dipping it into water in open-weave baskets for a short period of time (variable according to the nature of the quicklime) before tipping this onto a platform to slake to a powder, which might then be sieved and mixed hot with sand, or set aside for later mixing; it might be similarly dipped and then tipped into a barrel to slake, cook and be stored (De la Faye 1777, and others). Alternatively, the quicklime might be spread upon a flat ground and sprinkled with water sufficient to effect the slake, before being sieved and mixed or set aside in heaps, covered with a tarpaulin or, more typically, with sand, both to retain heat and to mitigate the onset of carbonation before being mixed with sand later, though usually within a week (Treussart 1842, others). Lump lime might otherwise and more commonly be slaked in a ring of the sand that would form the mortar – water would be added to the lime and the sand banked over it to retain the heat of the slake. If the lime was hydraulic and slow-slaking, this might be left for many hours, typically 12 hours, before being mixed – usually cold by this time – with the sand and either used immediately or banked. If the quicklime was pure or feebly hydraulic, the hydrate and typically dried sand would be mixed together promptly and thrown through an angled screen to remove the larger lumps (if for finer joints, such as brickwork) before mixing to a hot mortar, or simply mixed through to a hot mortar. This would then be used hot, or set aside as coarse stuff. These two latter methods were undoubtedly the most common and persisted well into the 20thC, particularly for hydraulic limes, being used in the air by this time. The more aggressively hydraulic limes used in the UK, as late as the 1960s and 1970s, possessed a significantly higher free lime content than any available today, so that slaking might be slower than for the pure limes, but never excessively so. The dry-slaking method applied to these ensured that the necessary temperature of the slake was achieved, which might not always be the case with an hydraulic lime slaked by the 'wet' hot mixing method (see below), particularly if too much water was added in the first instance, a common complaint made against masons by some engineers.

Putty for finish coats, or for gauged brickwork or the finest ashlar, was similarly made, although with a slight excess of water added in the first instance, before being diluted once the slake was complete, and pushed or poured through a 'hair sieve' and, if not used whilst still hot – which it often was (Langley, Pasley, others) - left to thicken for several weeks before use, either on its own, with hair added, or with a small proportion of very fine sand or marble dust. On a grander scale, stepped lime troughs might be used – the lime slaked in the upper chamber with an excess of water insufficient to compromise the temperature of the slake, before dilution and running into a lower trough or basin through a grate that would remove larger unslaked lumps. The lime would then thicken in the lower basin, if for use on its own as a mortar; or sand would be promptly mixed with it whilst it remained hot to form a mortar for immediate or later use. Slaking by the addition of small volumes of water, subsequent dilution to form a dough-like paste and storage in a pit to allow for late-slaking, described by Vitruvius, was the 'Roman' method of allowing for late-slaking, or to ensure the slaking of all parts. This was for fine stucco finishes, not for building. Pliny has been oft-quoted as saying that lime slaked in this manner, and for this purpose, was required to be kept for a minimum of three years. This is a mis-translation – the time-span was actually 3 months – a period of 'curing' that crops up through time (Alberti, Millar, others) in association with lime for finish coats or other ornament. Alberti asserts that all mortars might be treated this way to advantage, implying that this was not the norm at the time

(1460), when limes were being slaked and used fresh for ordinary building. Alberti, like Palladio and numerous Palladian architects in the UK during the 18thC, insofar as they write about mortars at all (as mortar design was then still very much the domain of the masons and bricklayers at this time not the architect), repeat what they understood Vitruvius to mean, an error reproduced during the 'Lime Revival' and extended to putty lime made increasingly by 'drowning', weak in binding properties.
In France, there was a greater willingness to slake the lime on its own, to a thick paste, before mixing it immediately with the sand, or else storing it in a pit in the ground. Biston (1837?):

"Slaking by fusion, also called ordinary slaking, has to be done in impermeable basins with only the necessary quantity of water to reduce the lime to a thick mush. We will be careful to give all the water it needs in the first instance, only coming back to it at the moment of the effervescence (to add more) or else, wait for it to cool and then add some more water. We will forbid in all cases, the method followed by some masons of drowning the lime in a large quantity of water, reducing it to a milky consistency before pouring it into permeable pits where it dries out and loses its qualities. When we need to keep the lime after it has been run, we will cover it with earth or sand….

With care, we will need to put the quicklime into a basin, to put a quantity such it will not spill out during slaking. We will then throw the water on the lime, wait a bit and when the bubbling begins to decrease, we will stir the gruel in such way as to be sure that all parts of the limes are dissolved. When the gruel is homogenous, it will be run through a grid opening into an earth pit to conserve the lime until it is used. It is essential to throw right into the basin all the water necessary for the slaking. It there is not enough, we will have to wait until the gruel has coolled down before adding any more water, otherwise, the lime will become lazy, will remain grainy and resistant to mixing."

More commonly, the slaking 'basin' would be formed of the sand that was to make the mortar. This was labour-saving, increasing efficiency. As described above, a ring of sand would be formed. The 'dry-slaking' method described above could also be a 'wet-slaking' method. Whilst brick-layers – particularly in London – would seem to have preferred the former, stonemasons seem to have preferred the latter, which delivers a particularly cohesive and adhesive mortar, which bears the weight of a laid stone without significant squeeze – it 'holds up', as well as 'locking-in' the water, making it reluctant to disassociate from the mortar and run out, staining the wall, although all hot mixed, lime rich air or feebly hydraulic mortars display excellent water retentivity. Workability and water retentivity diminish the more hydraulic the lime used – one of the reasons that builders in the past, and for so long as they designed the mortars, preferred to use fat and feebly hydraulic limes for building in the air, resisting until at least the end of the 19thC the growing consensus among engineers and other professionals, that hydraulic, including eminently hydraulic limes should be used in their stead, as being 'more durable' and better guarantors of the longevity of their creations. Modern analysis would indicate that the builders – the masons, bricklayers and plasterers – were correct; the pursuers of hardness much less so, though, of course, the understanding of conservation are inevitably a response to the softer materials used in the past and are not as much shared by modern construction technology, though perhaps they should be.

'Wet-slaking' was generally – although not necessarily – performed - like 'dry-slaking' – within a ring of the sand or aggregate with which the mortar would be made, and in the proportion deemed necessary. This seems to have been the most common method in North America, a melting pot of numerous craft traditions from within Europe and elsewhere, though, of course, dry-slaking also went on. The procedure was the same, but with an excess of water added in the first instance, typically in one go, but otherwise in a steady initial flow from a rosed watering can. The excess of water was not significant – being just enough to slake the lime to a thick paste. A large excess, whilst it would make the mortar easier to mix, it was generally understood, risked 'drowning' the lime, reducing the temperature too much, and compromising binding qualities. As late as the 1951 British Standard code of practice, when fat and feebly hydraulic limes were routinely run to putty and the quicklime was being thrown into water, rather than water initially added to the quicklime, in contradistinction to historic practice, even in the 19thC, it was prescribed that twice the volume of the lump lime in water be used in the first instance the initiate the slake – not so much of an excess, therefore, as to risk drowning the lime and reflecting the traditional understanding that typically twice the volume of water be added to the quicklime within its ring of sand to slake it to a thick paste. Richardson (1897) qualifies this by saying that 2 ½ times the volume of the lime in water would guarantee the slaking of most of the quicklime without compromising performance. Slaking would commence immediately, or almost so, with a fresh high calcium or feebly hydraulic lime with a high free lime content. Sand would be banked over this and as the sand covering cracked with the expansion of the lime, these would be closed, to retain heat. Heat retention was considered essential. Some authors go so far as to say that slaking should not be done on a windy day, or in cold weather (lest hot water be used), to be sure that necessary temperatures are achieved. On site, more quicklime might be added on a cold winter's day, to lift the temperature of the slake somewhat.

However, and in contrast to some modern myths about hot mixing, if the water necessary to effect the slake, or just a little more water than this, is added, the temperature of the slake will be around 100 degrees C, sometimes 120 degrees C. In modern hydration plants, 120 degrees C is the sought-after temperature (pers comm Calbux guy). If too little water is added in the first instance, temperatures may rise to 300 or 400 degrees C, 'burning' the lime. Van Der Kloes (1914), states that the temperature of the slake should be as 'high as possible' and the influence of higher than traditional temperatures upon the performance of the material would be a worthwhile area of study. In the context of hot-mixing, however, the consequence of burning the lime is clear and is oft-mentioned historically – a lime that is 'burned' will be 'chilled' the moment the additional (almost inevitably) cold water necessary to complete the slake is added. This arrests the slake, leaving a multitude of small, unslaked lumps which will never mix in thereafter, leaving the mortar 'short' and wanting in lime binder. These are *not* the lumps found typically in old hot mixed mortars, it should be said, which are partially slaked under-burned or over-burned lumps, often containing the unburnt core of the original limestone (see Chapter Bill on the analysis and identification of hot mixed mortars).

Once the slake is complete (a matter of few minutes, typically) and whilst the lime (and sand) remain very hot, the lime in a state of thick paste, the sand and the lime are mixed together and well-beaten to form a mortar. More water may need to be added to bring it to the required consistency, depending upon the accuracy of the first addition of water. An experienced mortar mixer, familiar with the lime and the sand of his or her locality, would quickly learn how much was 'just enough' and might add sufficient to bring the mix straight to a mortar without need for further addition. It is a common complaint, however, that the masons added too much, too soon, to make the mixing easier. This potential and reliance upon the integrity of the mixer, might be seen as the primary hazard of wet-slaking.

The 'ring-of-sand' method, whether initially to a dry or a wet slake, was the most efficient method of reducing unwieldy lump lime to a mixable form. Especially when deployed as a preliminary to hot mixing the lime and aggregate, it delivered an eminently workable and adhesive mortar. By virtue of the hot-mixing process, the essential qualities of workability, water retentivity, cohesiveness ('tenacity', as this was called in the past), and bond strength, were similar whether or not the mortar was used hot or cold. When cold, the mortar acquires a certain 'elasticity' (ideal for plastering) that it does not possess when still hot. It is also typically slower to achieve its initial set – in part because the mortar stiffens as it cools and typically demands a further addition of water to 'sweeten' it before use, increasing the amount of water that will need to evaporate and promoting shrinkage. Well-beating the coarse stuff will often bring the mortar back to suitable workability without the addition of more water, however. Used hot, the mortar has greater flow – it will press more easily into open joints, in pointing, for example. The primary advantage is that the inevitable stiffening will happen in the wall, speeding the work, whether this is in building, pointing or plastering. Modern research would indicate that hot mixed mortar used hot has a greater porosity that that used cold, but as David Wiggins's research (herein) importantly flags up, 'porosity' is not always effective porosity. A typical hot mix has an immediate air content of 4% (Ken Truschik), significantly less than an air-entrained NHL, and ultimate effective porosity will be determined mostly by the free lime content, once carbonated, and the particular pore size distribution of calcium carbonate. A wet mortar will have more pores than a stiff mortar and harling or roughcast mortars, frequently applied hot, were typically applied in a very wet, almost slurry-state.

Whether in Britain, Spain, France or North America, and doubtless all around the world, the 'ring-of-sand' method, whether carried out in a basin of sand or in a mortar box or in a pit (both of which would be covered to retain the heat), the quicklime slaked alone and then promptly mixed with the sand whilst still hot, is termed the 'ordinary' or the 'common' method – indicating very clearly that it was the method used by most craftsmen for most purposes.

There was, however, another hot mixing method which, though it required a little more labour in the first instance, was deemed to deliver a tougher, stronger, more tenacious mortar, with an enhancement of the essential characteristics of a mortar mixed by the ordinary or common method.

Vitruvius alludes to this method in his discussion of mass concrete, when quicklime and brick and stone aggregates were mixed together before the addition of water after which all would 'boil together'. This was unquestionably the method by which the British, at least, made concrete for footings and foundations after the rediscovery of the potential of mass concrete during the earliest 19thC. Gillmore characterised the method of mixing pulverised blue lias or feebly hydraulic quicklime with sand and larger aggregates before adding the water and launching the still slaking mass into foundation trenches from scaffolding around 10 feet above the trench bottom, as the "English method', distinguishing such concrete from 'beton', made by the French in a fashion more akin to the 'ordinary' mortar-making method, the quicklime initially slaked to a dough-like paste before being mixed (one would imagine whilst still very hot, to take full advantage of the 'flow' of the hot lime) with the aggregates and pozzolans. Langley (1750) had made explicit that water limes at this time were made with pozzolans as the only aggregate, but that these were mixed and pounded with 'hot lime' – indicating once more the deployment of the 'ordinary' method.

The pulverising or powdering of the quicklime before slaking, however, made the 'ordinary method', if not redundant, then an unnecessary complication of the process. Moxon (1703) clearly indicates the engagement of the sand and the lime during slaking as preferable to slaking by the ordinary method, though he prescribes layering the quicklime and sand before initiating the slake (the most common traditional method in Germany (Schmidt 2015) –

"When you slack the lime, take care to wet it everywhere a little, but do not over-wet it, and cover with sand every laying, or bed of lime, being about a bushel at a time, as you slack it up, that so the steam, or spirit of the lime may be kept in, and not flee away, but mix itself with the sand, which will make the mortar much stronger than if you slack all your lime first and throw on your sand altogether at last, as some use to do."

Batty Langley goes further. For building mortars, he insists that the sand and the lime be mixed together as the lime slakes.

"Inside Mortar is used for Vaultings, Foundations, Partition and Party Walls , insides of Fronts, and other Parts, which are hid from the Eye and not exposed to the Weather. This Kind of Mortar is generally made with Pit-sand which requires more or less Lime as it abounds more or less with loamy Particles; and therefore when Pit-sand is of a loamy, fat Nature, to 1 Load, (viz. 24 heaped Bushels) put 1 Hundred of Lime; but when it is a clean sharp Grit as Thames Sand then to 1 Load of Sand put 1 ½ Hundred of Lime, **which mix up together as the Lime is slacked in small Quantities….**

Out-Side Mortar for Fronts, Tiling, &c. exposed to the Weather, should be made with the sharpest Grit-sand that can be had, as being best able to withstand the Insults of Rains, &c. which Loamy Sands cannot so well do — and which therefore should not be used in any Part of a Building, that is exposed to the Weather.

The Proportion that the Lime should have to the Sand, is as 2 is to1, viz. **2 heaped Bushels of unslacked Lime to 1 ditto of Sand"**

Higgins (1780) confirms this general practice, not only for building, but for plastering mortars, with the latter laid down a while to allow for late-slaking.

In 1777, de la Faye, engineer to the king describes both the ordinary and 'sand-engaged' methods most succinctly:

"…If we soak limestone after it has been burnt in a kiln, it will warm up and its pores will open, facilitating its mixture with the sand and give some solidity…If we mix two parts of sand freshly extracted from the river with one part of powdered quicklime, it will create a very fatty and adherent mortar."

Pasley, military engineer based at Chatham Dockyard, writing in 1826 says that it was already the norm to grind hydraulic lime to a powder before slaking – to hasten the otherwise tardy slake – and goes on to say that this practice was becoming the norm for fat limes too. If mortar machines encouraged this, any perceived advantages would encourage the adoption of the method even on smaller projects, where mortar mills might be less justified, even had this method of mixing not been already established craft practice.

Pulverising lump lime by hand would be nothing like as arduous as breaking uncalcined stone – it became even more straightforward on larger sites with the introduction of mortar mills, and 'edge-runners' as roller pan mixers were originally described in old texts.

Today, powdered or kibbled quicklime, 5mm to dust, is readily available across the world, being the most appropriate form of quicklime for industrial uses unrelated to building. Accidentally, perhaps, in the absence of initially limited understanding of hot mixing methods by interested practitioners in Scotland and England, they have been the basic forms of quicklime used in the early 'hot mix revival'. Both are eminently suitable for mixing with sand before the commencement of the slake. As the embrace of hot mixing has extended, in tandem with growing research into historic methods, so lump lime has become more used, although generally – and logically - the mortars are made in a pan mixer, which also allows the typically 15 to 40 mm lump commercially produced also to be initially mixed and then slaked with the sand, reflecting craft practice once mortar mills and roller pan mixers became commonly used. The 'hand'- or rather shovel- mixed method is rarely deployed on site, though some individuals prefer it and seem to enjoy the physical exercise it entails.

For pointing, it is entirely practicable to mix small batches of hot mixed mortar in small rubber trugs, with a trowel, which not only facilitates the production of a well-beaten mortar but also its immediate, hot use. The quicklime for this is typically either powdered or kibbled, use of the former eliminating any risk of late-slaking disrupting the mortar surface, (just as the use of powdered quicklime on a grander scale, for plastering, also eliminates the same hazard, allowing confident use of hot mortars for the purpose).

Happily, even this method – stumbled upon by experiment in recent years - has historic precedent and recommendation, having been described in detail by Robert Dossie in 1771, along with its perceived advantage over the common method, on a small and on a grander scale:

"**Take of unslacked lime, and of fine sand, in the proportion of one part of the lime to three parts of the sand,** as much as a labourer can well manage at once: and then, **adding water gradually**, mix the whole well-together by means of a trowel, till it be reduced to the consistence of mortar. Apply it immediately, **while it is yet hot,** to the purpose, either of mortar, as a cement to brick or stone; or of plaster for the surface of any building.

It will then Ferment for some days, in drier places; and afterwards gradually concrete or set; and become hard. But in a moist place it will continue soft for three weeks or more; though it will, at length, attain a firm consistence…

The superiority of this to the common mortar is **owing to the intimate commixture of the lime with the sand, at the same time it is combined with the water**, before its attractive power, be diminished by its combination with water: and **this shews the defect in the common method of making mortar**: where the lime is slacked before it is (p25) commixed with the sand; and where, in part, old mortar, common earth, or other substances, with which lime has no peculiar specific attraction, are generally added, or used wholly in the place of sand."

During the 19thC, and with the use of mortar mills, it became common, perhaps initially in the USA, to run quicklime to a slurry or a thin paste immediately before adding the sand or other aggregate. This might reasonably be characterized as a form of hot-mixing, but involved the potential or actual drowning of the quicklime, understood to weaken the binding qualities of the mortar. However, this was done to facilitate faster mixing and, in the particular knowledge that the air lime mortar would be gauged with natural cement to compensate for this perceived weakness. Wright (1845), whose work offers the first reference to this new practice, is very clear about this:

"The lime, thus deluged with water, **loses probably some portion of its binding qualities, but the mortar at Fort Warren almost always contains hydraulic cement;** and as this substance sets rapidly, it is highly essential that the lime should be thoroughly slaked before the admixture of the ingredients. With the view, therefore, of ensuring this, as well as from regard to convenience and economy, the lime is reduced to the milky consistence before-mentioned, and allowed to remain in the vat as long as possible. **It should be remembered, that the above method applies only when cement is added to the lime. When no cement is used, the**

lime must be slaked in the ordinary way, as the drenching of the lime would greatly impair its binding properties…."

During the 20thC, ordinary Portland cement displaced natural cement as a suitable gauging material, and fat and feebly hydraulic limes were increasingly run to putty on site. After a brief uncritical dalliance with 1:3 or 1:4 opc: sand mortars at the end of the 19thC (LCC standards suggested 1:4 cement_sand mortars for underground works, 1:3 quicklime:sand mortars for above-ground works), and before the structural problems of such mortars used above ground became apparent (Schaeffer 1932, others), cement-lime mortars quickly became the norm for general building work – retaining some of the known advantages of pure and feebly hydraulic mortars, such as workability, reasonable water retentivity and bond (Boynton and Gutschick 1964), but with faster setting and earlier compressive and tensile-strength gain, more convenient, if not necessarily more appropriate to the increasing pace and volume of construction. The lime used was typically industrially produced hydrated lime – run to a paste the night before, in best practice but also mixed as a dry powder with the similarly dry powdered Portland cement and sand. Where quicklime remained readily available, and being cheaper than pre-slaked hydrated lime, builders would tend to make their cement-lime mortars with quicklime, albeit frequently run to a paste before mixing and Geeson still allows this option in 1952. Some cement-lime mortars, at least, will still have been 'hot-mixed'. The prejudice of the lime revival against the use of hydrated lime was not shared in the early days of its industrial production and use:

: "The proportion of impurities in hydrated lime is generally less than that in the lime from which it is made. **In building operations, hydrated lime may be used for any purpose in place of lump lime, with precisely similar results** The consumer must pay the freight on a large amount of water, but the **time and labour required for the slaking is eliminated** and there is no danger of spoiling it either by burning or incomplete slaking…**For all building purposes hydrated lime is to be preferred to lump lime.** By its use the time and labor involved in slaking may be saved **and the experience of the labourer is eliminated as a factor in the problem."** (Circular No.30, 1911, US Bureau of Standards).

(Picture of burst cement-lime plaster, Rudston church. Picture of gate piers Snaith))

Hot mixing persisted for hydraulic and magnesian limes during the 20thC. Masons preferred to slake hydraulic limes on site and distrusted the reliability of pre-slaked, bagged varieties, so that site-slaking allowed for adjustment. As more hydraulic limes came to be used for ordinary building works, perhaps seeming softer and less aggressive than such as 1:1:6 or 1:2:9 cement-lime mixes, methods often proposed for the slaking of the more hydraulic limes became the norm, being termed 'sand-slaking.' This method should be distinguished from hot-mixing, though it included common elements of procedure:

Hydraulic quicklime was placed in a basin of sand made of the due proportion of sand and lime for the mortar. Water was added in sufficient volume to slake the lime and sand was banked over this. The whole was then left for at least 12 hours, on account of the slower slaking of the more hydraulic lime. The British Standard (1951) requires a minimum of 36 hours, by which time, of course, the quicklime and the sand will have cooled and will be a cold hydrate when mixed with more water and the sand to make a mortar.

"HYDRAULIC LIME MORTAR
preparation from quicklime
Slaking. Hydraulic quicklime should be fresh and should be slaked as soon as possible after delivery. The quicklime should be slaked upon a clean platform or in a suitable container. Lump quicklime should be piled into a heap, any lumps larger than 6 inches being broken down. Water should be thrown on or sprayed on as the heap is formed.
Ground quicklime should be piled into a heap. Water should be sprayed on, and the heap turned over three times to mix the lime and water thoroughly.
Care should be taken not to use too much water; approxiamately 70 gallons is required per ton of quicklime.
The heap of lump quicklime or ground quicklime should be covered with fine-aggregate, banked down to retain the heat and left undisturbed for at least 36 hours or longer, until required. The heap at all times should be protected from the rain." (BS 121-201 1951)

Similar methods are discussed from at least the early 19thC onwards for the processing of more hydraulic limes. The dry – or very minimally moist – slake allowed the lime to be kept for up to 10 days without its setting up, whilst a slight excess of moisture in the first instance facilitated later slaking within the heap:

"The best mode of slaking hydraulic lime is to sprinkle it, as it comes from the kiln, with about **one fourth of its bulk** of water….**Before sprinkling the lime, it is to be surrounded with the mortars that are to be mixed with it, and when it is slaked and gives out no more vapours, it is to be covered with these mortars. The lime is left in this state for twelve hours at least, and for eight or ten days at most. The quantity of water necessary to bring the mortar to the ordinary consistence is afterward added." (Treussart 1842)**

Treussart's description of the practice with a more feebly hydraulic lime used during the construction of Strasbourg Cathedral illustrates a more nuanced method, as often applied to feebly hydraulic limes in the UK and which may be seen as a form of hot mixing – large volumes of lime heaped and processed the next morning would retain significant heat when mixed:

Since 1817, this process *[aspersion]* has been employed at Strasburg, where considerable masses of lime were operated on. A small building was erected near the works, into which the **hydraulic lime**, not allowed to arrive too fast from the kiln, was put, to be protected from the weather; the building was boarded on the sides and top, and, in case of rain, covered with a tarpaulin. By the side of this lime-house, a larger shed was constructed, the top only being boarded; a plank floor, on which the mortar was mixed, was laid under this shed. There was a measure, without a bottom, which contained about 10 cubic feet, each dimension of the box being about 2.20 feet, this was placed on the floor and filled with lime; which being done, the same measure was used **for the sand, which was placed around the lime, without covering it:** with large tin watering pots of known capacity, water, **equal in bulk to about one-quarter the bulk of the lime, was thrown on:** the workmen knew they were to empty the watering pots but a given number of times; and the lime being all in sight they saw that they should throw the greater quantities on those parts of the heap where lay the largest lumps of lime. **As soon as the slaking became energetic, the lime was left to itself until the vapours had ceased; it was then turned a little with a shovel, or a rod was thrust in, and if any lumps were found still entire, either for the want of water, or because they were too much burned, a little water was poured on these lumps. A regular form was then given to the heap, and the surface being slightly pressed with the back of the shovel, the lime was covered with the sand that had been placed around it. This process was completed towards evening — as many heaps being prepared as it was presumed would be required during the whole of the ensuing day. By**

thus leaving the lime, over night, in heaps, the slaking is complete; portions which have too much water impart it to those which have too little, and the water becomes thus uniformly diffused through the heap.

