A CRITICAL REVIEW OF HISTORIC LITERATURE CONCERNING TRADITIONAL LIME AND EARTH-LIME MORTARS

VOLUME ONE: DISSERTATION
VOLUME TWO: APPENDICES (USB STICK)

NIGEL DAVID COPSEY

MA (BY RESEARCH)

UNIVERSITY OF YORK, DEPARTMENT OF ARCHAEOLOGY, CONSERVATION STUDIES

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ABSTRACT

The focus of this research is an assessment of historical texts on the manipulation of lime to make mortars: how these were made and to which ends they were used, as illustrated by published writings upon the subject from the UK, France, Spain and North America. The insights from this research are balanced against the professional experience of the author in using traditional mortars for 15 years, as well as being supplemented by research into archived building accounts and the personal testimony of retired craftsmen.

The general conclusion of this research is that many of the core beliefs and materials of the 'Lime Revival' and conservation practice over recent decades have not been informed by historical understandings or historical precedence in the use of lime mortars, or, indeed, by well-recorded craft practice, especially in terms of materials. The principles of like-for-like and compatible repair of historic fabric requires a radical reassessment and practical shift in favour of hot mixed lime and earth-lime mortars if these fundamental conservation principles are to be observed.

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I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

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1. INTRODUCTION

There has been a revival in the use of traditional hot mixed lime mortars in recent years. This has led to a reassessment of the use of lime mortars in traditional building conservation practice. The growing experience of those already working routinely with hot mixed mortars indicates that many of the current 'best-practice' rules evolved during the 'Lime Revival' of the 1970s, and more especially those rules associated with the use of natural hydraulic limes (NHLs), do not necessarily apply to lime-rich hot mixed mortars. The Lime Revival gathered pace after the conservation of the West Front of Wells Cathedral under the direction of Robert and Eve Baker, as well as of Crowland Abbey and Exeter Cathedral after 1975. The Bakers wrote little down – their philosophy was carried forward by those who worked with them (Burman 2018). It has arguably shaped 20th and 21st-century building conservation to the exclusion of a number of sound historical understandings and experience of traditional craft practice, and its most commonly used materials, whilst at the same time promoting excellent and considered craftsmanship and conservation ethics and a general, commitment to the use of air limes, eroded in recent decades by the almost blanket use of Natural Hydraulic Limes. The primary research question is to what extent has recent conservation practice with traditional, and particularly lime mortars been reflected or informed by craft practice and the written discussion of this in the past, particularly in regard to mortars? The central hypothesis is that modern practice has been little-informed by historic knowledge or understanding but that this knowledge or understanding relies not only upon the close reading of historic texts but also upon practical experience derived from the routine use of traditional materials and the dynamic interaction of previous knowledge and the use of these materials in a practical, 'real-world' environment. The author has been using earth, earth-lime and hot mixed air lime and pozzolanic mortars in this environment for 15 years. The conclusion may be drawn that the 'Lime Revival' is in need of wholesale, root and branch reassessment in line with the insights to be derived not only from historic texts, but from the observations of material science, and particularly of mortar analyses, and from growing practical experience, as well as from recent research into the character and performance of Natural Hydraulic Limes, all of which carry similar weights of importance and all of which are generally complementary and allow for instructive synthesis.

An investigation of historic texts on the use of lime and lime mortars to illuminate and inform modern conservation practice was identified as an urgent necessity in a paper adopted by the European Commission in 1998 (Zacharopoulou 1993 &1998), but this demand was little attended to. In the UK, at least, it coincided with the rush to NHL-use, a trend that was not founded upon a review of the literature of historic practice, nor indeed upon much beyond hearsay and an inadvertently limited focus upon relatively few sources (Holmes 1993; Lynch 1994; 1998). These were mainly limited to the late 19th and early 20th centuries, as well as to the occasional text that had argued against the use of fat limes and in favour of hydraulic limes for building in the air, Vicat in particular (Holmes 1993) (see Appendix Two). After 1997, NHLs were heavily promoted within the conservation industry, largely displacing putty lime mortars, both of which were overly lean in lime compared to historic mortars on analysis (Forster

2004; Lynch 2007; Copsey 2013). Hot mixed air or pozzolanic air lime mortars were rarely considered suitable for conservation work, although most mortar analysis indicated – and continues to indicate – otherwise. This research makes the case that traditional lime mortars were not only lime rich, but were also typically hot mixed, or otherwise prepared, directly from quicklime, whether these were mixed from pure, nearly pure or naturally hydraulic limes, or incorporated variable volumes of pozzolanic addition. Concretes, limewashes and plasters were similarly prepared in the past.