In the morning the sand and lime of each heap were mixed together, and passed twice under the rab (rabot) before adding any water: in this way, if there were any stones, or pieces of lime imperfectly slaked, they were easily found and rejected. Water was then added in sufficient quantity to bring the whole to the state of very soft paste; because in this dilute state the mortar is, with less labour, mixed more perfectly….

At Strasburg the precaution was always taken of **making up only one or two heaps of mortar at a time; so that it should not have too much time to dry before being used, and that the masons might find it in the state of paste, in the heaps in which it was deposited after being well worked**….

Sand-slaking, however, as prescribed by the Brtish Standard, and as advocated for brick-laying, typically, with more vigorously hydraulic limes, in the early to mid-20thC, is not, strictly speaking, hot-mixing – it is rather a convenient and efficient method for slaking a slow-slaking and late-slaking prone material. The mortar it delivered was not of the same character as a hot mix, being less adhesive and less cohesive, in keeping with its hydraulicity.

"Sand is placed on the banker and a large ring made. The lump lime should then be placed into the middle of the ring of sand, and the pieces of lime broken as small as possible. Sufficient water should then be put on the lime, using a watering-can or a hose with rose attached. The lime should then be covered with sand and the whole allowed to stand from twenty to twenty-four hours. It can then be mixed together with the shovel or larry into a paste form ready for use. All the unslaked lumps should be taken from the bed of material and should not be used. (Frost 1925)
Even so, the embrace of more than feeble hydraulic limes was relatively short-lived for building in the air, even where it was embraced. Mitchell's Construction of 1912, whilst re-iterating the sand-slaking method states clearly that more aggressive hydraulic limes are suitable for general use:

"**Hydraulic limes only should be used as the matrix for lime concrete, and they are most suitable for constructional work…**

Hydraulic Lime Mortar The strong hydraulic limes are usually ground into powder to facilitate the slaking. **Slake the lime by sprinkling it lightly with water, then turn it up together in a heap, and cover it with sand. After 24 hours it may be made into mortar by adding the proportions of sand and water.**

One part of lime and 2 parts of sand make excellent mortar."

By 1947, Mitchell's Construction states as clearly that "Mortar prepared with hydraulic lime **may be unreliable and cannot be recommended for general use",** preferring the reliability and consistency of cement-lime mortars.

By the time of the 'Lime Revival', even cement-lime mortars – and certainly the more benign versions, such as 1:3:12 and 1:2:9, made with hydrated lime and ever-stronger ordinary Portland cement, had begun to fall from favour and most new construction was being executed in straight cement-sand mortars. This remains the case today, with 1:5 the favoured mix, though extensive research in the USA in the 1930s and onwards clearly demonstrated that this was the worst possible mortar – having the least workability, water retentivity and bond (B & G: Palmer, US Bureau of Standards).

These are the circumstances in which John Ashurst (EH 1988) could entertain the notion that a 1:1:6 mortar might be appropriate for use on traditional fabric, at least as an exterior render, and then to see imported NHLs of significantly greater hardness than even Blue Lias, always considered the 'hardest of all water limes' available in the UK as being similarly appropriate for all manner of conservation work. NHL use swiftly became the norm from the later 1990s onwards. It has taken nearly 20 years for the in depth research into currently available NHLs to challenge this hegemony (see The Problem with NHLs).

The 'Lime Revival' had mistakenly assumed that putty lime, often drowned during slaking, had been the primary binder used historically. This mistaken assumption was shred by most academic researchers into historic lime mortars. As discussed elsewhere, lime putty was used as a mortar, without sand, in situations where residual lime lumps, of any dimension, would have been a nuisance or an obstruction to good work, such as lime finish coats, gauged brickwork and the finest stone ashlar. It became a common binder only when supplemented by either natural or Portland cement.

Hydrated lime had much more historic precedent as a binder, but was dismissed as inferior in its industrialised mass produced form, at least, often quite sanctimoniously. This position is unsustainable in the historic context of lime use – very many buildings were constructed with hydrated lime in the USA, with and without cement-gauging and much interior plastering was executed from the earlier 20thC onwards in north America (Lazell 1915), Britain and doubtless elsewhere, with hydrated lime run to putty shortly before use, sometimes with as little as 1/15th or 1/20th part of Portland cement added to the coarse stuff (Sawyer 1951):

The increasing use of hydrated lime for plastering is due to the fact that it is easily and quickly prepared; it takes up less space than lump lime, and it is reliable. The erection of putty bins or the digging and lining of pits in the ground, the slaking and 'running' of the lump lime, the 'popping' or 'blowing' on finished surfaces due to particles of unslaked lime in the plastering material, are all largely or wholly eliminated by the use of hydrated lime….(Sawyer 1951)

John Smeaton and other engineers preferred the use of hydrated lime over hot mixed or wet-slaked hot lime, although, as Batty Langley illustrates, with his prescription that all pozzolanic mortars for water works, whether of trass, brick-dust or forge ashes should be made with 'hot lime', which is to say, by the ordinary method of mixing. Smeaton saw a certain compatibility between a dry hydrate (typically, for him, an hydraulic lime, such as Blue Lias) and the finely ground pozzolanic additions he specified along with (but not exclusively with) sand also added. When Langley and others before the publication of Smeaton's seminal Narrative of the Building of the Edystone Lighthouse in 1791, discussed pozzolans, they did so without Smeaton's pioneering insight that it was fired clay that gave to a lime mortar, whether already hydraulic or not, the property of setting underwater. By experiment, and without realizing it, Smeaton arrived by experiment at an optimally economic underwater mortar of 2 parts sand: 1 part pozzolan: 1 part pure lime as the leanest in pozzolan that would work – a mix in which all of the lime would be combined with all of the fired clay to form calcium silicate, leaving little or no residual free lime. Before this, pozzolanic water limes – such as those offered up by Batty in 1750 – were comprised of 3 parts of pozzolan to one of lime, 2/3 of the (frequently expensive) pozzolan performing solely as aggregate.

In any circumstance where the lime had to be carried a great distance – lime from the Charlestown works in Fife was shipped to the Caribbean, for instance – the lime would be slaked to a hydrate at the kilns and packaged for transportation to site. This was not only lighter but avoided the general inevitability of air-slaking when lime was carried any distance. Smeaton quickly found that carrying unslaked quicklime around the Cornish coast from Watchet in Somerset to Plymouth, led to significant loss of power through air-slaking, and so resolved to ship the uncalcined blue lias rock to Mill Bay docks for burning to quicklime for use at Edystone (Smeaton 1791).

This sort of economy could also extend to hot mixing. Davy (1839) contributes surprising nuance to the debate over preferences for or against 'dry' and 'wet' slaking:

"Builders employ two methods of compounding their mortar: — First, when it is required to convey it in a dry state to the work, it is done by forming a bed of lime, surrounding it with sand, and then throwing on the lime a sufficient quantity of water to slack it, and covering it up immediately with sand; after it has remained some time in this state, it is turned over, and, if necessary, screened. The mixture is now in the state of a dry powder, and can be carted to the work, where more water is added and it is chafed up for use.

The other method is employed when there is convenience for making it up at the work. In this case it is what is termed " larryed. " Thus: — the lime is put into the middle of a bed of sand, and a large quantity of water thrown on, and with lime-hoes mixed up immediately until completely incorporated. It is then allowed to remain for a few hours, when it becomes set, and of proper consistency for use. The lime when turned up in this way will admit of a larger quantity of sand, as all the particles of lime are dissolved, whereas by the first method there are always small particles of the lime which cannot be properly mixed, however much it may be chafed up." (Davy 1839).

It was not uncommon for hydraulic limes, in particular, to be slaked to a hydrate before engagement with the sand, as has already been demonstrated, usually by aspersion but sometimes by air-slaking:

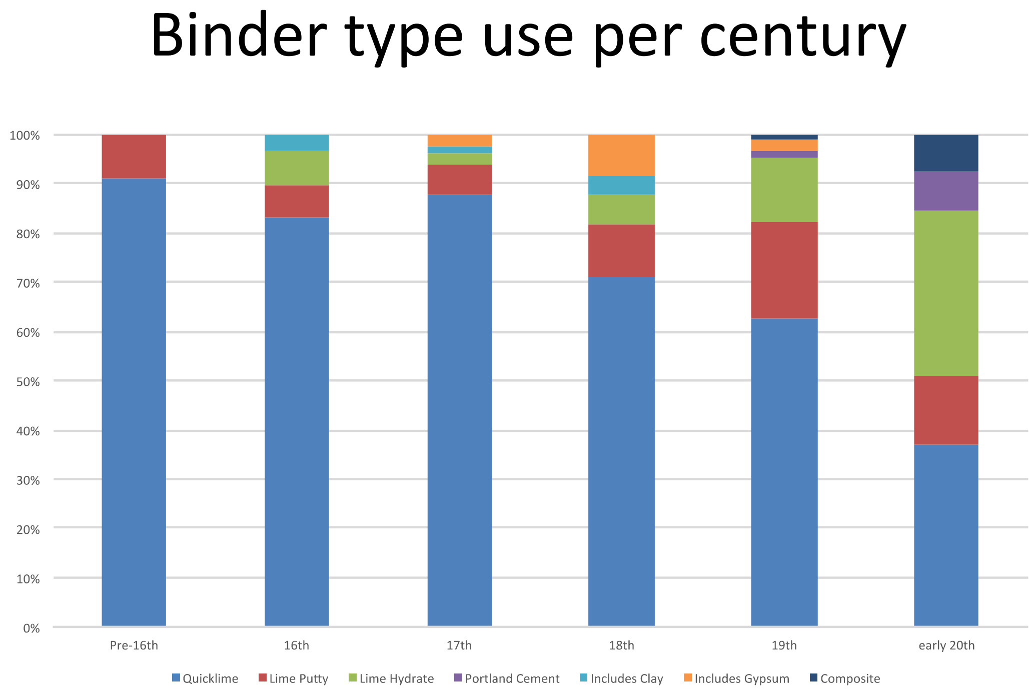
"In the immediate neighbourhood (of Bath, Somerset), it is known among masons by the name of Bath brown lime, and when prepared for cementing, or in combination with the patent metallic cement, is what is locally termed " wind slacked-" namely — after having been burned, it is placed in covered sheds, but open at the sides, the atmosphere being allowed to operate upon it; should the slacking proceed too slowly, a small quantity of water may be sprinkled upon it to stimulate the process, but on no account should water in a considerable quantity be added; it is therefore much, better (if possible) to allow the atmosphere to act for this purpose. The lime, when thus slacked, is converted into fine granulated particles, and is among workmen said to be " alive," as it will run from an iron shovel similar to quicksilver. The colour of the lias, previous to burning, is blue; when it has passed the kiln, it is brown." (Davy 1839)

No historic text displays the prejudice against dry hydrated lime that was routinely displayed during the 'lime revival' and Lazell saw and clearly set out the potential advantages of an industrially produced, quality-controlled and scientifically slaked version of a product routinely produced on site in the past, though, it must be said, that one of the biggest advantages he saw was that it liberated him, as a specifying architect, from reliance upon the skill and experience of the craftsmen on site – strengthening his position thereby, and weakening theirs.

The primary problem with hydrated lime use – as with putty lime use – during the lime revival was its being mixed at too lean a proportion of lime to sand. (See Mortar Proportions below).

Hydrated lime fresh from the works and mixed to historic proportions can be a perfectly useful and serviceable material, although most limeworkers would prefer to use other forms. Sand-slaking, as described in the British Standrd 1951 is a method of producing hydrated lime on site for relatively swift use, of course.

Anna Schmidt's compelling analysis of more than 3000 historic mortar samples gathered by the Scottish Lime Centre Trust over the years makes clear the hierarchy of lime manipulation over the centuries, however. The vast majority of mortars in the past were hot mixed from pure or feebly hydraulic quicklimes, and the majority by this method until the 20thC, when dry hydrate became the dominant lime binder, although still only just over-taking hot mixing. In every century until the 19thC, putty lime was used in a very small percentage of mortars, with more being used in the 19thC than in any other. Putty lime use was lower even in the 20thC, in this sample, than was hot mixed mortar use and around a third less commonly than dry hydrate. (Schmidt HES 2018).



Research Anne Schmidt courtesy Jessica Snow, Historic Environment Scotland

Mortar Proportions.

One of the fundamental errors of the 'Lime Revival' was to generally embrace the 1 binder to 3 aggregate ratio that had become embedded in practice during the 20thC, initially in association with cement-lime mortars.

Pre-20thC century lime mortars were always much richer in lime than this, as Gerard Lynch pointed out in 2007 (BCD), though the import of his paper on the subject seems to have been substantially avoided. That said, many practitioners using lime putty had been – and were – mixing at 1:2 and mortar analysts such as Peter Ellis at Rose of Jericho frequently recommended lime putty: sand mortars mixed at 1:2 for works to historic buildings the analysis of the original mortars of which had concluded that they had been hot-mixed. Ellis, along with most others working in the field of conservation assumed that hot mixing from quicklime was dangerous, and too hazardous to be allowed in the modern building industry. For most, this was received knowledge, not experience, nor even observation, and the association of hot mixing with 'danger' pervades most writings on lime in which it was mentioned at all, including the most apparently authoritative. In the earlier days of the 'Lime Revival' and still on some sites, quicklime was being slaked to lime putty on site for use on its own as a binder, or with pozzolanic or Portland cement addition. In our experience, slaking quicklime to putty is a more potentially hazardous activity than hot mixing quicklime with sand and as demonstrations of hot mixing have been given around the UK, Ireland and elsewhere over recent years, there is often a vague air of disappointment, as well as a slight sense of having been misled in the past.

The identification of originally hot mixed mortars by mortar analysis has been common in the more recent past, but this was only very rarely coupled with a recommendation to use the same, despite the basic principle of modern conservation that the materials of repair should be like-for-like, or, at least that repair materials should be very similar in character and performance to those originally used. Some might recommend putty lime mortars, with or without a small volume of pozzolanic addition; others, and particularly in recent decades, would recommend mortars with a natural hydraulic lime binder. The default proportion for each was generally 1:3, lime putty or hydrated NHL to sharp sand aggregate. Even more recently, NHLs have been increasingly specified at 1:2 ½ or even 1:2, mixes that were certainly preferred by craftsmen and women as offering more workability, particularly in the case of NHLs. Although for both lime putty and for NHLs, such mixes, approaching 1:2 unconsciously reflected historic proportions, putty lime of sufficient density to mix effectively to a mortar at 1:2 was not always available, in part due to the method of slaking in an excess of water; and NHLs at 1:3 were already perceived to be harsh-working and 'too strong' by many craftspeople, setting as fast as the cement-lime mortars they were increasingly told could not be used – suspicions that have been borne out by recent Historic England/Bath University research – and mixing NHL-richer mortars would only add to this strength, density and brittleness, though it certainly improved the workability.

Some masons – the author included – adopted gauged lime putty: NHL mortars for use in north America and Yorkshire, where 1:3 putty lime; sand mortars had always been problematic and, particularly in Scotland, quicklime: NHL mortars became commonly used in tandem with the general embrace of NHLs across the UK in the early 2000s. The SLCT and Laing Masonry, in particular, played a valuable role in promoting and disseminating such practice, and it was hosting SPAB scholars in the mid-2000s, several of whom were apprenticed at Laings that first alerted the author to the practice of hot mixing. These mortars, high in free lime but with a faster set, have performed very well (Frew & Revie HES 2018), as have those made with putty lime and NHL in equal proportions, even in very cold and challenging climates. (IMAGES :Amos Brown & Ridditch St Stephens). The Foresight Research Project (2003) had indicated that a mortar mixed with equal parts of air lime and NHL as binder would deliver a mortar 80% weaker than would have been the outcome had only NHL been used. Wiggins's research indicates why such mortars have been successful, enjoying a significant and necessary free lime content and developing a high level of effective porosity (see The Problem with NHLs below).

Lynch (2007), by reference to his experience and observation and by reference to historic texts, clearly demonstrated that most historic specifications or recommendations for mortars assumed that the lime called for was counted as quicklime, not slaked lime, and that quicklime typically doubles in volume during slaking, giving a mortar significantly richer in lime that 1 part to three aggregate. That historic lime mortars were richer in lime than 1:3 had, of course, been generally observed by most conservation craftspeople. Few, however, had taken sufficient notice of the fact, nor wondered, or even been aware of, how such proportions might have been readily achieved. Hot mixing was, until recently, an almost entirely forgotten craft practice, referenced by very few authors and barely at all in academic papers. Stafford Holmes had mentioned it in Building with Lime, and, along with Wingate, in Small-scale Limeburning (along, in the latter, with the assertion that it was 'too dangerous'); Lynch had also discussed it in his publications, and regularly demonstrated dry- and, more occasionally, wet-slaking in his training and educational work. Both Holmes and Lynch, however, were generally content with the existing pattern of mortar use, deploying either lime putty or NHL. The latter tended to equate modern standard strengths of NHLs (2.0; 3.5; 5,0) with traditional categories for hydraulic materials (feebly; moderately: eminently hydraulic), but he was by no means alone in this. Lynch also doubted the 'authenticity' of lime putty made using modern, industrially produced high calcium quicklime, arguing that bricklayers, at least, had always used feebly or even moderately hydraulic lime. This is true, in the case of feebly hydraulic lime, of the second half of the 19thC in London and where grey chalks were locally available, and true of parts of the 20thC in the case of the more energetically hydraulic limes, although 'preferred' might be the more operative word. Pure chalk limes and very feebly hydraulic limes burned from almost or relatively pure limestones locally were, however, the stuff of most building work, including brick-laying around the UK and Europe, and even in London, for most of the historic period. The power and the alacrity of initial and/or ultimate strength and tenacity could be – and regularly was – enhanced by a relatively small addition of cheaply and locally available pozzolanic addition, such as pulverized brick or tile, or wood ash, depending upon situation or circumstance, and without any sacrifice in workability. It was of practical and economic benefit to the craftsman in using a pure or nearly pure quicklime that would slake rapidly and reliably and with maximum efficiency whilst generating the necessary heat. Slaking methods became more cumbersome the more hydraulic the lime used became, and the quality of the material more variable and less reliable, at the same time as the mortars delivered were less workable or agreeable to use.

In the brief period when traditionally burned blue lias hydraulic lime from Tout Quarry in Somerset and immediately after the unfortunate demise of such production, when a relatively weak Lincolnshire 'grey chalk' lime were available, such assumed equivalence was not so problematic. Both had a high free lime content and reasonable workability, especially when limestone dust was added as a component of the aggregate, and were much less aggressive in their set. Either might be mixed at 1:2 and, depending upon purpose, promote no ill-effect. The author used the blue lias NHL successfully in Vermont (Carving Studio PIC) and in Malton, North Yorkshire and the Lincolnshire NHL 2.0 in the Malton area. When production of the latter ceased in 2007 (?), those who had not already been routinely using imported NHLs from mainland Europe, tended to switch seamlessly to these. The data generated by the Foresight Research had been from the blue lias and the Lincolnshire NHL. This had been unalarming. As late as 2015, Michael Beare in the BLFJ seamlessly and uncritically applied this data to the then currently available NHLs, promoting their use not only for conservation but for new build as well. In fact, the typical strengths quoted might be as easily applied to a hot mixed mortar mixed to historic proportions with a small volume of pozzolanic addition and air limes used as controls in the HE NHL research, have shown similar compressive strengths to those produced for the Blue Lias and Lincolnshire NHL by the Foresight research. Any strength of mortar might be readily produced by the hot mix method, depending upon the type and proportion of pozzolanic addition, as they commonly were in the past. If the addition is less than 10% by weight of the lime, the necessary pore structure remains intact and the mortar, eminently workable.

Historically, workability was all. It might even be argued that workability was taken to be the measure of quality and, even, of performance. Up to a point, the more lime there was in the mortar, the more workable it was, although too much lime – and craftsmen were frequently accused of adding too much lime – would promote undue shrinkage.

Neve (1726) recounts discussions with craftsmen in Sussex and in London in which their preferred mortars are very lime rich, indeed, some having more lime than sand. As Pasley observed in 1838, the temptation to increase the lime content was common" because it requires less time and labour in mixing, which saves trouble to the labourers, and it also suits the convenience of the masons and bricklayers better, being what is termed *tougher*, that is more easily worked."

Moxon says that "…Here at London, where for the most part our lime is made of chalk we put about 36 bushels of pit sand to 25 bushels of quicklime…", otherwise 1 bushel of quicklime to 1 ½ bushels of sand. This might deliver a mortar of 5: 3.6, or 2:1 ½ lime:sand.

Langley (1750) recommends that outside mortar be composed of two heaped bushels of unslacked lime to one bushel of clean, sharp sand, a mortar proportion of around 4 lime to 1 sand. His recommended pozzolanic mortars for water works, however, are generally comprised of 2 heaped bushels of hot lime (slaked to a powder or a paste) to I bushel of whichever pozzolan.

Ware (1756) generally concurs, suggesting that Vitruvius's lime sand proportion is too lean in lime for successful use in the British climate, recommending that 'two-thirds of lime and one of sand would be the best quantities', having already observed that 'the common practice of this time allows less than a third part, more in some places, and in others they are made equal.' This conclusion, he says, is based upon his own experience and extensive experiment. He shares the concern of Bastion (1837) and Vicat that in normal slaking practice on site, the masons added too much water in the first instance, to reduce the necessary labour of beating a less flooded mortar to the desired fattiness and consistency.

The most commonly encountered lime: sand proportion on analysis, however, ranges between 1:2 and 1: 1.5. Mortars are sometimes richer than this, but very rarely, if ever, leaner than 1:2. Lime content might vary according to which sand or other aggregate was used, but 1:2 binder: aggregate ratios were the general norm for most general purposes. Lime finish coats might be of pure lime, either made to putty or run to putty from previously slaked hydrate; they might be 1:1 with fine silver sand or marble dust, the former becoming common in the 19thC. They might have a small volume of gypsum added to speed set, reduce initial shrinkage or harden the surface finish, but the previous coats would be more like 1:2 with added hair and sometimes, in earlier periods, added hay, as base-coats transitioned from earth-lime to lime-sand. A lime-lump rich mortar on analysis after acid digestion might indicate a lime content of 1: 1.5, or richer in lime than this, but it should be remembered that residual lime lumps are aggregate, not binder. Whenever the use of already slaked lime is specified, the call is usually for 1 part of slaked lime to two parts of aggregate, and this would indicate the conviction that this offered the optimum balance between workability and control of the inevitable shrinkage associated with rich, pure or nearly pure lime mortars.

One reason, perhaps, for the adoption of 1:3 or often 1: 2.75 binder to aggregate mortars during the 20thC, apart from economy and a mis-reading of historic definitions and terminology, was an uncritical reliance upon void tests as a guide to mortar proportion, water being added to a given volume of the selected sand until it brimmed, the assumption being that all that was required for a good mortar of necessary cohesion and tenacity was to fill the interstices between the grains of sand. Such a thought had clearly not entered the heads of craftsmen over the centuries and the several engineers who invested time in thinking about this –

doubtless responding to their observation that practitioners had long ignored such consideration, and with general success, concluded that more lime was required than that necessary simply to fill the voids. Gillmore offered the fullest analysis of why this might be so, whilst still assuming that the lime used would be generally in the form of quicklime:
"(Whilst)…it might be inferred that the **minimum amount** of the cementing material that can be used in any case is exactly equal to the volume of the voids in the sand, when the latter is well compacted *[typically 1:3]*. This theory supposes that there is no shrinkage in the matrix while hardening, and that the manipulation *[slaking]* is complete. But as these conditions can never be fully attained in practice, it is **unsafe to descend to this inferior limit.** Moreover, mortars composed on this principle would **be deficient in both *adhesive* and *cohesive* power,** from the fact that the particles of sand would present a large area, practically void of matrix, **to the surfaces of the solid materials that are to be bound together,** and would, for the same reason, be in **more or less intimate** contact with each other throughout the mass. In order to avoid these defects, **it is customary** to determine the amount of cementing matter to be used in any particular case, by adding **45 to 50 per cent** to the volume of void space in the sand." (Gillmore 1861).

Richardson, an admirer of Gillmore, reiterates this in 1897:

"A mortar made of lime paste should, theoretically, contain so much sand that the cream of lime **will more than fill the voids**, that is to say, the volume of the mortar should be greater than that of the sand. **In fact it is necessary that it should considerably more than fill them in order to thoroughly coat each particle and provide for shrinkage. If too much sand is present there is not sufficient cementing material to make a firm bond, while on the other hand, if there is too little the mortar will tend to shrink and crack on drying. If too little lime is used the deficiency must be made up with water, that is to say, the paste is made very thin."**

The due proportioning of mortars historically had been well understood by engineers across Europe from the mid 18thC onwards, as evidenced by the routine mention and specification of 1 quicklime: 3 aggregate, the quicklime routinely described as 'lime', since the general use of quicklime to make mortars was taken as read. The consensus among such engineers, however, was that masons would very often, left to their own devices, add more quicklime than this, which engineers considered to be unnecessarily wasteful and uneconomic.

William Pasley (1826) set about establishing the appropriate range of mortar proportions consistent with good workability and necessary performance, settling upon 1:2 quicklime: sand as the minimum and 1:3 quicklime: sand as the maximum proportion. Given the dominance of 1:3 slaked lime to sand during the lime revival, this is relatively shocking – Pasley's motive was to determine the *maximum* amount of sand (the cheapest ingredient) to which 1 part of quicklime might be added without compromising performance. A lime mortar mixed with 1 part of relatively wet lime putty might, in fact, contain somewhat less than 1 part of actual (slaked) lime to the 3 of sand.

He was as concerned as others that masons left to their own devices would use too much lime, wasting resources:

"The prejudices of common workmen are all in favour of using an excess of lime, upon which they consider the whole essence of good mortar to depend. In public works, it therefore becomes necessary for the Engineer to guard against this propensity *[but see below for what he considers appropriate proportions]*, as they imagine that they are doing a service to Government by wasting the more expensive material; and, if they are not strictly looked after, **they will make the mortar according to their own judgment, in spite of general directions to the contrary." (1826)**

"In respect to the proper proportion of lime and sand which ought to be used in mortar, it is known that when the lime is in excess the mortar may be plastic and convenient to use, but that it never hardens properly. If, (p6) on the contrary, the sand be in excess, the mortar becomes too short, as the workmen style it – that is to say, not sufficiently plastic at first, and may eventually crumble to pieces… If the lime be of good quality, and dependence can be placed upon the diligence of the persons employed making the mortar, one part of unslaked lime to three of sand, has been held as a better proportion than the above, and has very often been used in Government works…It appears to me that, for common mortar *[which is to say, fat or feebly hydraulic lime mortar]* for the walls of buildings, the former *[1:2, quicklime:sand]* may be considered the maximum, the latter *[1:3, quicklime:sand]* the minimum, proportion of lime that ought to be used….(Pasley 1826)

Across Europe and North America, other engineers came to similar conclusions and arrived at a similar range of proportions for fat and feebly hydraulic limes, depending upon the quality and character of the lime. When the fat or feebly hydraulic limes were mixed already slaked, the typical lime: sand proportion was 1:2 (Vicat eg)

Pasley (1838) was also clear that it was customary for the lime : sand proportion to be expressed in quicklime and aggregate unless the use of already slaked lime was explicitly stated:

When the proportion of sand to lime is stated in the above manner, which is done by Architects as part of their specification or general directions for the execution of a building, it is always understood, when nothing is expressed to the contrary, that the parts stated are by fair level measure for the lime, and by stricken measure for the sand, and that the lime is to be measured in lumps, in the same state in which it comes from the kiln, without slaking or even breaking into smaller pieces…the expert labourer employed in this operation, on receiving general directions to use as much sand as possible without making the mortar too short, will from habit serve out the proper proportions of lime and sand with all necessary accuracy, without measuring them….(1838)

Nor were hydraulic limes mixed at 1:3, slaked lime to aggregate. The typical proportion was 1:2 hydraulic quicklime: aggregate, or even 1:1. The more hydraulic a quicklime was, the less it would expand upon slaking, hence 1:2 for moderately hydraulic limes, typically, and 1:1 very often for natural cement or eminently hydraulic mortars. It was commonly asserted that any sand reduced the strength and the workability of a natural cement (and later a Portland cement) mortar, but that the addition of variable volumes of sand was of economic benefit and that the diminution in strength was not of great significance in the case of such energetically strong binders. Smeaton's mortar for the Edystone Lighthouse was 1 part of true pozzolan from Italy to 1 part of moderately hydraulic blue lias lime from Watchet, Somerset and the addition of pozzolan to hydraulic lime was by no means uncommon.

Most engineers, as most masons, were content to specify and use lime mortars mixed by volume, but, of course, the bulk density of different limes can vary (see the Problem with NHLs, below), and inattention to this variability may lead to mortars technically insufficient in lime content. Henry Scott (1862) set about marrying typical bulk density with the site practice of mixing by volume. His conclusions might be seen as surprising, as they would suggest the use of mortars even richer in lime than many, if not most, of those used in the past:

"… **we may conclude, that with hydraulic limes such as the Lias (weighing 50lbs. the cubic foot), 2 cubic feet of sand may be added to 1 cubic foot of lime; that with feebly hydraulic limes, such as the Dorking and Halling grey chalk limes, 2 ½ cubic feet of sand may be added to every 50lbs. of lime; and in the case of pure limes, if we are compelled to use such miserable stuff, we shall not be losing much in resistance if we increase to 3 cubic feet of sand for every 50 lbs. of the lime…."**

This is to say that just less than a 25 kilogram bag of powdered quicklime would be added to 3 cubic feet of sand.

Scott was generally contemptuous of craft practice, as well as of the relative power and control exercised by masons regarding mortar design and mixing. He looked "confidently forward to the day in which we shall feel quite independent, as respects mortar making, of the workman's traditions." He was not alone in this – Burnell (1857) and Lazell (1915), amongst others shred the sentiment and Burnell, as well as Scott, sought to put the craftsmen 'right' on their practice. Scott's particular beef was the preference of the crafts for fat or feebly hydraulic limes for use in the air over more aggressively hydraulic limes for this purpose, of which he – along with Vicat, Sloan (1852), and others was a keen advocate. Scott bemoaned the difficulty of altering "**the practice of those who have grown grey in exalting 'practical experience,' and in the comfortable persuasion that the bricklayer knows best how to make good mortar, and can be trusted to make it…**". All of these authors and advocates for hydraulic lime at the same time make clear that the routine use of fat and feebly hydraulic limes was universal at the time:

"We should particularly distrust, in the choice of slaking methods, the ignorance and the routine of the masons, who often reject the best method of slaking only because it produces less expansion than the other. Sometimes, the workers reject, with the same reasoning, types of lime which would be preferable to the ones they are used to use. Thus, in the region of Calvados, **half of the limekilns produce hydraulic lime for the consumption of farmers to enrich their fields whereas this same lime is not at all used by the masons,** because it does not expand as much as the others and because it hardens quickly, therefore the workers would have to change how they work. *(Biston 1837 pp203-204)*

"In the ordinary constructions, we prefer to employ fat limes and sand to gather stones and to build walls because this mortar is abundant and cheaper. In humid places, in particular underwater, wherever we wish to stop the action and infiltration of water we use a mortar that hardens underwater or we use some 'béton'."
Hassenfratz 1825

Smeaton concurred, along with many others, including Pasley who was content to build above ground at Chatham with high calcium chalk lime mortars:

, " It is not to be wondered at that workmen generally prefer the more pure limes for building in the air, because being unmixed with any uncalcareous matter, they fall into the finest powder, and make the finest paste, which will of course receive the greatest quantity of sand (generally the cheaper material) into its composition, without losing its toughness beyond a certain degree, and requires the least labour to bring it to the desired consistence; hence mortar made of such lime is the least expensive; and in dry work the difference of hardness, compared with others, is less apparent."

The lobbying of engineers was well-intentioned, of course, and had a certain logic. The concept of compatibility of repair and original materials did not exist historically – indeed, they perhaps could not exist until the consequences of using the hard and increasingly aggressive hydraulic materials that became available towards the end of the 19thC (the routine use of natural cements for exterior renders in urban centres after 1796 notwithstanding) which seemed to answer the structural demands of engineers and the ego-centricity of some architects, upon softer and more porous traditional fabric built by craftspeople wedded to highly workable and similarly softer and porous mortars became apparent during the earlier 20thC. Schaeffer alerted people to this as early as 1932, but his observations fell upon deaf ears, perhaps, except insofar as in the UK and in the USA, cement-lime mortars were arrived at as a suitable compromise between excessive hardness and rapidity of set and a version, at least, of workability and relative deformability, in belated response to the embrace of hard, dense and rapid setting Portland cement.

Uniquely, in 1857, Burnell had had a moment of great insight:

"….To use a hard, quick-setting material upon a yielding base, is a degree of ignorance totally unaccountable on the part of any professional man of average discernment."

By the time of a later edition of his treatise, he could not speak highly enough about the properties and potential of now reliably produced Portland Cement, recommending its liberal use for everything….

These were very different views of the world and of construction that came into full-blown collision at the end of the 19thC. Cement-lime mortars were the compromise between the two, advertised as offering the 'best of both worlds', though by this time, the ascendancy of architects, engineers and other specifying professionals within the building hierarchy and particularly as it attached to mortars and mortar design, and the general exclusion of craftspeople from this role – one they had enjoyed for 2000 years, at least, was effectively complete.

A RIBA Committee writing in 1946 was able to speak eminent sense but without recognizing that the previous 60 years or so represented in many ways the negation of this good sense:

"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 (p6) rationale of established building traditions, which should be altered only with the full knowledge of the consequences…"

This battle of ideas and of different worlds continues to this day and the current preference for pre-mixed 'conservation' mortars some of them based upon dubious science and containing unknown additives in unknown proportions, such as air entrainers and water repellents (see Wiggins, herein) both of which may compromise bond and effective porosity; most of them based upon NHL binders, to which given quantities of water are added by rote, and which may be mixed by trained monkeys, may be seen as the logical conclusion of Scott's ambitions for mortar design.

Experiments with these proportions show….

The modern revival in the use of hot mixes has been generally based upon mixing 1 part of high calcium quicklime to 3 parts of aggregate, some of which might be limestone aggregate. Using powdered quicklime, this proportion might be extended to 1:4 without subverting historic prescriptions, as all of the quicklime will become binder. When lump lime is used, 1:3 quicklime: aggregate would be considered prudent. Because of our extensive use of overly lean NHL mortars over the last 20 years, many craftsmen and women have become un-used to seeing shrinkage in mortars, whether applied as pointing or rendering. Some, whilst enjoying the enhanced workability of hot mixes have taken to mixing particularly render coats at 1:6 quicklime: aggregate. In contradicting centuries of craft practice and more or less scientific investigation by engineers, this should be seen as an error, fraught with the possibility of premature failure of these mortars akin to much – but by no means all – work with over-lean putty lime mortars. Undue shrinkage of lime rich mortars may be mitigated by aggregate choices, controlling the water content of the mortar more rigorously and by good preparation and beating of these mortars (the latter being optimally delivered by roller pan mixers). Beyond this, some shrinkage is – and was always – normal and inevitable. Dealing with shrinkage was always a part of a limeworker's lot and was, it should be said, the price paid for desireable workability and necessary performance.

None of which is to say that there will not be occasions during the conservation of culturally significant historic fabric when a leaner, deliberately more sacrificial mortar, will be appropriate. The lime-lean putty lime mortars used by Professor Baker at Wells Cathedral and Crowland Abbey in the mid-1970s have proved suitably sacrificial – they have deteriorated during the last 40 years without promoting damage to the original fabric. At Wells, many of Baker's mortars remain sound (Durnan). Hot mixed lime mortars, mixed to historic proportions would have done as little damage and, perhaps, have lasted indefinitely. Repairs were effected at Crowland using hot mixed pointing and mortar repair mortars, as well as hot mixed and applied sheltercoats. The primary feedback from conservators using hot mortars and surface treatments here and elsewhere has been that these are easier and less problematic in use than their putty lime or NHL-based equivalents.

Plasters

The author is not a plasterer. Plasterers, particularly, although by no means exclusively, since the inception of the 'lime revival', have stayed generally true to the historic practice of using fat limes in their trade. This has begun to break down in recent years, due to competition from others using NHLs and under-cutting more traditional plasterers, but the author is unaware of any skilled plasterers who would prefer to use NHLs in their trade, lest for more exposed exterior renders. Even when it became the norm to use feebly hydraulic limes for building works, especially in and around London, after the earlier 19thC, or wherever such 'stone limes' were readily available, interior plastering was always assumed to use pure or very nearly pure limes, generally of non-hydraulic chalk upon or adjacent to the chalk formation of England. Their lesser durability was not considered significant for interior use and the alacrity and potential completeness of their slake was considered an advantage.

As discussed above, the wet-slaking of such pure limestones and the laying down of the dough-like paste produced for as long as necessary for all lime lumps to have slaked, had been common practice across the Roman empire to produce lime for stucco finish coats, with marble dust or similar fine aggregate added. In the chalk regions of England, chalk flour was often added to such finish coats, and still is, certainly by lime plasterers in East Anglia, where it is seen to reduce the shrinkage of these, as well as of previous coats, the chalk aggregate being much coarser. In later plastering practice, quicklime would be slaked to a similar dough-like consistency and then diluted after slaking to facilitate its being easily passed through a sieve to remove these lumps, before being allowed to stiffen once more for use – often within 2 weeks of slaking, but up to three months, depending upon the lime (Millar 1897).

The lime finish coats traditionally applied over earth base-coats were typically much thicker than for two- or three-coat work with lime, typically around 4mm, but as frequently thicker than this and up to 8 or 10mm. They were always rich in ox-hair to mitigate shrinkage. Neve quotes such 'white mortars' in Sussex as being 6 parts lime to one part hair, though some of the lime *may* have been in the form of chalk dust. It is unlikely that such finish mortars were 'hot-mixed', except in the sense that they would always have been made by initially slaking the quicklime with slightly more than the minimum water necessary, or by initially dropping the quicklime into around twice its volume in water by the method described in BS 121:201 1951 (see above), both methods guaranteeing the minimum necessary slaking temperature and maximising the potential power of the lime.

For much of history, the plasterer's craft had used earth and earth-lime mortar as much as it had used lime-sand mortars – the two were complementary materials of a single craft tradition, as they were for masons. Indeed, in more rural parts, stonemasons and bricklayers were also the plasterers, as they were often also the roofers.

As late as 1747 in London, it was routine for the base-coats of ceilings, at least, to be executed in loam mortars:

"He first nails on the Laths upon the Ceilings, **upon which he lays a Coat of Clay, mixed with Hair, or hay; over which, when dry, he lays a Coat of fine Plaister.** He is attended when plaistering by a Labourer, who holds the Plaister up to him in a hod; he takes it off the Hod with a Trowel, like that used by the bricklayer, and lays it up on a Trowel peculiar to his Business; which is a flat plate of iron, with a Handle fixed upon the Back of it instead of the End." (Campbell 1747),

perhaps flagging up the primary advantage of using base-coats of earth or of earth-lime – their not needing to carbonate prior to the application of subsequent lime coats, whilst offering similar workability and tenacity to lime-sand mortars.
Nor should it be forgotten, particularly in the medieval period and still commonly in Tudor times, within high status buildings that much plastering had been done using gypsum, made from the local calcination of alabaster, and in reflection of common practice in the Paris region of doing the same, making plaster of Paris, which was also imported into England for its exceptional quality. Rondelet (1803) discusses the extensive – and preferred use of gypsum plaster for many purposes, including for exterior renders:

"Plaster can be considered a type of lime which does not need any other material apart from water to form a solid body of a medium hardness. For this reason alone, plaster will be preferable to mortar if it could resist for a longer time to the bad weather and humidity. Despite this inconvenience, plaster is a useful material in all of Paris where it is of good quality and when it is used appropriately. As this material sticks equally to stones and wood, we may use it with advantage for the construction of vault walls and renders. We coat walls, timber frames, floors etc in such ways that from the floor of the ground floor to the roof, a house can be covered in plaster and seem of one piece of the same material."

Nonesuch Palace was not only rendered in part with gypsum, but this was used to model its exterior mouldings and statuary (Dent).

Exterior, as well as interior, gypsum plasters are very commonly found in Spain, where the climate facilitates their survival. In the UK, what experiments were made with selenitic limes for exterior renders, were generally short-lived, for the obvious reason that gypsum is readily soluble in water. Even in France, they were not expected to endure longer than 15 or 20 years (Rondelet 1803). In Spain, early gypsum work included aggregates – sand and even crushed brick, but Rondelet makes no mention of such habits in Paris.

(PIC of gypsum staircase, Gandia)

Very early mortars from Mohenjo-daro were composed of gypsum, sand, clay and lime (Jaggi O P 1969 History of Science and Technology in India, Vol 1 Atma Ram):

"In some of the important-looking buildings, gypsum cement of a light gray colour was used on the outside to prevent the mud mortar from crumbling down. In a very well constructed drain of the Intermediate period, the mortar which was used contains a high percentage of lime instead of gypsum. Bitumen was found to have been used only at one place in Mohenjo-daro. This was in the construction of the great bath ..."

Gypsum was formed after firing at around 400 degrees C, more readily and earlier achievable, perhaps, than was the minimum 900 degrees C required for the calcination of lime stone.

In medieval England, "Where masonry was particularly exposed to the influence of wet, it was a common practice to use instead of mortar a cement composed of wax and pitch and resin, applied in a molten condition" (Salzman 1952).

Returning to lime plasters, it was *not* the norm before the 20thC to slake the lime for base-coats to a putty, although such practice had become more common in metropolitan centres during the 19thC:

"(For plastering) The safest mode of preparing lime and hair, when the stone is of a strong nature, is by forming a pan or bin of a convenient size, perfectly water-tight, and about 18 inches in depth. A large tub must then be procured into which the lime, **after having been well slacked** must be put and mixed with a proper proportion of water, and run through a sieve with apertures not exceeding a quarter of an inch, until the pan is filled, when the hair and sand must be added, the whole being well incorporated with a drag or three-pronged rake. There must then be a small hole made at a suitable height in the side of the pan, to allow the water to escape. After thus remaining until it be sufficiently set, it may be taken out of the pan and made fit for use by the labourers. This composition is used for the first or pricking-up coat, and for the floating of ceilings and walls. It is also used for mouldings and cornices which require much stuff, in which case it is mixed with plaster of Paris…" (Nicholson 1842)

Thus, a dry-slaked lime might be run to putty after sieving and, usually the day before use; or else the lump quicklime was hot mixed by the ordinary method before being laid down as coarse-stuff in order for any late-slaking of the lime to occur.

Nicolson continues to say that "Plasterers' Putty is prepared from unslacked lime, the process being performed by immersing the lime in water where it remains until it be completely dissolved; the liquid being then strained through a very fine sieve must be left in this state until set, when it is considered fit for use."

Higgins (1780) clearly indicates that slaking of the sand and quicklime together was common in the 18thC:

"The plaisterers, who use a finer kind of mortar made of sand and lime, observe that their plaster or stucco blisters, when it contains (p41) small bits of unslaked lime; and as their purpose is to work their stucco to a smooth surface, and to secure it from cracking, or any such roughness…and as the hardness of the stucco is not their chief object, they very properly keep their *mortar* a considerable time before they use

it, to the end that the bits of imperfect lime, which passed through the screen, may have time to slake thoroughly." (Higgins 1780).
Millar (1897) offers greater regional nuance, as well as basic procedure:

"There are three methods of slaking 'lump-lime' - the first by immersion; the second by sprinkling with water; and the third by allowing the lime to slake by absorbing the moisture of the atmosphere. Rich limes are capable of being slaked by immersion and kept in a plastic state. They gain in strength by being kept under cover or water. All rich limes may be slaked by mixing with a sufficient quantity of water, so as to reduce the whole to a thick paste. Lump lime should be first broken into small pieces, placed in layers of about 6 inches thick and uniformly sprinkled with water through a pipe, having a rose at one end…and covered quickly with sand. It should be left in this state for at least 24 hours before being turned over and passed through a riddle *[dry-slaking]*. The layer of sand retains the heat developed and enables the process of slaking to be carried out slowly through the mass…

Mortar …for plasterwork it is usually composed of slaked lime, mixed with sand and hair and is termed 'coarse stuff'…In Scotland the coarse stuff is generally obtained by slaking the lump lime…with a combination of water sprinkling and absorption. The lime is placed in a ring of sand, and in the proportion of one of lime to three of sand, and water is then thrown on in sufficient quantities to slake the greater portion. The whole is then covered up with the sand, and allowed to stand for a day; then turned over, and allowed to stand for another day; afterwards it is put through a riddle to free it from lumps, and allowed to stand for six weeks to further slake by absorption. It is next 'soured' - that is, mixed with hair ready for use. Sometimes when soured, it is made up in a large heap, and worked up again as required for use…. Now, while all this precaution is taken in regard to plastering, in making mortar for building the lime is slaked and made up at once, and it is frequently used within a day or two. But this is not all. Limes which are unsuitable for plasterwork, known as hot limes, and which, when plasterers are obliged to use them, must be slaked for a period of - not three weeks, but more - nearly three months before using, and are then not quite safe from blistering, *are the limes mostly used for building purposes."*

All of this said, the material evidence is that many plaster mortars, both base and second coats, for both flat walls and run in-situ cornices, were mixed and even applied whilst still hot and Lazell bemoans this practice still in 1915, in New York City:

"In the present practice more often than not, the plaster is placed on the wall or the mortar laid between the bricks within a few hours."

Abraham Rees (1819), in a long, detailed description of the process of and the general need for the souring of lime mortars (which he defines as the process of laying them down, not exactly as Millar does),

"if it be intended to have a perfect kind of plaster, which is capable of remaining smooth on the surface and free from blisters, there is an absolute necessity for allowing the lime of which it is composed, to lie for a considerable length of time in maceration with water, before it is wrought up into plaster, which is a process or operation that is here termed souring,

but also suggesting that the more pure the limestone, the less the need for such souring will be and asserting that the objective should be to use the lime or the coarse stuff as promptly as possible, since the longer it is kept, the lesser will be its usefulness and ultimate strength, "In the making of good mortar, it will consequently be necessary to get the best burnt lime, and to only suffer it to macerate or sour with water a very short time before it is wrought and applied."

As Nicholson indicates in 1842, the addition of gypsum to plaster finish coats, was common from the earliest period. Vitruvius counselled against it, even in his time:

"For these (ceiling finishes), **gypsum is the last thing one wants to mix in;** instead, they should be composed of marble sifted to a uniform consistency, **so that one part will not anticipate the other in drying, but the whole will dry at a uniform rate…"** Vitruvius

The addition of small volumes of gypsum had a double practical advantage – it accelerated the initial set at the same time that its expansion upon setting counter-acted the tendency of the lime to shrink.

In the early years of the 20thC it became quite common for the first time (although Gillmore had spoken of it as a possibility, when early setting was essential, in the 1860s) to add gypsum to first and second coats as well, under pressure of time in new-build construction.

"For many years it was the custom, when work had to be hurried, to mix plaster of paris with the coarse undercoating in order to speed up the hardening process and allow work to proceed without waiting for natural drying to take place….
It has to be realised that when plaster of paris or any other setting agent is added to lime, it is only that agent which actually sets, not the mass of lime with which it is mixed, and that the moisture contained in the mass has still to be evaporated; also, until evaporation takes place, the lime cannot carbonate….