The main body of this thesis comprises a review of historic texts (see Appendix Nine) with supporting research into archived building accounts and specifications (see Appendix Five). It incorporates insights from relevant recent literature on the subjects of hot mixed lime and earth-lime mortars (see Appendix Two) and alludes to wider analysis of shifting relations of production within the building industry, insofar as these affected mortar choices and design (See Appendices Six & Seven). The extensive primary research conducted into documentary building accounts from across England forms Appendices One & Five, which latter comprises edited transcriptions from archive material, the word-count restrictions of an MA format preventing their inclusion in the main body of the text. Extensive transcriptions from old texts relevant to lime, earth and earth-lime mortars form Appendices Nine & Ten. Appendices Eight & Eleven elucidate evidence from material science in support of general observations and conclusions. Several chapters relevant to the research are held within the Appendices – a review of relevant recent literature (Appendix Two), a summary of observations from archived building accounts (Appendix One) and a section of the historic literature review focussed upon Concretes, omitted from the main body only for reasons of space (Appendix Three).

2. METHODOLOGY

The methodology of this dissertation has been straightforward – the comparative review of historic texts that treated of lime and lime mortars, occasionally of earth or earth-lime mortars, spanning the period from 160BC to the mid-20th century by a practicing stonemason and conservator familiar with the materials discussed. The texts have ranged from the more technical, written by engineers and chemists, to those written as parts of encyclopaedias or other 'guides' to building, as well as construction industry texts and the writings about their craft and craft practice by stonemasons, plasterers or bricklayers, and by architects. In the region of 300 texts have been consulted, published in the UK, France, Spain and North America. Neither the Spanish texts consulted, nor the majority of French texts, have been translated into English until now. These translations have been done, for this research, by Emeline Michel and the author.

The geographical and chronological range of texts consulted has been determined not only by availability and language but by the general hypothesis that such broad ranges are essential to draw out the constants of craft practice, as well as to identify difference (see Appenidix Four) and to illustrate this general constancy across time and region, from 18th Century North Yorkshire to Ancient Rome; from Devon to North America, and so forth and to demonstrate that craft practice across the world has been driven by the nature and necessary performance of the base materials – lime and earth and other aggregates, as well as by the objectives, patterns and priorities of traditional forms of construction and by the social context of these, particularly in the changing relations of production and the shifting roles within these of practitioners and professionals. This has been complemented, on occasion, by the personal experience of the author and others using these materials, and the occasional testimony of retired craftsmen. Technical research from the earlier 20thC has also been consulted and incorporated.

Many of the old texts have been downloaded from www.archive.org or via Google Books, the same sourced from a variety of universities around the world, but referenced by original editions consulted. The principal library consulted has been the British Library, Wetherby. Other works have been purchased, being published in the UK. Archives visited are listed in Appendix Five.

A review was also undertaken of more recent academic and practical papers on the subject of earth-lime mortars (relatively few) and of hot mixed air and hydraulic lime mortars, as well as upon air lime and pozzolanic air lime putty mortars (see Appendix Two). While these latter do not reflect the focus or preoccupations of most historic texts upon the subject of lime or earth-lime for building, they do offer insights into the limited basis for more recent technical publication.

Beyond this, published, transcribed building accounts, as well as several hundred building accounts and, where available, building specifications held in archives and local history record centres around England have been consulted, transcribed and analysed, offering a 'control' to the content of the old texts, as well as targeting a variety of geologies to examine the potential variations in craft practice that might be determined by such difference as well as those aspects that remain essentially the same. Archives visited are listed in Appendix Five. The archive research is designed to provide insights into the 'culture' of lime use and the organization of lime and masonry works. This includes working practices, materials, the seasons when lime work is being executed and the erosion of craft 'power' as hierarchy was being built into the building trades, particularly with the role introduced for specifying architects and quantity surveyors, and the subsequent embrace of industrially produced 'standard' forms of slaked lime and cements.

Insights from historic texts have been assembled within categories of use as well as of form of materials, although over-laps will always be found in situ and the base materials for each purpose are remarkably similar.

All sources have been read through the eyes of a practicing stonemason and building conservator long-experienced in the use of the types of traditional mortars for repair and conservation that have been the focus of this research – all have been interpreted in relation to the author's personal experience and understanding.