Internal Plastering – Plastering to internal surfaces is carried out with sanded mixes of a) lime, b) plaster or c) lime gauged with either plaster or cement….

Nowadays, plastering is hurriedly done on walls, etc that have not properly settled down, subjected during application and afterwards to jarring and other disturbance from other tradesmen working on the completion of the building. These conditions have led to certain modifications in practice, with the idea of facilitating application earlier in the building programme, and in a shorter time; also to give the sufficient early strength to enable the work to withstand vibration etc, without weakening the bond. To ensure this the lime is gauged with material having a more rapid set, hydraulic or otherwise, plaster or cement being commonly used. Alternatively, plaster may be used without lime, sanded for undercoats, and either lightly sanded or alone for finishing coats. " (Modern Practical Building Magazine 1937)

Sawyer recommended as little as one twentieth part of Portland cement to the coarse stuff for interior works in 1951, and interior plasters of probable 1:2:9 or 1:3: 12 are not uncommonly encountered in old buildings, executed in the 20thC, but before it became common in refurbishment to 'tank' interior walls with much harder and much less breathable sand-cement mortars prior to the application of gypsum skim finishes.

Also in the 20thC, it became common to run quicklime from mortar mills into large and deep lime pits, typically dug on site. Conservation stonemason David Edgar's grandfather, NAME, was a scaffolder based in Liverpool in the 1950s:

"…He recalls lime pits on sites all over the UK in the 50s. He told me that lump lime was delivered to site and put straight into the roll-pan mixers (he described a circular drum with a lip of only 6 inches or so, and a stone wheel rotating and crushing the lime – he said it was like a flour mill). He says that the plasterers had a "soil-pit" dug up to 10 ft deep and this is where they ran the lump lime to putty. Interestingly, he remembers it going into the soil with the consistency of milk. He reckons they couldn't have left it more than 2 weeks before using it – and that it was still hot and dangerous when they opened the pit up to use it. He made specific reference to a couple of council estates being built in the 50s, in north Liverpool. Brick exteriors, lime plaster interiors, apparently. He said the brickies used the putty too,

I asked him if he ever saw the lump lime being mixed with sand right away and used there and then and he said "no, that was your crowd, the stonemasons, who used it like that (Edgar pers comm 2016)".

Similar was still being practiced at Wells Cathedral when conservation works began in 1975.
In both cases, it is almost certain that the coarse stuff produced was gauged with Portland cement (or with gypsum for plasters), just before application.

Throughout the lime revival, lime plasterers continued to use lime putty, but as the sole binder, sometimes enhanced by the addition of small volumes of pozzolan – some, at least, had doubtless never stopped, whilst industrially produced hydrated lime was extensively used as the primary binder during the earlier 20thC, not always run to a paste or putty before use, in both the UK and, perhaps more extensively, in the North America. Many stuck to, or else came to prefer plasters mixed at 1:2 slaked lime: sand, reflecting historic proportions.

In recent years, numerous plasterers have switched to hot mixed lime plaster, mixed typically at 1:3 powdered quicklime: aggregate, finding the additional adhesiveness and better water-management (the water being much better locked-in) of such mixes. When made with powdered quicklime, as most have been, such hot mixed plasters may be applied hot without fear of late-slaking, and hot application has been found to result in less shrinkage as well as earlier stiffening, though actual carbonation rates remain slow, and are the slower the greater the proportion of the lime, lest this is for thin finish coats. Whilst eminently ‚sticky' and more ‚flowing' when hot, a hot mix allowed to cool for some hours, or overnight, will be no less adhesive whilst being somewhat more elastic, which some might prefer, although initial stiffening will be somewhat less rapid. None of this is to say that putty lime-based plasters are especially inferior – as with mortars for other uses, they will be workable and effectively applied, as well as fit for purpose, and will never cause dampness or decay to the fabric they are a part of. Exemplary and durable work has been regularly and routinely accomplished with putty lime bound mortars throughout the period of the lime revival and continues to be effected today. It has been a shock, and even an embarrassment to the author to have discovered in the course of the research that has informed this book, to discover how little historic precedence putty lime has had as a primary binder. It would be a mistake, however, and as has hopefully been demonstrated elsewhere, to assume that only interior plasterers routinely used pure or nearly pure limes for their trade – it is just that the location of their craftsmenship allowed them to continue much longer in doing so, and with the explicit approval of specifiers and engineers otherwise increasingly condemnatory of such routine use elsewhere upon the building.

Limewashes and Sheltercoats

The typical specification for limewashing – called 'lime-whiting' historically was generally two coats, sometimes three, and immediate indication that limewashes used during the lime revival have been somewhat different in character.

Limewashing was routine for both low and high status buildings. York Minster was routinely lime-washed, still in the 19thC, with recipes that often included egg-whites or other proteins (Holton 2011?). If not limewashed, then buildings were colour-washed, with alum, not lime as the binder. These latter were much thinner surface treatments, and remained common for brickwork late in the 19thC (Hammond 1890). The original and regular lime-washing of stone buildings was anticipated and expected by the masons who built them, just as, very often, was lime rendering part of the original construction. Such renders would be lime-washed. Most of these treatments have been lost, sacrificed to an increasingly archaeological ideology that celebrated the 'antiquity' of naked stone facades. This ideology remains dominant today, and many home-owners, as well as conservation professionals, baulk at the idea of re-establishing lime renders (which predominantly survive in the west of the UK, where driven rains reinforce their utility, or in high places, where similarly driven rain is the norm. Look closely at any stone building, and upon its more sheltered parts, such as just beneath the eaves, or in architectural nooks or crannies, one will usually find evidence of historic lime- or colour-washing. Copperas and alum was a common combination – in London, Lincolnshire and very much so in North Yorkshire, the coast of the latter having been a centre for alum production from the late 15thC onwards. Copperas, or ferrous sulphate, often referred to as 'green copperas' in London due to its green colour when applied, and before oxidisation turns it to a deep orange hue, was a by-product of alum production, the two elements separating from intimate combination to produce each. Colour-washes reunited them, as well as offering a mild biocidal effect. Across Europe, the patterns of traditional building construction are more extensively preserved, albeit too often these days, renders are renewed with cementitious materials and colour coats with modern, non- or very little breathable paints, and naked stonework or even brickwork is much less generally observed. This perhaps peculiarly British pre-occupation with bared masonry has clouded our appreciation that breathable and inherently porous surface treatments, whether of earth or lime renders or of lime wash, or both, were not primarily an aesthetic, but actually an important structural element of traditional building technology. A lime render high in carbonated free lime enjoys eminent effective porosity (see Wiggins, Chapter). This is only enhanced by the application of a limewash entirely or, if pigmented, almost entirely comprised of free lime. Research by the Portuguese Technical University has recently demonstrated, and contrary to expectation, that all substrates, from the most to the least porous, will be dried more effectively – and to greater depth – with a limewash treatment than without it (Viega et al 2010). Similarly, a render-coat, even one as thin as a typical Scottish harl, will also maintain the main body of a wall in a greater state of dryness than would be the case in its absence. This effect will not be re-produced if the render coat or limewash is based upon cement or NHL binder, although an older 1:2:9 or 1:3:12 cement-lime render will have significantly higher levels of free lime than a typical NHL 3.5 or NHL 5.0, and an NHL 2.0 would need to be mixed at 1:2 to begin to approach similar levels of free lime content as even a 1:2:9 mortar. NHL limewashes tend towards excessive brittleness to boot.

Historically, and particularly in London and other metropolitan centres, lime renders were displaced quite early by renders composed of harder, denser binders – it was generally assumed by architects and engineers that exterior surfaces demanded coatings significantly harder and stronger than the bedding mortars. From the later 18thC on, patented mortars based variously upon more energetic hydraulic limes, often with gypsum addition, or even of quicklime slaked with sulphuric acid instead of water to produce calcium sulphate, gypsum (Keene's or

Scott's cement) were deployed, along with natural cement renders (after 1796) and then, of course, Portland cement renders from the later 19thC onwards. Such mortars are not the focus of this book, except insofar as they caused serious problems for most of the structures to which they were applied. Many, especially those which contained gypsum, failed very soon after application, and were typically renewed with natural cement renders. Most of these patented materials were fundamentally incompatible with the fabric to which they were applied, most of which was constructed using either earth-lime or hot mixed air or feebly hydraulic lime mortars. Most will have promoted dampness in the fabric of the buildings; most were too brittle to endure upon flexible and deformable fabric without cracking, thereby allowing the damaging ingress of more moisture.

Across much of the UK, however, fat or feebly hydraulic lime renders remained common and would have been routinely limewashed as part of their maintenance. The historic perception that porous materials let water into themselves as readily as they let water out of the interior fabric – and which led so many down a wrong road – endures today, even in the world of building conservation, where 'capillary closed-vapour open', pre-mixed repair mortars are commonly promoted and 'patented' in imitation of the commercially driven mistakes of the past. As david Wiggins's and others' informed research indicates, effectively porous and hygroscopic building materials, whether bedding or pointing mortars, interior or exterior plasters or applied paints, do not lead to wet buildings – in fact, they lead to dry and drier buildings than we have become used to, such has been the abuse of our traditional fabric with inappropriate and little-breathable materials. Earth-lime and fat and feebly limes of high free lime content, typically hot-mixed, are eminently breathable and the application of these to traditional fabric quickly dries this fabric, as our own experience has demonstrated on numerous buildings across the UK in over a decade of using such mortars.

Historically, lime-washes were made according to the same, basic principles of lime slaking for mortars. They were typically made straight from quicklime and this quicklime was slaked with the necessary minimum of water to ensure the necessary temperature of the slake to maximise the proper performance of the lime.

A slight excess of water would be added to the lump lime to effect the slake; or else the lump lime might be added to a similarly calculated excess of water. Stirring would commence immediately, to encourage the breaking down of the lump. Once slaking was complete, or as it reached completion, and whilst the lime paste remained very hot, more water would be added to dilute the wash to the desired consistency.

The process was identical, in fact, to the preparation of lime putty for gauged brickwork, or of hot lime grout for walls, but with further dilution:

"The Mortar in which rubbed and gauged Bricks are set is called Putty, and is thus made:

Dissolve in any small Quantity of Water, as two or three Gallons, so much fresh Lime (constantly stirred with a Stick) until the Lime be entirely slacked, and the whole become of the Consistency of Mud; so that when the Stick is taken out of it, it will but just drop; and then being sifted, or run through a Hair Seive, <u>to take out the gross Parts of the Lime</u>, is <u>fit for Use."</u> (Langley 1750)

"The term putty, better known as the cement for fixing glass in windows, is applied in brickwork to a very different substance, which is nearly the same as hot lime grout, It is made by dissolving in a <u>small</u> quantity of water, as much hot lime as, when slaked, and continually stirred up with a stick, will assume the consistency of mud…It is then sifted, in order to remove the unburnt parts of the lime, and should be used without delay (Pasley 1826)

There are farmers across the UK who remember this process, having used such limewashes in animal sheds for their sanitary and anti-septic benefits. In urban centres, hardware shops would supply limewash to customers, freshly slaking the lime in the back yard. ??? remembered making limewashes in his uncle's shop in Grewelthorpe, near Ripon in the 1930s and 40s. Customers would come with metal buckets to collect it for immediate use. (Oral history Grewelthorpe Village web-site).

As with lime putty for finish coats and for fine masonry joints, it was necessary for unslaked lumps to be removed by sieving, although this was not always necessary if the use was of a more rustic nature – larger lumps will tend to sink to the bottom of the bucket as the hot limewash begins to cool during application. For higher status use, the removal of unslaked lumps was essential, and the initial application of the limewash was but the beginning of a process. As the thickly applied hot limewash began to become gelatinous, the surface would be burnished, or polished with a dry brush. Externally, this process could make a limewash virtually impenetrable to driven rain; internally, it would advertise status and make a surface more amenable to wiping without dissolution of the lime. This could be time-consuming. On the Goddards Estate in Swindon during the 1860s, workers were paid 3d a yard for plastering, but 4d a yard for several coats lime-whiting, whether internally or externally (and houses were being regularly limewashed) (Wiltshire Archives **1461/928-940).** This seems quite counter-intuitive to us today.

During the lime revival, lime-washes were typically diluted from already slaked lime putty, the lime having very often been drowned during slaking and with poor cohesion as a result, if historic authorities are to be trusted. Hot mixing with quicklime generates a powerful bond between all of the ingredients of a mortar or slurry, with the aggregates (if there are any), the lime *and the water*, well-integrated together, indicating strong inner bond or cohesion. Pigments would be added to the slaking or just-slaked lime for this reason and craftspeople using hot lime washes today report that less pigment is required in a hot limewash than in a cold-mixed wash to achieve similar depth of colour. If tallow or linseed oil is to be added (in very small volumes), the heat of the slake will melt and thoroughly engage these additives with an efficiency that cannot occur if the same are added to a cold lime wash. Salt was also a common addition – often considerable volumes of salt – which was 'locked in' by chemical reaction with the lime and unavailable, therefore, to even the porous fabric of the building. This latter was considered to toughen the surface. The addition of oils or fats, however, is likely to compromise the effective porosity of the lime wash and should only be considered in the most exposed of situations. Bill Revie maintains, doubtless correctly, that a properly burnished straight limewash is the most resistant to penetration by driving rain (pers comm 2017).

Wherever possible, lime-washes, much thicker than we have become used to, would be applied hot, and applied thicker than has been the norm with limewashes made from cold putty lime. When the author lived in Andalusia in the 1980s, quicklime could be purchased in sachets at the local grocery store, to be slaked and used hot during the annual 'blanceado' of house exteriors.

A hot limewash, thick enough that a dipped brush will not drip, may be thickly applied and easily thinned a little on the wall – hot lime 'flows' and spreads very readily. As long as this is evenly applied, shrinkage and crazing is rare and the thickly applied wash turns to putty, in effect, in situ, at which point it may be left to simply carbonate or burnished.

The 'rule' of the lime revival, that lime wash should be applied in '7 water-thin coats' has no historic precedent, even in the 20thC. It was a rule, like others developed over the last 40 years, to make the best of using the wrong material. A lime wash mixed thickly from a cold lime putty will, if applied in the sorts of thickness observed upon the walls of old buildings, shrink and craze uncontrollably. The only means of achieving successful coverage is to dilute the lime wash to 'water-thinness', slowly building up to perhaps the thickness of one coat of traditional lime wash. It often lacks the deep lustre of a traditional, thicker-applied lime wash, and most certainly lacks similar tenacity, requiring regular re-treatment – a process that discourages many from applying it at all. A hot mixed and hot applied limewash may be anticipated to last decades, not months or years, in the absence of obvious decay mechanisms. The addition of fine aggregates – creating a lime 'sheltercoat' will potentially enhance this longevity.
(YORK HOUSE Pics)

The resistance of a hot limewash to crazing endures when the limewash is used cold, as long as the mixing was done 'hot', though it may be necessary to dilute the limewash somewhat more and so long as it is used whilst still fresh – typically, as many historic authors asserted about lime mortar use, within a week.

If it is pigmented, the colour will be immediately apparent as the limewash is applied, although darker, of course, than its ultimate, carbonated hue. This will surprise those familiar with the application of modern limewashes, which typically only attain colour upon carbonation.

Aesthetically, and in the same way as do lime renders, limewashes 'solidify' and 'ground' a structure, but more importantly than this, they make a significant and sometimes a necessary contribution to keeping a building dry. Limewash is the cheapest and at the same time the most efficient surface treatment that may be applied to a building of traditional construction. A single 25kg bag of quicklime, retailing at around £10 a bag can frequently be sufficient for the limewashing of a whole house exterior.

Sheltercoats.

Sheltercoats and sheltercoating are very much a product of the 'lime method' developed by Professor Baker during the conservation of stone statuary at Wells Cathedral, after 1975 and at Crowland Abbey after 1977, and its rationale and execution is beautifully described by Baker himself in one of his note-books:

…With regard to the durability of English building stone…we find that the stone of medieval buildings great and small was protected by lime and stone dusts covering the ashlar which served to prevent moisture and pollution entering the pores. The evidence reveals that even with Victorian thoroughness in scraping it away, there remains convincing proof that the sculpture (at Crowland) was painted and the mouldings were coloured with coats of paint and ground - keeping the stone face from pollution for at least two centuries. Today we cannot repaint either figures or mouldings since the surface has weathered back and is no longer a paintable surface and, of course, it would be completely out of fashion. But is is possible by the use of lime and stone dusts to obtain a more weatherproof surface; to repair badly exfoliated cavities and to prevent this hard calcite skin again thickening to the stage of exfoliation…

(After lime mortar repair) the masonry and figures were given a shelter coat of stone dust, brick through a 60s to 80s sieve, old lime putty and skimmed milk which after application was rubbed back hard until the higher parts of the stone appeared…Sheltercoats are varied to match changes in the stone so that the overall effect is not that of a coat of lime wash, though interestingly enough, the choir on the south side of Tewkesbury Abbey is still covered with medieval lime wash and here at Crowland the same treatment remains visible on the second and third tier figures to the right of the window opening…"

In current conservation practice, many adhere to Baker's practice of applying and then substantially rubbing off a shelter-coat generally colour-matched to the host stone when freshly cut. Others (the author included) prefer to apply similarly colour-matched sheltercoats as thicker, 'aggregated limewashes' (Holton), in keeping with the general observation that medieval stonework of all kinds was typically limewashed, and especially where evidence remains in situ of such limewashing.

Sheltercoats mixed with cold putty lime and well-graded aggregates during the lime revival have been perennially problematic, or, at least, irritating in use – the aggregates rapidly sinking to the bottom of the container after stirring, so that constant stirring followed by immediate application has been required.

Hot mixed sheltercoats, however, do not suffer this drawback – aggregates added during the slake hold up in the mix, in keeping with the normal cohesiveness delivered by the hot mixing process. Although these will settle over time and once the sheltercoat coold, stirring re-engages them and they remain in suspension throughout the application process.

Fresh-slaked sheltercoats will be applied hot, typically, as per limewashes. They are much less likely to dry too fast, and are certainly less likely to do so than cold putty lime-based versions. Sheltercoats should be mixed to a similar viscosity to limewashes, and prepared either by adding a small surplus of water to lump or kibbled quicklime, stirred during slaking and diluted to taste thereafter, or by incrementally sprinkling powdered quicklime into water until sufficient quicklime has been added to make the solution very hot and sufficiently thick. Sand and other aggregates may be added as slaking proceeds, or immediately after this is complete.

(Crowland Abbey, Foston, Malton Priory pics)

Hot Lime Grouts

The routine grouting of the cores of solid walls of traditional composite construction, with typically two leaves of stone, frequently dressed in different ways, the internal space between them carefully in filled with rubble and with fragments of stone, is frequently referred to in old texts. The intention was to fill the interstices between the stones with mortar, binding the two faces and the core together. Generally speaking, a solid, well-filled core is the key to a wall's longevity. Any voids within a wall will prevent the movement and exit of moisture from the fabric by capillary action and will channel intruding liquid moisture along unpredictable and often problematic pathways. The advent of cavity walls has perhaps dulled appreciation of this truth in the minds and practice of many, even of builders themselves. Few builders of new walls today will have been permitted to build solid walls at all in any way resembling those of the past, typically between 18 and 21 inches in thickness when of stone (although sometimes slimmer than this when made entirely of one skin of ashlar). Bricks walls, too, were often of similar thickness, but have become slimmer over time as the mortars used have become harder in their binders.

A conscientious mason will lay his or her core work in a good bed of mortar and endeavour to slap mortar into the interstices between the rubble as it is placed, making the mortar wetter, perhaps, to facilitate its movement into these. This will not always guarantee full closure of all of the spaces. To create a completely solid mass, therefore, regular grouting of the wall as it rises was common craft practice in all historic periods and is generally specified and insisted upon throughout the 19thC.

Archaeological examination of the walls of medieval buildings, when these were built with lime-sand and not earth-lime mortars, would clearly indicate the practice of hot lime grouting at this time. Lest the walls have dramatically settled or be rent apart by seismic or military force, voids within the core of medieval masonry are rarely to be seen. A scattering of air bubbles might be however (Doglioni, presentation, Valencia 2015), the result of a hot and perhaps still-slaking hot lime into a variously voided core.

Smeaton discusses the 'normal' practice of adding water to and diluting already hydrated lime for grouting, but most texts explicitly call for hot lime grouting. Davy (1839) says that this should be done with the just slaked liquid mortar, containing sand, 'used as hot as is consistent with the safety of the work', uniquely taking account of the potential hazard involved.

Pasley(1826), as well as others, extended the well-established masonry practice of hot lime grouting to brickwork, it being executed every three or four courses, although it must be said that the author has yet to dismantle a brick wall upon which this operation has been obviously performed in the stead of properly buttered bricks and properly mortar-filled joints:

"In the new docks in Her Majesty's yards at Sheerness and Chatham, grout was used for all the rough parts of the foundations and walls. It was composed of Dorking lime ground in the mortar mill, but not slaked, and of the proportion used for the lower part of the foundation…one part of lime to four parts of sand. These ingredients, mixed together dry, were wheeled to the walls, and made into grout…and pouring it **instantly** into all the vertical joints of each course of the brickwork. (later inspection during an alteration showed a)…very intimate cohesion of the parts.

"Mr Smirke, the architect, has recently made great use of grouted gravel for the sub-foundation of considerable buildings. One measure of pounded Dorking lime, **not slaked,** and five measures (in some cases, but more usually seven measures) of clean gravel are mixed together with water, and poured into the trench or excavation…

Hot lime grout has also frequently been used in rough work. This is made by stirring up (just-) slaked lime in water, without any other ingredient, and pouring it into the joints of each successive course…"

Pasley specified feebly hydraulic lime for the purpose, to encourage early stiffening, but a pure lime grout, poured hot and even still partially slaking, also stiffens readily, particularly amidst porous stone, and the addition of fine aggregates to the grout, particularly fine porous aggregates such as crushed limestone or sandstone, would enhance such stiffening, as would, of course, the addition of finely ground pozzolans.

The specification for the Canadian Parliament building in Ottawa, as well as calling for the building mortars to be used 'as hot as possible', further required that the foundation be built with "Large, well-bedded and well-bonded stones laid in mortar and properly grouted with hot liquid mortar" (Fuller and Jones 1859). The specified local limestone was, if hydraulic at all, only very minimally so.

The specification for the Palace of Westminster required that for the foundations and water works, "The granite work throughout is to be laid on a thin bed of mortar prepared as hereafter described, the face of the joints being pointed with cement, and the rest grouted full with mortar….

The mortar for the granite work is to be composed of one measure of fine ground genuine Italian pozzolana, two equal measures of clear river sand, and one equal measure of good fresh burnt Dorking lime mixed with water and well worked to a proper consistency, and in that state ground with edge stones…." (Barry 1839)

The primary advantage of using a hot lime grout, apart from its inevitable subsequent stiffening in situ, is the propensity of hot lime to flow. Experiments carried out with Doglioni in Valencia in 2015, with buckets filled with assorted stone and old mortar rubble saw the hot lime grout fully penetrate the matrix, in contradistinction to the behaviour of modern, proprietary conservation grouts of various chemical composition. When grouting standing walls with hot lime grout poured into a funnel and into an attached hose-pipe inserted into the wall, no blockages are typically experienced. All who have grouted with cold putty or natural hydraulic lime grouts will know that such free movement is not always so often the case.

The mixing procedure was similar to that for making putty lime or limewash, or, indeed, sheltercoats. For aggregated grouts, the ordinary method of mortar mixing might be applied, with dilution taking place as soon as the lime had slaked.

Concretes

Roman concretes were typically hot mixed and comprised sand, stone, true pozzolan from Puzuoli and/or pulverised and kibbled brick and, typically, air quicklime. These set promptly in the air and underwater and needed no 'expansion joints', being monolithic masses of concrete.

"whatever the weight of stones when they are cast into the furnace, they cannot have retained it by the time they are removed, when they are weighed, although their size remains the same, they will be found to have lost a third part of their weight because of the moisture that has been cooked out of them. And thus, **because their pores and spaces lie so wide open, they absorb the mixture of sand into themselves and hold together; as they dry, they join together with the rubble and produce the solidity of the masonry….**When these three ingredients (lime, rubble and pozzalana), forged in similar fashion by fire's intensity, **meet in a single mixture, when this mixture is put into contact with water, the ingredients cling together as one and , stiffened by water, quickly solidify.** Neither waves nor the force of water can dissolve them….
[In building with pozzalana underwater] unlike and unequal entities that have been forcibly separated **are brought together all at once.** Then the moisture-starved heat latent in these types of ingredients, **when satiated by water, <u>boils together,</u> and makes them combine.** " (Vitruvius 60BC Rowland and Howe 1999).

The use of monolithic concrete such as Vitruvius describes, whilst practiced by the Romans in Britain, ceased upon their withdrawal and did not see a significant revival until the turn of the 18thC, although fat lime floors were common before this, as they had been in Rome and Greece in the classical period, and similar decline did not occur in Spain, where the medieval walls of Valencia were constructed of mass, probably hot mixed lime concrete, 'Tapia Valenciana', distinguishing it from the more general rammed earth construction of the Moorish period, though this, too, had betwwen 10 and 20% lime content, doubtless added originally in the form of quicklime (Vegas Milleto Soria 2012).

Fat lime floors were time-consuming to lay and required significant on-going attention before they could be considered done. It is important to say, however, that the Romans and later writers on the subject of concrete floors saw this as a form of plastering – even in 1861, in the specification for the Canadian Parliament building in Ottawa, the laying of hydraulic lime concrete floors, as well as its topping with Portland cement finishing screed, was considered the remit of the plasterers (Fuller & Jones 1859).

This harks back to the earliest recorded uses of lime in the Neolithic period, when (hot-mixed) earth-lime floors were laid within dwellings otherwise constructed using earth mortars (Karkanas & Statouli).

Pliny (23-79 AD) describes 'Grecian Floors' thus:

"The ground is well rammed down, and a bed of rough work, or else broken pottery, is then laid upon it. Upon the top of this, a layer of charcoal is placed, well trodden down with a mixture of sand, lime and ashes; care being taken with line and rule to give it a uniform thickness of half a foot. The surface then presents the ordinary appearance of the ground; but if it is well rubbed with the polishing stone, it will have all the appearance of a black pavement."

Vitruvius:

FLOORING

…When the decking is finished in an upper story, it should be strewn with fern, or otherwise with straw, so that the woodwork will be protected from damage by lime. 3. Above this the underlayer is set down of stones no smaller than can fill the hand. Once the underlayers have been installed, if the rubble for the sub-pavement is new, then mix it **three to one with lime;** if it is re-used, then the mixture should be **five to two.** Then the sub-pavement is laid in with wooden rods by ten-man work gangs, and compacted by steady pounding. By the time the pounding is done, it should be no less than a *dodrans* (three-quarters of a foot) thick. Above this, a core of **crushed terracotta** should be installed, **mixed three-to-one with lime,** and it should be no less than six digits thick. Above the core the pavements should be laid to the square and to the level, whether they are in stone inlay or mosaic….

'Plastering the floors of the upper room' appears as an item in the building account for the New Hall at Pickering Castle in 1313 (Turton 1895), though this may have been effected with plaster of Paris, which is recorded elsewhere in the account for the making of a chimney piece. Plaster of Paris was much used in association with the laying of floor tiles during the construction of York Minster in the 14^{th} bd 15^{th} centuries, the gypsum being calcined on site (Brown 1862).

Lime-ash, as well as gypsum floors are commonly found across the UK, to upper and ground floors, as well as clearly pozzolanic concretes, typically around 2" thick.

Air lime mixed hot with significant wood ash addition will form a relatively fast-setting and robust concrete, as, surprisingly, will a 1:3 hot mix of powdered quicklime and wood ash without aggregate addtion – this latter also being lightweight and eminently porous.

Other traditional floor concretes will have been made of the mixed quicklime and fuel ash detritus from the bottom of lime-kilns, the majority of the quicklime having been removed clean. Higgins (1780) notes the use of wood or sea-coal ashes instead of sand for the lime concrete sub-floors beneath tiles, in order, the masons said, to eliminate shrinkage, He does not mention the inevitable hydraulic set such aggregates would have induced, writing before the publication of Smeaton's seminal insight into the source of hydraulic activity. Langley's earlier recommendation for such sub-floors was to take "two heap'd Bushels of hot Lime (putting) one heap'd Bushel of Brick-dust made from red Stock Bricks, which mix, beat, and work up, as before directed for Terrace" noting that this was 'This is an excellent Mortar for to lay Face Tiles or Ten Inch Tile Pavements in on Floors which are naturally wet or damp" (Langley 1750).

All proscriptions for the mixing of pozzolanic mortars, the aggregates entirely of pozzolan stress the necessity of well-beating the mortar to bring it to mortar consistency, rather than adding too much water. Langley says that such beating would be 'a good day's work for one labourer'.

Smith (1834), considering economic housing solutions for the rural poor of the Highlands of Scotland proposed floors of "a composition of **lime, earth, and engine ashes, mixed up in equal proportions**; this to be laid over to the thickness of 3 inches above a level stratum of dry stone shivers well beat down".

All of the above have been generally characterized as 'lime-ash' floors. Similar mortars were used for the lining of cisterns and basins.

Marshall accounts lime concrete floors to be an innovation in Yorkshire (and particularly in the Vale of Pickering in 1788, describing the method of their laying in detail:

"….MORTAR FLOORS. A new species of cottage flooring has lately been thought of, and is now pretty commonly formed, in this neighbourhood.

The materials are lime and sand; mixed in nearly the same proportion, and prepared in the same manner, as the common mortar of bricklayers; except, that for forming floors with is generally made stronger, and is always made up softer, than it is usually done for laying bricks in.

The *method.* The bed being prepared, the materials are carried on, in pails, **in a state between paste and batter;** laying them on four or five inches thick, and about one inch higher than the intended height of the floor, to allow for the settling, in drying. The whole being well worked over with a spade, the surface is smoothed with a trowel; and as it dries, is beaten, repeatedly, with a flat beater, to prevent cracking; the workman, in this operation, standing on planks.
A fortnight or three weeks dry weather will render it stiff enough to walk upon. If, after the last beating, cross lines be deeply graven on the surface, a floor of cement has the appearance, as well as the usefulness, of a freestone floor.

In France and Spain, concretes for building foundations and engineering works – called 'beton' - were typically made by a version of the 'ordinary' method, quicklime being slaked to a thick dough-like consistency before being mixed with the sand and larger rubble aggregate, though the lime may well have remained hot when this occurred. The emplaced concrete was compacted in situ with rammers.

This followed the same method as was often preferred in these countries for the the slaking of lime for general mortars, most succinctly described by Biston:

“Slaking by fusion, also called ordinary slaking, has to be done in impermeable basins with only the necessary quantity of water to reduce the lime to a thick mush. We will be careful to give all the water it needs in the first instance, only coming back to it at the moment of the effervescence (to add more) or else, wait for it to cool and then add some more water. We will forbid in all cases, the method followed by some masons of drowning the lime in a large quantity of water, reducing it to a milky consistency before pouring it into permeable pits where it dries out and loses its qualities. When we need to keep the lime after it has been run, we will cover it with earth or sand.

In Britain, however, concretes were always made by mixing the unslaked and previously pulverised lime with the other ingredients before the addition of water, immediately after which the concrete was launched from scaffold platforms raised over the work (from typically ten feet above its destination) before being leveled as necessary. This method was generally assumed to avoid the need for subsequent ramming, although some engineers felt that the impact might adversely separate the constituent parts from one another to the detriment of quality. Pasley says such tamping was anyway part of the process:

Concrete is formed by mixing lime, coarse gravel and sand together, with a moderate quantity of water, which is usually done on a large square board, having a margin raised a little above it on three sides only. The lime used for this purpose has usually been reduced to fine powder by pounding or grinding it, whilst fresh from the kiln; and it is generally considered of so much importance not to slake it until ready for use, that it has been customary to mix it with the gravel and sand in a dry state for a little while, before the water was added; after which the whole of these ingredients have been intimately mixed, with as much expedition as possible, by employing two labourers to work together at each of the mixing boards, which being always placed as near to the spot previously prepared for the foundation as possible, the concrete is either thrown down at once or wheeled a little way and dropped down from a temporary scaffold with moveable planks…into the excavation, where it is spread and leveled, and trodden down or sometimes rammed by other labourers below….Concrete made in this manner, according to the system first introduced by Sir Robert Smirke, throws out a moderate heat on the slaking of the lime, and soon begins to set, forming in time a kind of artificial rock….(Pasley 1838).

Brees (1852) says that concrete was first used for footings by Ralph Walker in 1815 at the West India Dock in London and then at the Customs House, ‘after piles had failed’. He adds that it should be ‘always used hot’ and advocated one to 7 or one to eight, even with feebly hydraulic lime.

In Pasley’s time, the limes used were the feebly hydraulic grey chalk limes from Surrey (Dorking or Mertsham) or from Halling in Kent. Once the railways made it possible to carry Blue Lias from Somerset, Leicestershire, Wales or Dorset, this was preferred, being recognised as of the strongest available character.

When feebly hydraulic lime was used, the proportion of quicklime to aggregate might be 1:6; once blue lias became the norm, the proportion was more often 1:7 or even, on occasion 1:8. This will be surprising to those routinely specifying modern lime concretes at 1:3 with NHL 5.0, typically significantly stronger and with a significantly lower free lime content than a typical blue lias NHL.

(Calgary Cathedral footing pic)

"… The concrete-work is to be formed in the proportion of six parts by admeasurement of clean Thames stone ballast, unscreened, and with rough and fine intermixed, and one part by admeasurement of the very best fresh burnt Dorking stone-lime (or other stone-lime as the case may be) beaten to fine powder on the premises without being slaked (Bartholemew 1840).

"… The concrete of the foundations of all the walls is to consist of 6 measures of gravel and sand to 1 of ground lime, **mixed dry, and then well worked together with water,** and in this state teemed and thrown into the work from a height of at least 10 feet, and is to be brought to a level surface at the proper depth to receive the first footing-course, which is to bed solid upon it…." (Barry & Lee Palace of Westminster Specification 1837)

Such uses for concrete were quickly adopted in North America, where either the French or 'English' method, as Gillmore characterised hot mixing of concretes, might be employed.

"Concrete (at the Canadian Parliament Building) to be formed of the best well-burnt hydraulic lime to 7 measures of gravel, sand and broken stones. The lime is to be ground and kept dry under cover in bags until used." (Fuller and Jones, 1859)

All 19thC authors writing in the UK concur on the use of lime lean, hot mixed concretes laid in whilst still hot. Burnell adds a nuance of particular relevance to potential modern applications of such concretes:

"Broken limestone appears to add very much to the qualities of concretes, betons and mortars. Very probably this may be attributed to the affinity between the molecules of the already formed carbonate of lime, and that which is in the process of formation; the new crystals may group themselves more easily about bodies whose form is similar to the one they are themselves to assume. Or possibly there may be a tendency in the chemical elements to arrive at a state of equilibrium; and the carbonate of lime may, therefore, be supposed to part with a certain portion of its carbonic acid gas."

Burnell could not have known this, but the use of limestone aggregates in mortars or concretes will enhance the effective porosity of a mortar or concrete, calcite having the pore size optimal distribution for effective porosity. The relatively low effective porosity of modern NHLs might be mitigated, therefore, by the use – in full or in part – of limestone aggregates (see Wiggins Chapter).

Clearly, these lime lean concretes have proved themselves entirely fit for purpose since their introduction during the 19thC.

They were generally displaced by Portland cement concretes at the end of the 19thC, but as late as 1901 Richards gives equivalence to concrete made with either Blue Lias or with Portland cement, both at a proportion of 1:8:

"Concrete. …the matrix should consist of either Portland Cement or Blue Lias lime and sand. The proportions for the concrete must depend upon the situation in which it is to be used; but for ordinary purposes the following may be accepted: 5 parts clean broken stone, brick etc: 2 parts sand: 1 Portland cement or Blue Lias lime. Or 7 parts Thames ballast (already containing sand): one part Portland cement, or Blue Lias lime."

The monolithic concrete walls of the first floor addition (1905) to the 1864 Marine Guardhouse on Cole Island, British Columbia, former site of a Royal Navy Magazine, were specified at 1:6 Portland cement: aggregate.

The foundations of other, late 19thC shell stores on the site were seemingly hot mixed with local air lime and Portland cement forming the binder.

(Pic of Guardhouse)

A concrete made as such a proportion, with modern Portland cement, possesses more than adequate tenacity with a much reduced density. It is to be wondered how the breathability of this might compare to a concrete made with a modern NHL 5.0 mixed at 1:3.

Mitchell's Construction continued to recommend hydraulic lime concretes for floors in 1912.

Specialist Mortars

In numerous building accounts, there is mention of 'cement' in contradistinction to the lime also mentioned. Many of these references pre-date the development of either natural or Portland cement; their quantities are generally low – they were clearly for purposes for which ordinary limes were inappropriate or likely to fail, though they often also contained some lime.

That said, some authors simply described common practices in other parts of the world, such as the inclusion of sugars in lime mortars, as was common in India:

Take 15 bushels of fresh pit sand, well sifted; add thereto 15 bushels of stone lime: let it be moistened or slacked with water in the common manner, and so laid two or three days together. Then dissolve 20 lbs of Jaggery, which is coarse sugar (or thick molasses) in water and, sprinkling this liquor over the mortar, beat it up together til all be well-mixed and incorporated and then let it lie by in a heap….the mortar… proves extraordinary good for laying brick or stone therewith.
Pyke and Halley (1732)

Dossie asserted that the addition of skimmed milk (casein) to the mortar would enhance its strength:

"**When a very great hardness and firmness are required** in this mortar, as in several cases where strong cement is wanted for stones; or for projecting parts of buildings, or other purposes; **the using of skimmed milk instead of water**, either wholly or in part, will produce the desired effect; and render the mortar extremely tenacious and durable." (Dossie 1771)

Rosin or pitch, egg-whites or blood might be deployed with similar effect.

(CEMENTS GLUES PASTES AND GUMS)

Mortimer (1708) recommends "a Cement of clean Hair and Tallow mix'd with unslack'd Lime and Yolks of Eggs well beat, and made into Powder, and mix'd well together" for stopping leaky cisterns and the like otherwise lined with clay and mortar.

Any fats or oils would need first to be melted to facilitate incorporation, and numerous recipes include 'unslaked lime', perhaps mainly for this reason.

Bitumen cements were also used, as they had been c2600BC in Mohenjo-daro (Jaggi 1969).

The Problem with Natural Hydraulic Limes (NHLs)

This chapter does not and will not presume to offer a detailed technical analysis of NHLs – which may be found not only among the writings of engineers from Smeaton onwards, as well as in numerous academic and technical papers of various practical usefulness over recent years. It is rather to give expression to the reservations about the use of these mortars, held by many stonemasons, plasterers and bricklayers in the past and which are shared by many masons today, who have been required to use these mortars for the repair and conservation of traditional fabric over the last 20 years or so; to examine the evidence for their regular use for building above-ground in the context of assertions during the lime revival that they were 'always' and 'frequently' used in this way, and to complement Wiggins's analysis of necessary pore structure and effective porosity with observations of the performance of NHLs used 'in the air' and primarily upon existing fabric not built with NHL mortars, but with earth-lime and fat or feebly hydraulic lime mortars. It will draw upon Cristiano Figuerides's and Historic England research into the properties and characteristics of modern, currently available NHLs and seek to demonstrate that these bear only passing resemblance to those used – mainly underground and underwater – in the past. It is the conviction of the author that currently available NHLs have very little usefulness in the conservation of the above-ground fabric of traditional buildings and, indeed, that such use has been mistaken and potentially damaging to historic fabric, most especially to that constructed wholly or in part with earth or earth-lime mortars, but also to that built with fat and feebly hydraulic lime mortars that enjoyed a high free lime content and a lower compressive strength than even the weakest of currently available NHL mortars. It will be argued that NHLs do not represent a like-for-like or generally compatible repair mortar and that long-understood problems of variability and variation, as well as of the practicality of their use 'in the air' raise serious questions about its advisability for new construction. Even for 'water lime' mortars historically, the consensus was that they were more reliably and predictably produced using mortars of pure lime, with pozzolan added in controlled and predictable volumes, reflecting Roman practice.

'Natural hydraulic lime' is not a term used historically before the 20thC, though, of course, the fact that it was made from naturally occurring, clay-bearing limestones was well understood once Smeaton had deduced that clay – and particularly – the silica and alumina content of these clays after firing in a kiln at traditional temperatures of around 1000 degrees C, were the primary source of hydraulic activity. Prior to Smeaton, there had been a variety of theories, focusing particularly upon the iron content of some limestones. Others had been content to observe that some limestones, from specific districts, produced, upon burning, a lime of somewhat harder and more rapid set, which might, depending upon its hydraulicity, set hard underwater. In districts where purer limes were not also readily available, these harder-setting limestones would naturally be used for general building works, although the prevalence of earth-lime mortars for general building across Europe well into the 19thC in many parts should not be forgotten, the general cut-off point for the routine, although never exclusive use of these for bedding and base-coat plaster mortars in England seeming to have been around 1800, coinciding with the full-blown seizure of the common lands by the rural ruling class, which deprived the general population of ready access to the raw materials of this long-established building tradition.

That the building crafts generally preferred to use 'pure or nearly pure' limes for their work, variously improved, according to intended use, by the addition of discrete volumes of pozzolans or other additives, was recognised by the advocates for the general use of more than feebly hydraulic limes (most of them engineers, who generally associated hardness with strength and greater structural longevity) was recognised (and understood) by Smeaton; more grudgingly by Vicat and his contemporaries, and with growing hostility and animus as the 19thC wore on, until the growing speed and volume of the construction industry in advancing capitalist economies; changing technologies; more extensive transport infrastructure and changing hierarchies within the building trades - particularly in the matter of mortar design and specification in our context - broke the resistance of those builders schooled in vernacular traditions and the long-established understanding of the value of the materials and practices of these. Cataclysmic events, such as the First World War, in which so many working class men were killed or debilitated, only enhanced this trend, robbing very many communities of centuries of accumulated knowledge and understanding, to be followed swiftly by the first major global crisis of capitalism and then another global war of devastating impact.
Before the arrival of the railways, lime had always been burned and used locally. Quicklime, usually in the form of lump, was carried distances to site circumscribed by its tendency to air-slake and 'lose power', in sacks or in barrels, or even loose upon carts; by pack-horse, wagons or by water. Lime-kilns were everywhere – as many still are, in various states of decay – and it was rare for lump lime to be transported more than around 12 miles. Inevitably, therefore, lime-kilns were relatively small in dimension, only growing to industrial size where water transport was immediately adjacent, or – particularly – once rail connections arrived. In areas where limestone was scarce, limestone would be brought to the kilns for burning. On the North York Moors, most lime-kilns nestle at road-sides for this reason. Along the length of the River Tamar, lime-kilns sit upon the banks, where they received pure limestone from Plymouth to be burned for agricultural and building purposes, the transport of lump lime from Plymouth itself having proved problematic – the premature slaking of large volumes of quicklime having caused the burning and sinking of some of the wooden-hulled barges. If lime had to be carried long distances, it was previously slaked to a powdered hydrate before being transported in barrels. (Victoria PIC). As binder production in readily packaged and transportable form and without the inconvenience of quicklime's peculiar characteristics, became big business, attracting significant capital investment, economies of scale and high levels of profit, and an anyway diminished cadre of lime-burners found it increasingly difficult to compete in the increasingly industrialised and class-conflict-ridden production of architecture, domestic or otherwise.
These 'new' materials did 'away with all the trouble, waste and unsatisfactory results entailed by the old method of slaking lump lime on the work.' (Eckel 1922), but also disempowered or gave expression to the disempowerment of masons and other crafts.

Modern NHL production – like that of ordinary Portland cement - is a function of this industrialised, capitalist production, not of traditional forms that had existed since time out of mind. In this sense, building conservation, and its associated 'low-tech' materials, has always been an anti-capitalist, even a socialist enterprise, consistent with the political perspective and ambition of one of its primary advocates, William Morris and the organisation he founded, the Society for the Protection of Ancient Buildings. (Morris Quote).

The naturally-occurring clay content of a limestone will vary not only from one quarry to another, but from one bed of limestone to another within the same quarry. An experienced lime-burner would select the beds to be burned according to intended purpose, when this was known to be of hydraulic potential, but, generally speaking, this inherent variability was treated with suspicion, and was not generally

embraced as an asset. It has long been understood that the strength of a mortar across the whole of a built elevation should be the same, to avoid differential in situ performance. The predictability of Portland cement after the refinement of its production process during the last quarter of the 19thC was a major reason for its embrace by engineers, architects and others, in contradistinction to its earlier and original form, which had given it a reputation for unreliability and poor quality control (Burnell 1857). As the Historic England NHL research has clearly illustrated, this variability remains an issue and is reflected in the European (and British) Standard, which allows the three standard grades of NHL, 2.0; 3.5; 5.0, to have three times more compressive strength at 28 days than its minimum required strength, whilst still be classed an NHL. An NHL 2.0 may be 7 Mpa (twice the minimum required strength of an NHL 3.5) at 28 days and still be marketed as an NHL 2.0. Very few historic lime mortars in the UK are stronger than 2 Mpa after centuries (Valek & Hughes 2004?). Previous to this standard, the British Standard had allowed for an hydraulic lime to be range between .75 and 2 Mpa after 28 days, the maximum having been less than the necessary minimum strength under the current standard. This reflected the typical strengths of traditionally used feebly hydraulic limes in the UK (Henry SPAB C21). Beyond this, the European Standard for NHLs – as for other cementitious mortars – is based upon a laboratory test regime completely unrepresentative of site practice or mixing regimes – a 100mm test cube, made with the minimum water content (and much less than is necessary to produce a workable mortar), and proportioned by weight, not volume, informs the data, meaning that the advertised strengths are greater than they are on site and do not offer specifiers a reliable guide to actual strengths and performance on site or in real structures. This same flaw attaches to most laboratory testing, especially freeze-thaw testing, which has been a driver of the deployment by engineering and other professionals specifying conservation works, mainly schooled in the pre-conceptions of modern building technology and often dismissive of the performance of traditional building materials - even when these have proven themselves eminently successful - to use increasingly hard and incompatible mortars in the repair and conservation of traditional buildings. NHLs have provided an opportunity for such professionals to believe they are using 'lime' whilst at the same time satisfying their proclivity for using mortars of far greater strength and density not only than is structurally required under modern codes, but which has only minimal historic precedent and, therefore, cannot be like for like. This process has found its apogee in North America, where even advocates of NHL use will acknowledge that the use of NHLs has little to no established tradition, their not ever having been produced on any scale, except 'inadvertently', (Michael Edison (APTI Mortars Workshop Montebello, Quebec 2017) though some were imported into Canada from the UK during the 19thC, along with Portland cement (Fuller and Jones specification 1859) for the execution of water and groundworks and for specific uses in association with highly exposed building elements.
The first call for what we would now call NHL to be banned due to its variability and unpredictable performance came in France at the end of the 18thC, from le Sage, whose opinion was scorned by Vicat (1837), who preferred to assert that the use of fat limes, 'at least for buildings of any importance' should be 'prohibited by law' in favour of hydraulic limes.

Vicat made an influential contribution to the trend towards hydraulic lime use in the air, which continues today. Smith's 1837 translation of his seminal work on the subject was re-published in the UK in 1998, just as NHLs began to be used once more in conservation, and giving this movement additional impetus. He first categorised the different strengths into Feebly, Moderately and Eminently hydraulic limes. It was one of the simple errors of the later 'lime revival' to equate these categories with those of the modern standard. In truth, some of the currently available NHLs would have been considered by Vicat and others to have been moderately, if not indeed, eminently hydraulic, not feebly, as has been so often – and continues to be - asserted in recent years.

Even so, Vicat himself did not trust natural hydraulic lime mortars. By the time he wrote his treatise, he had invested heavily in the construction of a factory on the outskirts of Paris to produce the hydraulic lime he so avidly recommended should be used, at least for buildings of 'importance' and high status. The hydraulic lime that this produced, however, was not an NHL, but an artificial hydraulic lime, made by a complicated process – pure lime was burned in the kiln before being slaked with an excess of water to form a lime of dough-like consistency. This was then mixed with clay, formed into balls and re-fired in the kiln to create an hydraulic lime for sale. Leaving aside the clearly commercial incentive he had to dismiss the properties of fat and feebly hydraulic limes in this context, this process was plainly over-cumbersome and unnecessary. Modern artificial hydraulic limes (designated HLs) typically include a gauge of ordinary Portland cement and the gauging of air lime mortars with natural cement was being practiced in the USA as early as 1845 to promote the early initial and deeper set of mortars used within the ever-thickening walls of military forts (Wright 1845).

Such distrust extended well into the 20thC. Mitchell's Construction of 1947 has already been cited, but its assertion that NHLs could not be relied upon is echoed by a 1946 RIBA Committee:

"The type of lime known as 'hydraulic' often makes excellent mortar, but this lime is not produced in large quantities, and as it is not the subject of any specification, it varies from one works to another," (RIBA/Ministry of Works 1946),

further evidence that apart from a brief dalliance earlier in the century, and at the tail-end of the 19thC, and apart from the use of NHLs primary for subterranean masonry (such as sewers and footings), the routine use of NHL mortars in the air had never become established or routine in the UK and that Biston had been accurate in his portrayal of stonemasons in the Calvados region, as rejecting readily available hydraulic limes in favour of their preferred pure or very nearly pure limes (see above).

Pozzolanic hydraulic lime mortars had been the norm for centuries, and Treussart, an engineer and contemporary, as well as an adversary, of Vicat's tested such 'water limes' extensively before concluding that "we are much more certain to obtain uniform results with hydraulic mortars, composed of fat lime, sand and factitious trass *[brick or tile dust; certain ashes]*, than with those that can be made of artificial, or natural hydraulic lime, and sand only."

In earlier periods, 'water limes' had been made with pozzolan and lime only (and typically hot-mixed, with just-slaked lime). Smeaton established that this was not necessary (see above), and that 2 of the three parts of pozzolan could be displaced by sand without ill effect, allowing a major cost-saving, as pozzolanic volcanic ashes were routinely imported from Italy, as well as from Holland (trass).

In the UK such water lime mortars had been made with feebly hydraulic lime also, often without even pozzolanic addition at all, though these struggled to set fully hard underwater, remaining of a soap-like consistency.

Indeed, and in part due to cost, quays and wharves had been built using common, fat limes 'faced up with fat lime plus pozzolan (from Italy) or trass from Holland', but by 1838, Pasley says, were constructed throughout with natural cement – not with NHL, though Blue Lias came to be more commonly used, perhaps, after the arrival of the railways, but usually, as Smeaton had used it, with pozzolanic addition. Water works associated with the Palace of Westminster, however, were effected using feebly hydraulic grey chalk limes and pozzolan after 1837.

Villeneuve, and others, indeed, saw a lime made from a limestone containing less than 6% clay to be an 'ordinary lime', not even hydraulic at all in any meaningful sense

"The calcination of the carbonate of lime containing from one to six per cent, of clay produces ordinary lime; if the quantity of the clay be greater (equal to from six to twenty-three per cent.) the lime is suitable to be made into hydraulic mortar. Beyond twenty-three to twenty-seven per cent, of clay the result of the calcination of the calcareous compound is termed cement." (quoted in Sloan 1852).

The typical clay content of a grey chalk lime used in England was less than 6% and frequently somewhat less than this (Holmes and Wingate). Blue Lias had frequently more than this, though much of the clay content might be inert. Gillmore (1861) considered Blue Lias to be a feebly hydraulic lime and Eckel (1922), discussing the merits of hydraulic limes,

Clay content is not an absolute guide to hydraulicity – silica and alumina must be 'soluble', which is to say, capable of chemical combination with the lime in the kiln, to form dicalcium silicate and/or dicalcium aluminate, or – when the limestone is fired in significant excess of traditional temperatures of around 1000 degrees C, tricalcium silicate and tricalcium aluminate, the reactions that form the basis of the exceptional hardness and accelerated set of Portland cements, an observation made early by Gillmore in 1864. Whilst NHL 2.0 may be fired at this traditional temperature, in most cases, NHLs 3.5 and 5.0 are not, although one available brand of NHL is fired at around 900 degrees C to naturally produce an NHL 5.0, artificial means then being employed to reduce the strength for the supply of NHLs 3.5 and 2.0 for the market, with all of its categories containing significant, if variable, volumes of inert calcium carbonate (Jefferson 2015).

Lean or 'meagre' limes – as well, often, as magnesian limes – were frequently high in clay content, sometimes being as much as 30% clay content. Little of this was amenable to combination with lime, so that these limes were not only notoriously slow to slake (and prone to very late slaking once in place), and harsh-working, but delivered only feebly hydraulic limes.

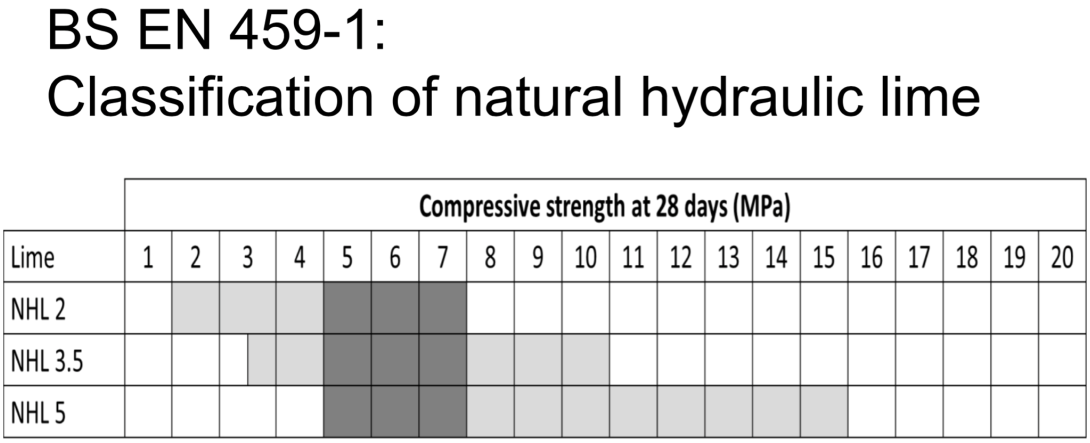
Gillmore (1881) scoffed at the idea that hydraulic limes used in the UK merited the description, but acknowledged that he had to treat of them only because 'the English used them'. He classed Blue Lias lime as only feebly hydraulic, whilst Eckel (1922) quoting another to provide his definition of hydraulic limes, confirmed that the optimum relative free-lime: silica proportions should be similar to those of traditionally used, more energetic water limes deployed historically in the UK.

"Mr Edwin states that "theoretically, the proper composition for a hydraulic limestone should be calcium carbonate 86.8% and silica 13.2%. The hydraulic limes in actual use, however, usually carry a much higher silica percentage, reaching at times 25%, while alumina and iron are commonly present in quantities which may be as high as 6%....The hydraulic limes include all those cementing materials (made by burning siliceous or argillaceous limestones whose clinker after calcination contains so large a percentage of lime silicate… as to give hydraulic properties to the product, but which at the same time contains normally so much free lime that the mass of clinker will slake on the addition of water"" Eckel was quite clear that the practice, then well-established, of burning hydraulic limestones at much greater than traditional temperatures offered a flawed product, which would contain tri-calcium slicates and aluminates and much less free lime than was desirable or even appropriate, bearing little relationship to historically or 'properly' burned hydraulic limes, the minimal free lime content of which he saw as being expedient only, the slaking of this minimum amount being sufficient to reduce the whole to a powder, thereby avoiding the necessity of investment in expensive mechanical grinding plant previously needed for the production of natural cement, a natural hydraulic lime burned at around 900 degrees C but with no residue of free lime and no generation of tricalcium silicates or aluminates." As early as 1802, Sir Humphrey Davy had advertised the necessity of burning hydraulic limestones at traditional temperatures to avoid the production in the kiln of clinker primarily composed of tricalcium silcates and aluminates. Hitchcock (1862) reiterated this:

"To obtain lime for water cement, the impure limestone should be broken into small pieces and subjected to a heat sufficient to expel the carbonic acid…care must be taken that the heat is not too intense, for if it is, the rock will become partially fused, and a glassy substance will result from the alkaline and silicious constituents of the rock. After calcination, the rock should be thoroughly pulverized and mixed with sharp sand, after which water may be applied until the mass assumes the consistency of common mortar, when it should be used immediately, especially if it possesses the setting property of some cements. The proportion of sand to be used with the cement, varies with the composition of the lime" (Hitchcock the Geology of Vermont 1861).

It remained an issue for Geeson as late as 1952, who importantly pointed out that if the lime was not subsequently ground to a fine powder, the tricalcium silicate and tricalcium aluminate clinker would remain substantially inert in a mortar (though mortar analysis might mislead an analyst about the hydraulicity of the mortar), suggesting that such material traditionally slaked on site – and when such clinker would have been picked out by the masons during or after slaking – would have been (and could be today) much less aggressive in its hydraulicity. If, however, the quicklime was 'extremely finely ground' without first extracting this clinker, Geeson was clear: "a natural cement results".

Eckel had pointed out in 1922 that such clinker – called 'grappiers' in the US - had been routinely separated out after burning, finely ground and sold as Grappier Cement, used for its rapid (and very hard) setting properties. The modern production processes of making pre-slaked hydrated hydraulic lime – the same limestone being burned often at ever-increasing increasing temperatures to produce hydraulic limes of increasing power and strength - to be bagged as a fine powder would indicate that tri-calcium silicates and aluminates may remain part of the mix and in Spain, where legislation requires that such constituents are declared upon the bag, a particularly fatty NHL, with a higher than average free lime content (around 65%), and not available in the UK, is said on the bag to contain 3% tri-calcium silicate (Lafarge Espana web-site).



(note that any of the NHLs tested by HE sit within the overlap of NHLs 2.0; 3.5 and 5.0 and could each be called either of the others without breaching the Standard)

The European Standard requires that an NHL 2.0 has a minimum free lime content of around 35%; an NHL 3.5 around 25% and an NHL 5.0 around 15%. Most technical data on producer's or merchant's web-sites simply quotes these figures, suggesting that all NHLs available are much the same and generally immutable, an impression confounded by the Historic England research. Free lime content is critical to good workability, as well as to effective porosity (Wiggins). It is also a significant contributory factor in water retentivity, bond strength and extent of bond (Boynton & Gutschick 1964), as well as the provision of some flexibility, or deformability, in a mortar. The swift embrace of binder-rich ordinary Portland cement mortars, often at 1:3, reflecting historic quicklime: aggregate proportions, led, in the USA, at least, to a rash of leaky buildings, in a place that had never embraced cavity-wall construction with the same enthusiasm as had been displayed in the UK, this wetting of the fabric being the opposite of what might have been anticipated. Investigation of the problem led to the demonstrable conclusion that the low water retentivity of cement: sand mortars had led to an immediate but visually imperceptible loss of bond between mortars and porous building units, such as bricks; the porous materials sucking the contact zone between themselves and the mortar dry, thereby preventing its proper set and bond, as well as in the harshness of their workability, encouraging poor workmanship, almost by default. The preferred solution, in the context of the 20thC building industry had been to recommend the use of cement-lime mortars (US Bureau of Standards) – 1:1:6, 1:2:9 and 1:3:12, depending upon load and exposure. Such mortars offered better water retentivity (although not as good as that enjoyed by 1:3 quicklime: sand mortars) without sacrificing the early initial set demanded by modern building technology, then, as today. They offered greater early deformability, to accommodate settlement and drying without structural cracking, whilst at the same time offering some economy of materials (Johnson 1926). Most particularly, they offered masons and others some approximation of the good workability they had previously enjoyed whilst working with fat and feebly hydraulic limes, reducing waste and increasing productivity whilst allowing easier manipulation of the materials than had become possible – in the filling of perpend joints, for example – with cement-sand mortars.

"Lime was once one of the most important of building materials, but its use is tending to become restricted on account of the employment of cement and the different makes of gypsum plasters that are today on the market. These substitutes are justly popular, on account of their more scientific manufacture and resulting standardised composition, which renders them easier to employ on modern constructional work where large quantities of material are mixed by mechanical means. Nevertheless, many builders of experience still hold that lime possesses a number of valuable qualities which up to the present have not been reproduced in other materials." (Modern Practical Building Magazine 1937).

These mortars were already and increasingly being adopted in Europe also, displacing what use of natural hydraulic lime mortars had begun to become established during the last quarter of the 19thC. For example, the first importation of natural hydraulic lime into the port of Oviedo, capital of Asturias, a province without any easily accessible common lime resources and into which it had been previously the norm to import purer lime mortars for use with sand or –still commonly in the late 19thC, with earth (those outcrops in the far west of this mountainous region having been used almost exclusively in neighbouring Galicia), was in 1875 (Garcia Lopez del Vallado 2009). Even this, when used for building in the air, and except for foundations and waterworks, had been used as a gauge to common mortars, presaging later Scottish practice, but even this was displaced during the earlier 20thC by the use of cement-lime mortars, these being more reliable and predictable in their behaviour.

Notably, cement-lime mortars were not considered ultimately stronger than, nor even as tenacious as, common lime mortars of traditional quicklime: sand proportion until the cement proportion of the binder content exceeded 40% (Bureau of Standards 1922 and confirmed by the Smeaton Project 1991?), so that a 1:2:9 or a 1:3:12 mortar (both extensively used for conservation and repair by the Ministry of Works in the UK during the

1970s, often with on-going success today) were of lesser tenacity than an air lime: sand mortar, their primary advantage being faster set and a lesser reliance upon the slaking skills of the workforce.

As notably, although this was not especially considered as significant at the time, even a 1:1:6 cement lime mortar had a higher free lime content than is demanded or delivered by most modern NHLs that meet the current standard, and 1:2:9 and 1:3:12 significantly more, giving to the latter two, relatively cement-lean mortars, at least, a potentially greater effective porosity, as well as somewhat lower ultimate compressive strength than most currently available NHLs. Historic England research has shown a 1:1:6 mortar made with stronger, modern Portland cement, to develop around 10.5 Mpa after 28 days – also its maximum extent of strength-gain (that such mortars would subsequently slightly weaken, as the HE cement-lime mortars have, was demonstrated by the US Bureau of Standards testing in the 1920s), whilst the maximum strength of a 1:2:9 is reached after 90 days (reflecting the increased free lime content, perhaps), being just shy of 4 Mpa. 1:3:12 mortar was not tested. Earlier 20thC versions of the same will have been significantly less strong. The 1:2:9 is weaker than around 50% of the NHLs tested after 2 years and 30% weaker than the strongest NHL (an NHL 3.5). It may be reasonably deduced that a 1:3:12 mortar, even one made with current-strength Portland cement would be weaker than all available NHLs after 2 years, perhaps sooner than this. All tested NHLs continued to gain strength after two years; the strength-gain of cement-lime mortars had stabilised within 3 months. This data is chastening, challenging numerous assumptions, not only about NHLs, but also about weaker cement-lime mortars. 1:1:6, still commonly specified for conservation works in the USA and Canada, would, of course, be too hard and rigid for use upon historic fabric, whatever its effective porosity might prove to be, and around 30 times stronger than the structurally necessary mortar of a wall of traditional, solid wall construction.

Pozzolanic mortars tested by HE at the same time and under the same regime, mixed by volume, as have been all of the mortars mentioned above and cured in a climate chamber reflecting seasonal and daily climatic variation, meta-kaolin added in proportions of 5, 10 and 20 per cent, by weight of the lime content, also stabilise by 90 days, achieving slightly more than 50% of their ultimate strength after 28 days, and achieve a maximum compressive strength of 1.3; 2.00 and 4.00 Mpa respectively. The mortar with 5% addition, in both speed of initial set and ultimate strength, was equivalent to that of the air putty lime control, whilst the mortars with 5 and 10% addition of meta-kaolin were significantly less strong than any currently available NHLs after 1 and 2 years, the ultimate strength of the latter being currently unknown. These strengths – coupled with a much higher than NHL fee lime content - are likely to be compatible with most historic fabric in the UK and elsewhere, as well as with modern building codes around the world for domestic and lower-rise dwellings, as well as enjoying a high free lime content and similar workability to a hot-mixed air lime mortar. The US Bureau of Standards demonstrated long ago that, for solid wall construction, a mortar with a compressive strength of only one third of an Mpa was entirely sufficient to sustain a 9 story masonry building(and regularly did), challenging along with others, the relevance of laboratory testing of mortars in language that even a structural engineer would recognise, whilst confirming what most masons have known by experience over several thousand years:

"This question of the strength of a mortar is apt to be given undue weight. Since masonry is assumed to weigh 150 lbs/cu ft, then the compression load at the bottom of a wall will be 150 over 144 times its height in feet. A mortar with a compressive strength of 100 psi should, according to this reasoning, be able to carry a wall 100 x 144 over 150 = 96 feet or about 9 stories. A mortar joint in a wall may possibly be 9" wide by 30' long by ½ " thick. In the joint the ratio is 9 divided by ½ = 18. If a mortar has a strength of 100 psi when tested in the form of a cube, it should theoretically have a strength of 1800 psi when laid up in a wall.
(National Bureau of Standards Bulletin no. 30, quoted in Boynton & Gutschick 1964).

It is the authors conviction, at least, that any serious attempt to combat perilous climate change should include the embrace of such pozzolanic mortars - rich in the free lime necessary to promote effective porosity, thereby keeping structures dry and thermally efficient, offering excellent bond and extent of bond within the fabric, as well as excellent water retentivity and workability – for new construction, as well as for the conservation and repair of old buildings. Only free lime can take back the majority of the carbon dioxide emitted during burning. It is estimated that Portland cement production is responsible for the generation of up to 10% of the gases responsible for global warming; the construction industry globally contributes around 60% of these. Whilst NHLs have been regularly touted as being 'green', and whilst they are burned at lower or slightly lower temperatures than Portland cement, their free lime content means that they re-absorb little of the carbon dioxide given off during manufacture, at the same time as they enjoy an effective porosity only marginally greater than a Portland cement mortar mixed to similar proportion (Wiggins).

Free lime in an air lime: 90 – 96%
Free lime after 5% pozzolanic addition: 80 – 86%
Free lime in historic Blue Lias NHL: 60 - 72%
Free lime in a 1:3:12 mortar: 75%
Free lime in a 1:2:9 mortar: 66%
Free lime in a typical NHL 2.0: 35%
Free lime in a typical NHL 3.5: 25%
Free lime in a typical NHL 5: 15%
Free lime in typical new build mortar of 1 part cement: 5 parts sand: ZERO.
Addition of air entrainers compromises bond.

Beyond these effects, the eminent workability of air and feebly hydraulic lime mortars encourages good workmanship, almost by default.

The modern strategy to improve the workability of both cement-sand and NHL mortars has been the routine addition of artificial, chemical air entrainers, which are also used to enhance theroretical frost resistance. When these are added on site, a mason in inevitable pursuit of workability – or working in very cold weather - will be tempted to elevate the volume of these above recommended maximums. However, artificial air entrainment compromises bond (Bureau of Standards, Palmer) as well as effective porosity. They are a very poor alternative to using free-lime-rich mortars that require no such aids to either workability or bond, as well as demonstrating generally excellent frost resilience in the absence of failed or failing architectural detail.

Other issues raised or confirmed by the HE research – confirmed, because many masons around the UK already knew this, by experience or instinct – are that NHLs, even of the same brand, vary in strength and setting power. In one experiment, the same brand of NHL was purchased on the same day in different parts of the UK. Upon testing, these were shown to have significantly different properties from each other at 28 days (Henry SPAB C21)

At the same time, the same brands tested in different labs, to the same methodology and to the requirements of BS EN 459, gave significantly different strengths, only 2 of the 6 tested reaching the minimum strength required by the standard at 28 days, notwithstanding that this might be considered a good thing.

Similarly, significant variance from the standard was found in the strengths of mortars cured during winter and summer conditions, with those cured in winter conditions generally being stronger than those cured during the summer, but with both being of significantly lesser strength than the standard strength requirement.

Similar disparity between declared and tested data was found within all data sets.

The greater strength gain of winter-cured samples may be explained by another characteristic of hydraulic lime mortars that was familiar to historic authors – the necessity for on-going hydration of these mortars and the proclivity of hydraulic lime mortars to dry too fast.

"Hydraulic cements set better and attain greater strength under water than in the open air; in the latter, owing to the evaporation of the water, the mortar has a tendency to dry rather than to set. This difference is very marked in hot, dry weather." (Kidder 1920)

"As water is absolutely essential not only for the initiation but also for the continuation and completion of the chemical processes involved in the setting and hardening of hydraulic limes and cements, it is imperative that the moisture should not be abstracted from the mortar too soon. Hence the necessity of protecting stucco from brilliant sunshine, or of repeatedly spraying it with water; hence also the necessity of dipping bricks in water immediately before using them, and of sprinkling a dry course of bricks with water before the bed of mortar is spread above it to receive the next course. With lime mortar, a moderate use of water in the same way is advantageous, although the lack of it has not so marked an effect as with cement and hydraulic lime.
Sutcliffe 1898

This had become apparent as natural cement had been used extensively 'in the air' for both external renders and deliberately robust mass construction, particularly of forts, frequently built in haste and in response to a newly perceived threat or weakness. Engineers routinely demanded the throwing of buckets of water onto the work after completion and for as long as was practicable.

Theoretically, at least, this on-going hydration should be carried out for the duration of the set, which we know to be longer than 2 years. Many of those who have used NHLs in the air with enthusiasm over recent years have done so in the belief that, as in similarly bad practice with cement mortars, they can apply them and walk away, once a short period of initial curing and hydration has been attended to. This is illustrated by the common complaint from those required to switch from NHLs to hot mixed air limes, that the aftercare required by the latter makes the task more onerous and time-consuming. In fact, the opposite is the case – an air lime mortar of historic lime: sand proportion receives all of – indeed significantly more than - the moisture necessary for its set when mixed to a mortar, enhanced by pre-wetting of the substrates.

(So, for mortar that sets soonest and to highest degree and makes best cement)…it must be suffered to dry gently and set; the (desiccation) must be effected by temperate air and not accelerated by the heat of the sun or fire; it **must not be wetted soon after it sets**; **and afterwards it ought to be protected from wet as much as possible, until it is completely indurated…and then it must be as freely exposed to the open air as much as the work will permit,** in order to supply acidulous gas…"(Higgins 1780)

It has been the common experience of masons and others using hot mixed mortars that constant wetting will induce on-going shrinkage, after that which may be anticipated shortly after placement, precisely because it replenishes the surplus of water necessary to achieve workability and effective use; and that the level of protection after placement is much less than they have been used to using both NHL and lime-lean putty lime mortars.

The high water-retentivity of such an air lime mortars, whether hot mixed or not, means that a minimum of protection will avoid any too rapid drying out of the mortar and facilitate gentle curing without need for further water addition. Indeed, the objective is for the excess of water added during mixing to be lost as rapidly as possible without this being too fast, to facilitate the onset of carbonation at the face (of a pointing mortar, for example). Once this case-hardening has occurred, it should be possible in most circumstances to walk away and allow the mortar to look after itself. The informed use of air limes, therefore, is much less demanding of time and after-care than that required by – but rarely given to – an NHL mortar. The absence of this on-going hydration can have a number of negative consequences – whilst a mortar may receive necessary hydration at its face, accidentally, from rain-fall (and particularly in regions of driven rain), the inside of the mortar receives no such on-going hydration, leading, on occasion, to a powdery aggregate, rather than a mortar, within the wall, or to an unconcreted mush. Beyond that, the absence of on-going hydration may lead to the shrinkage of an hydraulic lime mortar from contact with the stones or bricks it was supposed to bind or to the loss of firm contact with which was intended to prevent water penetration. The mortar, in other words, ceases to be fit for purpose in the absence of on-going hydration. It will potentially lead to wetter, not drier buildings and such effects have been regularly reported around the UK in recent years, even when NHLs have replaced previously applied Portland cement mortars. Indeed, some have been confused – buildings the fabric of which was understandably wet, having been re-pointed or rendered with dense cement mortars, having become wetter still after repointing or re-rendering with NHL mortars. On receipt of such hydration (which is, in fact, rarely practicable lest the mortar is continually or routinely underwater, explaining, perhaps, why these mortars were used in such situations historically, as well as being called 'water' limes, and, perhaps. Indicating where they belong), the mortars may well set close to their potential, but will then be too hard and too little effectively porous.

(HOLY ISLAND PICs)
In the case of most 'modern' mortars, frost resistance is a function of their lack of porosity (and breathability); in the case of traditional mortars, their frost resistance – or rather their frost resilience – is a function of their effective porosity coupled with proper building detail and appropriate use. The former offer frost resistance at the expense of historic fabric – elements of which will become more frost vulnerable – and appropriate building performance. Beyond this, it has been our experience that a hot mixed air lime mortar applied to an already wet or saturated substrate late in the season and unable to properly set before deeply freezing weather sets in, may itself seem to freeze solid at the face, and that this face will be friable upon thawing, but that this friability will extend only very little into the body of the mortar, which may be brushed down and knocked back and subsequently carbonate and set once the weather warms up. Any frost attack of an NHL mortar, on the other hand, will tend to destroy the mortar to its full depth. This difference is explicable by reference to the very different pore structures of these mortars and of the high density of 1 micron pores within a high free lime mortar (see Wiggins chapter). This difference also explains the efficiency with which the latter manage moisture movement and salt capture, both of which are problematic in a typical NHL mortar of relatively low effective porosity. Inspection of works executed with imported NHLs in the late 1990s reveals similar patterns of decay and moisture management to those more normally associated with the use of strong ordinary Portland cement mortars, although only the latter will potentially introduce damaging salts, at the same time as preventing their egress. Where salts are present in the building fabric – or are later received – from the ground or from the atmosphere, a traditional, typically hot mixed, but certainly high free lime content mortar, will gather these salts as water moves through them by capillary action. These salts will crystallise as the fabric dries – and perhaps seasonally – within or upon the surface of the lime mortar. Ultimately, this process may lead to the break down of the lime mortar at its face and demand like for like replacement. Too often, this has been, and continues to be seen, not as normal and necessary sacrificial behaviour, but as a 'failure' of the softer lime mortars and an indictment of their fitness for purpose, so that it has been typically replaced with a much harder, more dense cementitious mortar significantly less breathable than either the porous brick or stone and certainly less so than the original lime or earth-lime mortars within the fabric. The application of such a mortar reverses the sacrificial equation, challenging the stone or brick to manage moisture movement from the wall as well as to accommodate the expansion of crystalising salts as they move out of solution. The masonry units begin to decay, initially at their arrises, but sometimes in more dramatic fashion when

the moisture content within the wall becomes excessively high (stone is less breathable than lime mortar), and frost may also gain leverage, exploiting natural flaws in individual stones as well as flaws in construction, such as face-bedded sedimentary stones, laid' perhaps, by a mason who knew the wall he was building would be lime-rendered (PIC Yeoman's Course); perhaps out of expediency. This is a familiar picture across the UK and north America, often accentuated by the routine spreading of rock salts upon roads and pavements, from which it is splashed in solution onto road-side buildings and walls. Such decay can take some years to present, even when very hard cement mortars have been used, and the presentation of such similar decay in buildings repointed or otherwise repaired with NHLs ten and twenty years ago, in the context of Wiggins's conclusions that a 1:3 NHL 3.5 mortar enjoys only marginally more effective porosity than a 1:3 CEM II cement mortar, suggests that currently obvious decay in NHL-repaired buildings is but the harbinger of decay yet to appear, and that the campaign of best practice to rid traditional buildings of cementitious mortars may yet be extended to include those repaired with NHLs, too, over coming decades.

Softer stones, however, will begin to decay after repointing with NHL within years (Wroxeter and Nunburnholme chalk PICS).

The further and more immediate consequence of the application of minimally or less than necessarily breathable mortars to traditional fabric, of course, is the efflorescence of already present salts in fabric repointed stonework, particularly, but not exclusively, when the fabric has been previously damp and and over-wet as a result of previous repairs with Portland cement, itself a carrier of salts.

Walls of the Kings Manor in York, previously repointed with a relatively weak cement-lime mortar and without salt efflorescence before recent repointing with an NHL mortar, quickly became covered in salt efflorescence, all of it in the stone; none of it upon the new pointing mortar – a clear indication that the Magnesian limestone of its construction was more effectively porous (being composed largely of calcite) than the repointing itself. (PICS). Whilst surface efflorescence may not be damaging in itself, it is a clear indicator that much more damaging crypto-fluorescence, just behind the stone surface, will also be present, and very likely to lead to the degradation and surface powdering of the stone. The effects of this may be seen in the stonework of the newly constructed Heritage Skills Centre within Lincoln Castle. (PIC)

(PICS of Assembly Rooms Malton brickwork, Lincoln Ancaster work_

John Smeaton, exploring potential sources of hydraulic lime for use at Edystone had inadvertently advertised this potential as early as 1791, though he saw this as proof of the lime's durability, not of its hazards:

"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), 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 1791), though a typical blue lias lime was significantly softer and significantly higher in free lime content than any currently available NHL, such as was used to repoint the hard and durable Pennine sandstone of St Andrews Church, Studley Royal in the late 1990s.

The proclivity of NHL mortars to allow water ingress whilst at the same time preventing its ready egress may be best illustrated by the Archbald Moffat House in Moffat, near Dumfries. A west-facing gable had become thoroughly saturated within 2 years of having been repointed with an NHL 5.0. Repointed with a hot mixed air lime mortar, this gable dried to full depth within 2 weeks, though full carbonation of the mortars could not have been complete by this time. (PICS).

The Archbald Moffat House is built of a hard, relatively impermeable local whinstone laid in clay mortars, and such potential wetting up of earthen structures, especially of those built entirely of earth or earth-lime mortars must be of grave concern. As has been seen in the case of cob buildings in the English west country during the 20thC, rendered with cementitious mortars, once the earth becomes saturated, it will flow and lead to catastrophic collapse.

(ALISON PIC, Chalk Lump wall.)

Not very long ago, the SPAB, in the course of studying the improvements in performance of traditional structures after removal of relatively impermeable mortars and impermeable insulation, and their replacement with breathable alternatives, were perplexed when a cob house in Riddlecombe in Devon, re-rendered with a patent breathable insulating lime render showed only a 4% gain in thermal performance and a fabric wetter than whilst it had been cement-rendered. The composition of the cement render is not known (it may have been a cement-lime render), but the technical data of the new render revealed that it 'conformed to BS EN 459for NHL 5.0'.

PICS of same.

A further common problem with NHLs – familiar already when 1:1:6 cement-lime mortars have been used in the past in damp or exposed locations – has been the leeching out of uncarbonated free lime, which carbonates for the first time upon the masonry face. This is not only unsightly, and not only robs the mortar of calcium hydroxide, it begs the question as to whether the calcium hydroxide content of an NHL mortar is ever likely to carbonate at all. The development of the initial hydraulic set in a strongly hydraulic lime mortar envelops and encases free lime, potentially preventing its ultimate carbonation (pers comm Jefferson). It has long been questioned whether carbonation can much occur once the cement proportion in a cement-lime mortar exceeds 50% (Smeaton Project), though the free lime content is significantly higher than in all but an NHL 2.0, so it must be asked if similar effect is true of NHLs. It is oft-asserted that the ultimate carbonation set of an NHL mortar – and even its longer term hardness – is a result of the carbonation of its free lime content, when the earlier flash set is a result of the hydration of its dicalcium aluminate content and its later and on-going set the result of the dicalcium silicate set (Jefferson, Revie). In the normal run of things, carbonation of calcium hydroxide will occur when the moisture content of a mortar falls to 5%, a surprisingly low figure, though it will continue even when the mortar is all but dry:

" The setting of (ordinary) lime mortar is the result of three distinct processes which, however, may all go on more or less simultaneously. First, it dries out and becomes firm, Second, during this operation, the calcic hydrate, which is in solution in the water of which the mortar is made, crystallizes and binds the mass together….Third, as the per cent of water in the mortar is reduced and reaches 5%, carbonic acid begins to be absorbed from the atmosphere. If the mortar contains more than five per cent this absorption does not go on. While the mortar contains as much as 0.7 % the absorption continues. The resulting carbonate probably unites with the hydrate of lime to form a sub-carbonate, which causes the mortar to attain a harder set, and this may finally be converted to a carbonate. The mere drying out of mortar, our tests have shown, is sufficient to enable it to resist the pressure of masonry, while the further hardening furnishes the necessary bond" (Richardson 1897, also quoted in Kidder/Nolan 1920)

NHL mortars become 'dry' and close to dry to their full depth quite quickly and frequently far too quickly, so that carbonation should occur as quickly, and not be available so long after setting as to leech out, surely?

(PICS of Reading Abbey ruins and Lincoln Castle walls – wet and leeching).

All of the above would indicate that Natural Hydraulic Lime is not the consistent and reliable material that most specifiers have been led to believe during recent decades; that it rarely satisfies the mason's reasonable demand for fatty, workable mortars and that its use for conservation works represents a clear and present danger to the well-being and necessary performance traditional fabric, except in very particular circumstances.

That "although we give to this compound the name of hydraulic lime, it ought, in fact, to be regarded as a substance altogether different from lime; it is a new body with new properties" (Treussart 1842) was not sufficiently understood by those sections of the lime revival that embraced it so readily and without the necessary preliminary research has become increasingly evident over the last few years. That said, some research was, indeed, carried out. Swann and Hughes looked very carefully at the 'potential for NHL-use in conservation' in 1998 (BLFJ). After extensive testing, they concluded that only NHL 2.0 had any such potential, and that even this should be tested by further research. Most did not listen, it would seem.

It is to be hoped that anxieties about future decay will not, generally, come to pass and it must be stressed that none of the issues raised above have yet been seen to attach to works done with either the Blue Lias hydraulic lime from Tout Quarry, or the Lincolnshire NHL, both of which enjoyed a high free lime content.

The final and more visceral problem with NHLs is that masons, plasterers, bricklayers and conservators, as well as builders more familiar with cement-lime, or even with cement mortars, tend not to like them. It has been a surprise to the author, working with 'ordinary' builders within the North York Moors National Park, to introduce them to hot mixed lime mortars, that they respond very positively to the workability of these and that their expressed scepticism about 'lime' attached mainly to the NHL mortars they had been required by the Park to use (until recently, hot mixes now being very much upon the Park's conservation menu). This scepticism flowed from the perception of individuals not as immersed in some in the general culture of lime work, that these were very little different in both use and behaviour as the cement-lime mortars they had been told they could no longer use and which were akin to Devil's spawn.

Most conscientious craftsmen and women respond very positively to the eminent workability and usefulness of hot mixed air lime mortars – a workability and usefulness that is not diminished - and may even be enhanced – by the inclusion of up to 10% pozzolanic addition as a proportion of the lime content. In normal situations, even the objection of those wedded to NHL or cement-lime mortars, that fat limes 'set too slowly' is generally negated. A pozzolanic air lime mortar, whilst by no means fully set, may be typically ‘knocked back’ the morning after placement, if not, in some cases, on the same day they are laid.

NHLs are problematic to work with – stones will begin to ‘swim’ quite readily when a wall is being built, limiting the height by which they might rise; NHL mortars tend to squeeze, lest they be laid with less than optimum water content for both easy workability and immediate bond with the substrate – and this has become quite normal practice on the ground. Neither of these issues arises with hot mixed lime mortars, which hold up very well even when ‘too wet’, and rarely squeeze, allowing more height to be built without pause – indeed any pause other than the end of the day is generally quite unnecessary.

There has been a growing tendency for the specified or deployed proportions to be reduced from 1:3 to 1: 2.5 and even 1:2, offering more workability, but also significantly more density and compressive strength, despite the increase in the free lime available to carbonate and offer an increased effective porosity.

Many masons have routinely added limestone dust to hydraulic lime mortars over the years. Whilst this may have been done to increase workability, as well as to assist in colour matching to original mortars, it will also have increased effective porosity, the added calcite having the optimum pore size distribution to facilitate this.

NHLs have a relatively poor water retentivity, which decreases as the hydraulicity of the lime increases (and the free lime content diminishes), demanding apparent saturation of the substrates upon or into which they are placed and regular wetting after placement – hot mixed limes require nothing like as much and somewhat less on-going protection from premature drying out.

The lack of workability and adhesiveness of NHL mortars means that they are irritating to apply and that wastage of material is relatively high, and dropped mortars may not be subsequently scooped up and re-tempered for use, lest this is done immediately.

The often rapid initial set of NHLs encourages poor practice. Historically, it was oft-asserted that no hydraulic lime mortars should be knocked up or re-tempered once stiffening and chemical set had begun. Some manufacturers today encourage such knocking up even 24 hours after mixing, and not, it may be assumed, because John Smeaton ventured, after experiment at Edystone that his hydraulic mortar was no worse for, and perhaps a little improved by, such practice (Smeaton 1791). If a setting NHL mortar is knocked up, any chemical set that has by then occurred will be lost. The mortar becomes a little more fatty and workable as a result, because the balance between hydraulic binder and free lime has been adjusted in favour of the free lime, though the free lime content is far too insufficient in its own right to produce a mortar of sufficient tenacity without the hydraulic component. It is tempting, therefore, for masons in pursuit of workability to do it, especially when it is sanctioned by the manufacturer. In fact, the workability, as well as the free lime content of an NHL may be enhanced by the addition of air lime, in whichever form, and, though this will reduce its strength and slow its set, this would not be a bad thing, perhaps.

It is to be hoped that manufacturers of NHL around the world will positively engage with the outcomes of particularly the Historic England research and be open to the exploration of ways by which their products and production processes might be amended and adapted to produce hydraulic limes much more akin to those used historically and lend weight to already expressed calls that BS EN459, a producers standard, be over-hauled and remade as a generally relevant and reliable standard, not only for producers, but for specifiers and users as well.

Aggregates for lime mortars

Most of the engineers writing about lime mortars in the past write almost as much about aggregates as they do about lime in all its forms. The general consensus, informed not only by experience, but by extensive testing was that two parts well-graded coarser sharp sand to one part finer sharp sand to one quicklime represented the optimum aggregate component, suitably adapted when the proportion was 1:2. Such a mix is reflected in the practice of most masons working with lime, though the equation is sometimes reversed to 1 part grit sand to 2 parts finer sharp sand to 1 lime, whether this is already slaked or not.

From very early on, the demand is for the sharp sand to be clean, often washed, and free from clay or other contamination, though Langley allowed for finer, loamy sand to be used for building interior walls and some claims were made regarding the very feebly hydraulic effect that might be derived from ordinary (unfired) clays to be found in some sands (Boynton & Gutschick 1964). It would certainly seem likely that some sands indeed offered very mild pozzolanic effect – particularly those rich in iron or of granitic, or volcanic origin, the latter containing natural fired clays. Micro-silica, often in the form of slate dust, is a particularly powerful pozzolan (Walker & Pavia 2011). Some limestone dusts were also considered to possess weak pozzolanic effect, and Burnell, quoted above, saw limestone dust as potentially accelerating the set of a lime mortar, 'seeding' carbonation within the depth of the mortar due to its chemical affinity with the lime binder. Others saw great advantage in using crushed sandstone aggregate. Indeed, one writer, touring the country with a view to assessing local building stone resources to supply the burgeoning railway industry dismissed the potential of Pennine grit stones for construction, whilst advertising the value of the same stone crushed to aggregate (REF). Higgins (1780) tested different sands, including what we would today call soft builders sand, which he concluded made a very poor aggregate in combination with lime, due to its lack of grading (all grains being about the same size) and rounded profile. Most follow Vitruvius is preferring pit sand to river sand, although the latter was very much used historically, on analysis of the mortars. Most counsel against the use of salt-laden sea or beach sand or insist upon complicated methods of washing this before use. Smeaton relates that masons insisted that the use of such sands would lead to particularly slow-setting mortars that would tend to attract moisture in situ, keeping buildings damp. He tested sea sand, as well as the use of sea-water, and concluded that, for his purposes, at least, building a lighthouse on a rock in the ocean which was regularly over-topped by the waves, that the mortars were actually stronger, and certainly no worse than the norm, and beach sand was frequently used for the construction of sea defences, perhaps for this reason. In the absence of other sources, beach sands were commonly used and, as a matter of record, were the aggregates of most harling work on the Scottish islands. It remains unwise to use them upon inland, normally dry buildings.

An insight that is generally lacking, however, is how coarse the optimum sharp sand actually was.

It has been common throughout the lime revival for lime mortars to be made with quite gritty sharp sand. This is certainly of importance when the binder is intended to be NHL. It is a common feature of thickly applied stucco work and exterior renders in parts of Europe, such as the Czech Republic, (PHOTO?) where exterior renders remained the norm and did not all but die out as it did across most of the UK after the end of the 19thC. It remains a common expectation in those parts of the UK where rendering persists, though the general use of Portland cement mortars for such purpose has led to a diminishment in general coarseness, even for base coats, with standard 'plastering sand', or even soft builder's sand very often preferred.

It would seem, with experience, to be somewhat less essential for lime rich air lime mortars, the lime richness perhaps being the key to the successful use of finer sharp sands. The additional lime content more than coats all of the grains of a finer sand, leaving fewer, or smaller voids, between the grains. Lynch (W & D Hot mix day 2016), believes that sand-slaked soft builders sand may make an entirely fit-for-purpose bricklaying mortar, in part, once again, due to the additional lime content of a traditionally proportioned mortar. This may explain the past and continued prevalence of use of such sands in the UK, perhaps uniquely in the world, if not always for use entirely on their own then as a gauge for sharper sands. In much of North Yorkshire, typical historic mortars reflect the local availability of various aggregates – the sands found in historic mortars tend to be somewhat finer than those used routinely today; around Malton and Pickering, they tend to be heavy in limestone aggregate; very often, limestone dust is the only aggregate. In the sandstone districts, the aggregates are often crushed sandstone from local quarries, often of the same stone of which the building was constructed.

In our own practice, we will use 'grit-sand' (4mm down), 'plastering sand' (perhaps 2mm down) and a locally quarried fine sharp sand around 1mm down, as well as stone dusts similarly graded, or sieved. Our experience has been that increasing the proportion of the finer sharp sands to the grit sands generally reduces initial shrinkage, as does the introduction of very fine chalk flour as a component of the aggregate (generally either 1/6 or 1/3 part). This is the opposite effect to that which might have been expected, and was, indeed, discovered accidentally. Similarly unexpectedly, we have found that lime-rich finish coat plasters with only chalk flour aggregate and some added, short-cut ox-hair is loathe to shrink at all applied to a normal finish coat thickness and produces a mortar that is akin to butter in its texture and ease of application, avoiding the 'snagging' from the float that can occur when the fine aggregate is of 'silver' or kiln-dried sand.

The inclusion of lime stone dusts will almost certainly enhance the compressive strength of a mortar, and a mortar composed entirely of lime stone aggregate and air lime will enjoy a compressive strength significantly greater than one composed of the same lime and siliceous sands of low inherent porosity (Lawrence 2005). Lawrence also discovered that the water content of such a mortar had a neutral effect upon ultimate compressive strength, something that may not be said of a normal sand-lime mortar, particularly if its binder is hydraulic or otherwise cementitious. This would suggest that the aggregates for grouting would be usefully composed mainly of limestone or chalk. The presence of limestone aggregates also promotes earlier stiffening of mortars, another advantage, depending upon use. For repointing, a mortar composed entirely of lime and limestone aggregate may give greater initial shrinkage, however, depending upon the 'openness' of the pore structure.

In many parts of the UK, although particularly in coal-mining districts and industrial urban centres, such as in Lancashire and West Yorkshire, as well as in Bristol, the only aggregate was coal ash, sometimes even of coal itself, at least in part (ABERDARE PICS). This was a natural – and sustainable - response to the ready availability of such aggregates and was not typically improvised – merchants specialised in its collection and careful processing, perhaps washing the raw material, and most certainly grading it. These mortars are very tough, but the amount of inevitable pozzolanic reaction would be limited by the lime content, the majority of the ash being inert aggregate only. Certainly in West Yorkshire, it is relatively rare to see residual lime lumps in such mortars, suggesting that they were certainly wet-slaked and perhaps even made with a lime initially slaked to a paste and either sieved or left a while to 'mature'. These mortars remain something of a mystery – and exploration of their manufacture and characteristics would be usefully carried out. They are generally eschewed in favour of mortars blackened with pigment and made with ordinary sand aggregates, largely for fear of negative consequences associated with the likely chemical cocktail they theoretically contain. In our own 'kitchen-sink' testing, unprocessed, unwashed coal ash-rich mortars, hot mixed with quicklime to 1:3 propotion are 'slimy' to the touch; quite slow to reach an initial set and effloresce significantly upon setting. Bill Revie (pers comm) would insist that local sourcing of such materials – whether coal or coal-ash - is essential to successful use. The majority of the coal burned in the UK today is imported, a lot of it from Colombia, and this is likely to differ significantly from that used in the past.

Unquestionably, and as demonstrated in the practice of the highly experienced stone conservator, Nick Durnan, the careful selection of very well-graded aggregates, blended to produce quite complex, lime rich mortars may eliminate initial shrinkage altogether. Indeed, since adopting hot mixed pointing and plastic repair mortars, Durnan has observed that, in his practice, at least, hot mixed air lime mortars, with or without casein or small volumes of pozzolanic addition shrink less than those made using NHL 2.0 (Durnan BLFJ 2016).

For general building works, such meticulous attention to detail will rarely be exercised or, perhaps, be entirely practicable, and most masons and others working with lime will have their favoured local sands the general behaviour of which they will understand and respond to in their practice, and the balance or variety of these may vary according to the binder or the form of binder used. Any re-embrace of hot mixing tends to invite experimentation and trialling of different combinations, as well as of received wisdom, in our observation and experience, and this can only be a good thing.

Increasingly, our preferred 'basic mix' is 1 part grit-sand: 1 part finer, 'plastering sand': 1 part sieved limestone dust, 2mm down. This may be varied, with ½ a part of chalk flour: ½ part very fine sharp sand to form the third part of the aggregate, or, on occasion, the limestone dust may be displaced altogether by either chalk flour or by very fine sharp sand. For general building, we might revert to 3 well-graded grit sand to 1 quicklime, which may have somewhat less tenacity after curing, than the above. This will be as much an economic as a structural consideration, more expensive stone dusts being reserved for the necessarily more tenancious pointing or exterior plastering mortars. Others will have, or will work out preferred mixes, quite naturally.

Excerpts from Historic Texts Descriptive of Mixing Methods, Gazetteer

Advantages of hot mixing and mixes (Pat's account and mine)

Hot mixes are economic to produce; they offer mortars of eminent workability, encouraging good and efficient workmanship; they offer optimal water retentivity and excellent bond strength as well as consistent extent of bond. They demand much less after-care than other forms of lime. They are tenacious. They offer appropriate durability. The addition of small volumes of pozzolan enhance strength, durabilty and speed of set without compromising workability or other essential characteristics. They offer high effective porosity, keeping building fabric dry and thermally efficient and reducing the need for repair or replacement of building elements.

In pursuit of carbon reduction, lime rich, hot mixed mortars are not only the most appropriate like-for-like and compatible mortars for the conservation and repair of traditional buildings, but for sustainable, mainstream new build as well.

Most of the performance benefits of hot mixed mortars endure and do not rely upon the mortars being used whilst hot.

- The vast majority of lime mortars – for ALL uses – were hot-mixed – quicklime and aggregate mixed together as slaking of the quicklime takes place, or whilst the slaked lime remained very hot.
- Quicklime increases in volume by up to 2.2 times upon slaking, depending upon purity – a 1:3 quicklime: aggregate mix becomes a 1:2 or 2:3 lime to aggregate mortar, depending upon the relative bulk density of the lime and aggregates. Henry Scott, Royal Engineer, suggested in 1862 that the volume of 50 lbs of quicklime should be the 'datum' for mixing with three similar volumes of sand. The bulk density of a given volume of sand will be greater than the same volume of pulverised limestone, or other porous stone dust.
- The lime:aggregate proportion of most of these mortars was typically 2:3 or richer; very rarely as lean as 1:3. However, analysis reads lime content, not effective binder content – unslaked lime lumps are aggregate, not binder. Historic mortars erred on the side of 'too much', rather than too little lime.
- Putty lime mortars mixed at this ratio are generally too wet to be workable or may shrink unduly; aged putty lime (10 years old plus) is a very useful material in specialist hands and may be mixed successfully at historic proportions. However, putty lime was generally used on its own – as a mortar – for fine finish coats or for gauged brickwork, rarely as a binder. It was used immediately, or soon after slaking. Where used as a binder (increasingly in plastering during the later 19thC and into the 20thC), it was typically 'matured' for 2 weeks.
- NHL mortars mixed at this ratio would be generally too strong and hard for most conservation contexts, if they are not already at 1:3; Hydraulic lime mortars in the past were not mixed as lean as 1:3 – more usually 1:2. Hydraulic quicklime expands less upon slaking than high calcium limes. *For both fat and hydraulic limes, the typical proportions were considered* ***the most sand*** *that could be used without sacrificing workability and proper performance.* Masons were often criticised by more 'scientific' commentators for preferring more lime and less sand than this – but none of these critics entertained the notion of a mortar as lean as 1:3, slaked lime: sand, before the 20thC, when cement-lime mortars became the norm.
- The water content of a hot-mixed lime mortar is easily controlled by the mixer and may be varied according to intended use.
- Hot-mixed high calcium mortars are eminently breathable, before and after full carbonation.
- Hot-mixed lime mortars enjoy enhanced performance – better bond strength; greater than assumed durability and excellent vapour permeability – 2:3 ratio critical to this performance
-

Controlled and reliable gauges of pozzalanic material may be added as necessary without losing workability. In many cases, this will not be necessary.

- Hot-mixing is mistakenly assumed to be dangerous – the risks are entirely manageable and are the same as apply to all lime and cement binders. All limes are hazardous due to their high alkalinity.
- Hot-mixed high calcium mortars are accessible, economic and easy to use; make lime use straightforward; make sense to builders otherwise sceptical about lime and offer

appropriate strength, compatible performance and authenticity for the repair and conservation of most buildings of traditional construction.

Advantages of a hot mixed Mortar **(Patrick McAfee)**

High workability
Increased productivity
Fuller and better compressed vertical joints
Can lay wet stones
Cleaner work – no runs down the face of the work
Able to build higher without squeeze or 'swimming'
Joint surfaces can be finished the same day (particularly when mortars laid hot or with small additions of pozzolan)
Replicates original masonry mortars
Further increases in production when used hot

Disadvantages

Slower set than most have become used to

Hot mixing Methods for the 21st Century

Practicalities – problems of scale?

Historically, grand projects were effected using hot mixed mortars (Prague city wall eg; countless forts around the British Empire and in the USA; Canadian and British Parliament Buildings, etc etc.

General specifications.

The most commonly found historic mortar proportion encountered in fat and feebly hydraulic lime mortars is 2 lime: 3 aggregate. This was achieved by hot-mixing 1 quicklime: 3 aggregate. Successful mixes might also be 1:2 or 1:4. Historic mixes of 1:3 are rarely, if ever, found before the 20thC, when cement-gauged slaked lime mixes were typically 1 binder:3, eg 1:2:9. The additional strength of the cement compensated for the loss of lime Though a 1:2:9 mix was typically weaker and less tenacious than a traditional lime mortar mix, it gained an initial set quickly. Historically, hydraulic lime mortars were mixed from quicklime at 1:2 or 1:1, being mainly used underwater and underground. Fat lime pozzalan mortars (the pozzalan generally either trass, brickdust, forge ashes or wood ashes) were mixed at 1:3 quicklime: pozzolan, or richer. These, too, were generally used underwater. For less routinely wet places, the pozzolan typically formed 1/3 part, or less, of the aggregate in a 1:3 mix. For concretes, however, mixes were much leaner – between 1:6 and 1:8 or 9, initially with blue lias or feebly hydraulic quicklimes; later, with Portland cement. In the UK, concretes for all uses were mixed hot – the gravel, sand and quicklime mixed together before slaking, with necessary water then added. Elsewhere – in Spain and France – the quicklime might be initially slaked before mixing with the aggregates whilst still hot. Hot lime mixes more readily and initimately than cold, with less effort and more efficiency.

Mortar aggregates might be well-graded limestone dust and/or well-graded sharp and/or silver sand, or both. They might be a clay-bearing sub-soil, typically very fine in historic examples. The addition of limestone dust, 5mm to dust (or brick chips) will enhance porosity and aid carbonation at depth, as will chalk aggregate or powdered chalk, which latter seems to reduce shrinkage and assist 'flowability' in a relatively , and appropriately stiff mortar.

Hair (or hemp) can be added at 'dry-slake' stage or just before the mortar is used, during 'sweetening'. Pozzalan may be added either stage also, but may accelerate stiffening for being hot mixed.

Our most commonly used mortar is 1: 1: 2; quicklime: < 5mm limestone aggregate: < 4mm sharp sand, sieved down or not, according to intended end use. Alternatively, 1 quicklime: 2 sharp sand: ½ limestone dust: ½ chalk powder. Other times 1:3; quicklime: sharp sand.

When hemp is added (at the hot mix stage) for plasters, to enhance insulation value and reduce shrinkage, this will displace the equivalent (by volume) gauge of sand aggregate.

For earth mortars, the gauge of quicklime is generally 5 - 10%, wet-slaked with the tempered and otherwise improved mud. It was frequently more than this, depending upon purpose. Quicklime may be added successfully as powder or as still slaking putty dough. The addition of powdered quicklime to an earth mortar mixed beyond the liquid limit to fully engage the clays, will bring the mortar below this limit and increase its workability.

The temperature reached during slaking of a sand-lime mortar should be a minimum of 100 degrees C. If just the right amount of water is added, the temperature of the quicklime will be around 100 degrees C or a little higher. If too little water is added (which risks 'burning' the lime, the addition of more water during slaking then risking 'chilling' the lime, which leaves the mortar 'short'), temperatures within the lime may reach 300 degrees C. If too much water is added – or if quicklime is thrown into an excess of water – the temperature of the slake may not reach 100 degrees C – the lime will be 'drowned' and may lack binding qualities. When slaking to putty, the necessary water may be added to the lump lime, the slaking material stirred and then diluted with more water once the slake is complete. If the quicklime is added to the water, the ratio of water to quicklime should be around 2:1, with more quicklime and more water added as slaking proceeds, care being taken to neither burn nor chill the lime.

The volume of water necessary to complete the slake should be worked out according to the form and source of the quicklime before mixing. Just enough water will deliver a 'dry slaked' mortar; just enough and a little more, will deliver a thick paste.

Necessary water should be delivered in one go, or steadily by sprinkling.

Method A) mix quicklime and naturally moist aggregate at 1:3 and leave to 'dry-slake' for about 3 - 5 minutes or until super-fine dust begins to form or to rise from the mix, whether hand-mixing or mixing in a pan-mixer. Drum mixers are not generally suitable and hot mixing in these should be treated with great caution. Use tyre-rubber trugs (usually available from agricultural feed suppliers) – plastic buckets will melt. The maximum temperature at the dry-slake stage will be around 150 Degrees C, sometimes up to 175 Degrees C, sometimes less, around 102 Degrees C, depending upon the moisture content of the sand. It should not be left to become too hot, however. **Wear eye protection and dust masks and all other appropriate PPE, as for all lime (and cement) products. Have sugar solution (Diphoterine) to hand for eye-wash.**

Incrementally add water sufficient to make a mortar of the desired consistency.

Leave for 10-15 minutes before use or set aside for later use, when a little more water may need to be added during the beating. Maximum temperature after the addition of additional water and the completion of the slake will be unlikely greater than 58 Degrees C

B) Heap moist sand and hollow the heap. Add lump or kibbled quicklime at typically 1:3 proportion by volume. Add the water necessary to effect the slake (typically around 2 volumes of water for each volume of quicklime) before mounding the sand over the quicklime. As the quicklime expands, cracks will appear in the sand covering, which will also begin to dry out. These cracks should be closed to retain the necessary heat of the slake. The sand and lime may then be mixed together whilst still very hot, more water being added to bring the mix to a mortar consistency. Alternatively, the dry sand and lime mix may be passed through a screen to remove larger unslaked lumps of lime. The screened material may be stored for later mixing to a mortar or, more typically, be mixed through to a mortar. As more hydraulic limes, much slower to slake, came to be used during the 20thC, this method was varied – water was added to the sand-enveloped quicklime and left for 12 to 24 hours, before being mixed with the sand after cooling and 'banked' in a minimally moist condition and left for late-slaking to proceed, before being later knocked up to a mortar.

Modern quicklimes may be highly reactive, so that they will 'spit' upon the addition of water – in this case, ensure coverage of the quicklime with sand before beginning to add water. As the quicklime slakes, continue to add water (but do not drown or burn the quicklime) and to agitate the mix with shovels. Add more water once most slaking is complete and until the mix has been brought to the required mortar consistency. Use immediately or leave for later use. The mortar should be well beaten.

A version of this in a pan mixer might be to lay alternate layers of lump lime and aggregate in the mixer, which is turned off. Turn on the mixer and add water incrementally until mortar is produced, or

C) Using granulated or lump lime. Add all aggregates to the pan mixer and well mix; add granulated or small lump lime. When well distributed, add a full bucket of water and then train the hose into the mixer at low pressure, stopping occasionally, until a sloppy mortar consistency is achieved. This will begin to stiffen as slaking proceeds and as the mortar cools. If not used hot, it may need knocking up with more water before use. This method produces no dust. It may be achieved in a drum mixer, though pan mixers are always to be preferred.

This method can be used for powdered quicklime also. Procedure as above. When hose not available, add full bucket of water to mixer and then gradually add another as the slake begins. Little more water will be needed, but may be added when slaking is complete according to end use of the mortar.

b) or c) will also be the methods if the intention is to 'dry-slake', adding just enough water for the slaking of the quicklime to take place and leaving a slaked 'dry-mix' mortar to be set aside for later knocking up and use, or to mix a 'coarse stuff' which will be moist but not so moist as to be used as a mortar without the later addition of more water during knocking-up.

D) As for B), but add sufficient water to effect the slake all in one go – just enough for the quicklime to slake to a dry hydrate or a little more water to produce a thick dough-like paste. Cover with sand and leave to cook. Temperatures within the quicklime should not much exceed 100 degrees C. Mix sand and lime together whilst still very hot, adding more water in small increments as necessary (do not 'drown' the lime after first wetting).

If the quicklime is hydraulic, add just enough water to produce a dry slake, cover and leave to cook (slaking may take 24 hours). This will dry the sand. Mix sand and lime together after 24 hours, screen or sieve as necessary and set aside as a dry mix for later use. If for immediate use, mix straight to a mortar as soon as slaking is complete and use immediately. The latter method may retain unslaked lime lumps which may disrupt the mortars in situ.

E) Add good helping of water to the mixer (but not significantly more than is required to effect the slake), then sand and/or other aggregate, which will produce a sand slurry. Then add the quicklime and more water as necessary, bringing quickly to a mortar. This method will minimise dust. It may be characterised as a 'wet-slake' method, with all ingredients, including necessary water, all together from the start.

F) Mixing putty lime or limewash. Add just enough water and a little more to lump lime. Stir as slaking proceeds. Once slaking is complete, add more water as required (for lime wash eg). Thick, dough-like lime putty should be pressed through a sieve to remove lime lumps. The use of powdered quicklime will remove the need for sieving, but stirring will be essential as slaking proceeds.

Alternatively, add powdered quicklime to a small quantity of water (no more than three times the volume of the powdered quicklime) to produce a thick, dough-like putty.

This may be mixed with sand at 1:2 or diluted with more water (and well-mixed) to produce a limewash, which should be mixed thick enough that a dipped brush does not drip and applied whilst still hot for maximum effect.

"The Mortar in which rubbed and gauged Bricks are set is called Putty, and is thus made:

Dissolve in any small Quantity of Water, as two or three Gallons, so much fresh Lime (constantly stirred with a Stick) until the Lime be entirely slacked, and the whole become of the Consistency of Mud; so that when the Stick is taken out of it, it will but just drop; and then being sifted, or run through a Hair Seive, to take out the gross Parts of the Lime, is fit for Use".

(Batty Langley 1750 London Prices of Bricklayers' Materials and Works)

From British Standard CP 121.201 (1951)

Lime Putty. Lime putty may be prepared from the quicklime or dry hydrate of either non-hydraulic or semi-hydraulic lime.

A) *Preparation from quicklime.* The slaking vessel or pit should first be partly filled with water to a depth of about 1 foot and enough quicklime should then be added to cover the bottom and come about half-way to the surface of the water. Stirring and hoeing should begin immediately, and the quicklime should not be allowed to become exposed above the surface of the water.
Should the escape of steam become too violent or the quicklime become exposed, more water should be added immediately. The mix should boil gently and, as it thickens, more water should be added. Water and then quicklime should be added alternately until the requisite quantity of milk of lime is obtained.
The stirring and hoeing should continue for at least five minutes after all reaction has ceased. The resulting milk of lime should then be run through a sieve of 1/8-inch mesh into a maturing-bin. It should be protected from drying out and remain undisturbed for a period of at least two weeks to permit it to fatten up to lime-putty.

Both may be used immediately (still hot) or shortly afterwards.

G) Slaking by immersion or aspersion. This was not uncommon in the past. For the immersion method a basket of lump lime was held underwater until soaked ('until it stops whistling' Del Rio 1859) and then tipped out onto a board (for immediate use) or into a barrel (to cook and be stored for later use) to slake to a dry powder. As such, it could be sieved before mixing to remove lumps. Mixed whilst still very hot, it delivers a good, workable mortar. The aspersion method saw the lump lime laid out in 6" layer before sprinkling with just enough water to effect the slake. This was done on site, close to the works. Once slaked, the hydrate was banked up with sand for prompt use – being knocked up to a mortar within a week, typically. Lime slaked by immersion and loaded into sealed barrels might be transported long distances without premature carbonation – from England to the West Indies, for example. Lump lime could not be similarly transported without risk of some air slaking. Some stucco workers in Italy still deploy immersion slaking, but mix and use the lime: marble dust finish mortars hot.

Typically for plasters and renders, hot-mix (to a mortar) the day before use, using Calbux 90 powder, although base coats may be applied hot. The mortar will improve overnight, becoming somewhat less 'tacky' and more elastic. When lump lime is used, the coarse stuff mortar may need to be laid down for longer than 24 hours to avoid late slaking. Some quicklimes – in either powder or lump – will require longer than 24 hours storage after mixing to avoid the risk of late-slaking. This is only necessary for plastering. Pointing mortars made from lump lime may require similar. For pointing, we tend to use powdered quicklime.

H) Gauging with NHL.

When the binder content is 50/50 (slaked) air lime/NHL the mortar will be typically 80% less strong than if NHL alone had been used (Foresight 2003).

Gauging with NHL will produce a feebly hydraulic lime which will set up more readily in damp situations and have a high free lime content contributing good effective porosity. It will be appropriate for exterior renders and harling coats where driven rain is common and where more rapid setting is required. It can encourage the use of appropriately deformable, effectively porous and 'softer' lime mortars by craftspeople unfamiliar with hot mixed air lime mortars and who can find the adhesiveness of these a culture shock. NHL gauged mixes are less 'sticky' although they retain good workability. The variability in strengths between different 'brands' of NHL, as identified by Historic England research is not especially significant in the context of gauging, which is offering a 'helping hand' to the air lime mortars in particular environments. The free lime contribution of the NHL will be highest in most NHL 2.0s.

Which NHL? Practitioners in Scotland tend to use NHL 2.0 at a ½ air quicklime: 1 NHL 2.0: 6 aggregate, having before used NHL 5 and NHL 3.5. Bill Revie recommends the use of NHL 5.0.

1:1:6 air quicklime: NHL: aggregate would an alternative mix and closer to the typical historic lime: aggregate proportion than the above.

Gauging of 'common mortar' with hydraulic lime became common in Northern Spain at the end of the 19thC. Work done with gauged harling mortars in Scotland over the last 20 years, often in severely exposed situations, have proved entirely successful to this day (Frew and Revie HES Technical Paper 2017).

Mixing method:

Hot mix the air quicklime by methods A to E above. Once slaking is complete, add the chosen volume of NHL and add more water as necessary; use promptly. Coarse stuff may be mixed and stored ahead of time, but the mortar will be cold.

Alternatively, add the NHL at the same time as the quicklime. This may stiffen more quickly than with the above method, the heat of the slake accelerating the on set of the hydraulic set. Use immediately.

Lastly, St Astier kibbled hydraulic quicklime is becoming available in the UK. This may be used instead of hydrated bagged NHL. Cornish Lime have settled upon a mix of 1 part hydraulic quicklime: 3 parts Calbux 90 powdered quicklime: 12 parts aggregate as being the most workable and appropriate for use in the Cornish climate. All quicklime would be added at the same time, the high reactivity of the air quicklime accelerating the otherwise slower slake of the hydraulic quicklime. This would offer a feebly hydraulic lime.

Mixing and applying Limewashes

Curing.

Rapidity of initial set will be variable depending upon the moisture content of the repaired fabric, the relative porosity of the substrate and the relative humidity of the atmosphere, as well as the relative humidity within the pores of the mortar itself.

Using hydraulic mortars, whether NHL or Portland cement-gauged limes, we have become accustomed to relatively fast-setting mortars and worry when setting is slow. We have become unaccustomed to initial shrinkage of placed lime mortars, and worry when this appears. A typical pozzolanic mortar will be ready for 'knocking back' within 1 or two days of placement, without drying too fast, even during cold weather.

We have also become accustomed to regularly wetting pointing mortars after placing, which is *essential* for hydraulic lime mortars to properly set. Whilst this may sometimes be necessary with hot mixed air lime mortars, *generally it is not.* Continued spraying will inhibit or prevent the onset of carbonation and 'case-hardening' and promote ongoing shrinkage. Ideally, therefore, mortars should be placed and hung down with hessian or other protection and left alone until stiffened and knocked back. After case-hardening, occasional spraying may be recommended, but is not strictly necessary *unless pozzolan or NHL has been added to the mortar* – the water given to make the mortar is generally sufficient to facilitate the set and setting will not begin until the water content is reduced.

For repointing, the mortar should be relatively stiff whilst still pliable. Mortar should be pushed into pre-wetted joints with a pointing iron and left slightly full. It should not be tidied up or over-worked.

As the mortar begins to set and stiffen and approach leather-hardness, surplus mortar should be scraped away using lengths of plastering lath and the face beaten with a stiff bristle brush to remove laitance and to roughen the surface.

If initial set is tardy (due to saturated substrates, low temperatures and/or high relative humidity), use lath to remove the latience earlier than this, to open the mortar to the air, but do not attempt to 'knock back' until further stiffening has occurred.

Unless reproducing a particular historic pointing pattern, full, flush pointing should be the default finish.

Regular misting after this stage will be of benefit for 7 – 14 days, but is not essential so long as the curing is slow and steady. Early misting may prevent the onset of carbonation and should be avoided until carbonation is underway, as indicated by 'case-hardening'.

Fat lime mortars gauged with either NHL or pozzolans will require more misting and even regular re-wetting to set and to bond within themselves and to the substrates properly. This should be done for as long as possible. Failure to deliver on-going hydration will deprive the mortars of necessary 'tenacity'. This necessity was well understood historically; it is rarely fully appreciated in modern usage of hydraulic mortars.

Protecting the work with hessian is recommended for at least 7 days – longer, if the mortar is hydraulic. The necessity for protection independent of atmospheric humidity applies particularly to hydraulic mortars.

The water necessary to bring a fat lime to a workable mortar consistency is all the water necessary to effect carbonation and set. The mortar needs to lose a fair proportion of its moisture content in order for carbonation to begin and this begins only at the outer face initially – producing 'case-hardening'. Carbonation to full depth may take a long time. *In the meantime, the mortars are load-bearing and entirely fit for purpose, and, in solid wall construction, will accommodate settlement of the fabric without cracking or disruption.* Immediate or rapid hardening of mortars is a demand of modern – *not of traditional* - construction technology.

Traditionally lime rich mortars carbonate more slowly than the over-lean putty lime mortars specified during the lime revival. There is more lime to carbonate. This should not be viewed as a problem. Once 'case-hardening' has occurred, further protection of hot mixed fat lime mortars should not be seen as essential, though it remains so for hydraulic mortars.

"The setting of lime mortar is the result of three distinct processes which, however, may all go on more or less simultaneously. First, it dries out and becomes firm. Second, during this operation, the calcic hydrate, which is in solution in the water of which the mortar is made, crystallizes and binds the mass together. Hydrate of lime is soluble in 831 parts of water at 78 degs. F ; in 759 parts at 32 degs., and in 1136 parts at 140 degs. Third, as the per cent, of water in the mortar is reduced and reaches 5 per cent., carbonic acid begins to be absorbed from the atmosphere. If the mortar contains more than 5 per cent, this absorption does not go on. While the mortar contains as much as 0.7 per cent, the absorption continues. The resulting carbonate probably unites with the hydrate of lime to form a subcarbonate, which causes the mortar to attain a harder set, and this may finally be converted to carbonate. The mere drying out of mortar, our tests have shown, is sufficient to enable it to resist the pressure of masonry, while the further setting furnishes the necessary bond." (Richardson C (1897) Lime, Hydraulic Cement, Mortar and Concrete. Part I. The Brickbuilder Vol 6 April. Rogers and Manson Boston).

Hot mixed air limes enjoy a strong bond between not only the lime and aggregate, but between both of these and engaged water – they let this water go with some reluctance and rarely dry too quickly, even at the face. They are less likely to lose excessive water into even dry porous fabric.

Hot mixed shelter coats and limewashes perform better than those cold mixed from putty lime and may be applied hot or cold. They should be mixed to a relatively thick consistency – such that lime will not drip from a dipped brush.

Harled/rough cast render coats were typically applied whilst still hot (Revie).

Pozzolans

Pozzolans are typically fired clays added to an air lime mortar to enhance or to accelerate initial set. Mortars with significant volumes of added pozzolan will set underwater and were commonly preferred for hydraulic works over natural hydraulic limes. Common pozzolans historically were volcanic ash from Puzzuoli, Italy; Trass, volcanic ash from central Europe; low-fired brick dust; forge ashes, ironstone dust, coal and wood ash. Smeaton and others concluded that the minimum pozzolanic addition for underwater use should be one third of the aggregate, eg two parts sharp sand: one part pozzolan: 1 part quicklime. Such a mix, if all fired clay or other pozzolan combined with the lime, would leave no free lime in the mortar and no calcium carbonate, which served no function underwater. Underwater mortars were often richer in pozzolan than this and, before Smeaton, might be 3 parts pozzolan to 1 part quicklime.

For building in the air, the pozzolanic content was typically much lower – probably not exceeding 10%. Research into pore structures and functional performance of hot mixed mortars by David Wiggins (HES 2017) would indicate that up to 10% pozzolan (calcined china clay in this case) does not disrupt the necessary pore structure, but that this is progressively disrupted by volumes or weights of pozzolan in excess of 10%. In most situations, less than 10% will be sufficient, between 5 and 8%, depending upon the pozzolan. Such low level addition was very much the domain of craftsmen in the past – it is not much discussed by engineers or other professionals. Wood ash and pulverised brick would seem to have been the most commonly used. Primarily, these will hasten initial set in damper situations, but deliver a mortar of similar (and appropriately) lower strength to a straight air lime mortar, if sometimes a little stronger. This is comparable to a feebly hydraulic lime mortar. Grey chalks had typically between 3 and 6% clay content before firing.

The addition of unfired clays will deliver some feebly hydraulic properties to mortars when added to a hot mixed mortar. Oyster shells contain some clay and will have such an effect; as will degraded granitic aggregates and iron-rich limestone aggregates. Powdered slate dust will also enhance the set of otherwise air lime mortars.