Reference has also been made to a selection of mortar analyses carried out by materials scientist, William Revie, for buildings from the Roman period through to the mid-20thC, all of which emphasise the preponderance of typically hot mixed air lime mortars, with or without added pozzolan. Representative examples are included in Appendix Eleven.

These primary and secondary sources have been synthesized into as comprehensive as possible a narrative of mortar use over many centuries, at the same time as drawing out the practical lessons that may inform current and future practice with compatible and like-for-like materials, as well as avenues for useful future research.

3. GLOSSARY OF TERMS

The 'Lime Cycle' (see Figures 1-4, 50-55)**:** a generally schematic iteration of the processes by which limestone is fired in a kiln to produce quicklime which is then slaked, in a potential variety of ways, to produce a material that may be used on its own or in combination with earth, crushed stone, pozzolans or other aggregates, particularly sands, to produce a mortar for building purposes, which will then set by carbonation, chemical or hydraulic activity, or both in parallel reaction, returning to a version of the original limestone. The lime cycle has been variously over-simplified and even used to lend a mystical air to the process; has embedded often mistaken assumptions about craft practice and forms of lime used, and has generally excluded reference to hot mixing and to earths.

Air Lime; Fat Lime; Pure Lime - pure or nearly pure lime that sets by carbonation only.

Natural Hydraulic Lime - made from impure, clay-bearing limestone which sets by chemical reaction with water, as well as, in part, by carbonation. Termed feebly, moderately and eminently hydraulic according to volumes of clay and power of set. Variable in their mineral composition and behavior not only between sources but within the same source.

Hydraulic Lime: typically, a combination of air or feebly hydraulic lime with added pozzolans - typically fired clays - and which sets by both reaction with water and carbonation.

Pozzolans - a general term for any fired clay, or other silica-rich material that may react with lime to form dicalcium silicates and aluminates. The term derives from a volcanic ash favoured by the Romans which was sourced in the vicinity of Puzuoli. See Figure 92.

Quicklime - the product of burning limestone at around 900 degrees C during which burning all carbon dioxide and all water is driven from the stone.

Slaking - the process by which quicklime is given back its water prompting an exothermic reaction. Sometimes used for the addition of water to an already slaked dry hydrated lime.

Hydrated Lime - strictly speaking, quicklime that has been slaked. Typically used to denote dry hydrated lime, both pure and naturally hydraulic.

Lime putty: a typically pure or nearly pure lime slaked with an excess of water to create a thick, dough-like paste for prompt or later use on its own or as a binder.

Aggregates: typically sand or limestone dust or earthen material used to bulk out a lime or clay binder, to strengthen a mortar and/or for economy of binder. Pozzolanic materials were also used as aggregate.

Earth Mortar: sub-soil of variable clay, sand and silt content, improved or otherwise by the addition of sands or other aggregates

Earth-Lime Mortar - as earth mortar but with the addition of small volumes of air lime to enhance tenacity and performance. See Figures 56-91.
Hot mixed lime mortar: a mortar made by engaging unslaked, substantially slaked or just-slaked lime with sand or other aggregate whilst the lime is very hot. See Figures 20-43.
Natural Cement. Made by firing naturally occurring clay-rich calcareous nodules at around 900 Degrees C, the kiln product ground to a fine powder. Sets by hydraulic reaction. Unlike NHL, has no residual free lime.
Portland Cement: made from blended clay and limestone (often chalk) fired at high temperature and ground to a fine powder. Sets by hydraulic reaction.
Cement-lime Mortars. Originally common, air lime mortars gauged with natural cement; then, 'pozzolanic' addition of around 15% of Portland cement to hasten initial set; by the second and third decades of 20thC and the realization that cement-sand mortars caused problems for traditional building fabric and performance, a 'compromise' mortar enjoying the 'benefits' of early setting with some of the bond, workability, water retentivity and efficiency typically delivered by high free lime content. Used throughout the build, these deliver mortars of suitable utility and – in the form of 1:3:12; 1:2:9 and 1:1:6- have generally contributed to buildings of appropriate and successful performance (see Figures 5-16). Their use for conservation and repair of buildings constructed using traditional mortars has been frequently more problematic although not always unsuccessful.
Limewash see Figures 93-102. Also called lime whiting. Typically air lime slaked with a minimum of necessary water, subsequently diluted with more water to facilitate sieving and application in thin layers with brushes. Pigments might be added during slaking. Frequently applied whilst still hot from the slake. Common salt was a common addition; casein, wood ash, tallow or linseed oil also, as well as zinc sulphate. Tallow or other fats would reduce or eliminate capillarity, 'water-proofing' the limewash.

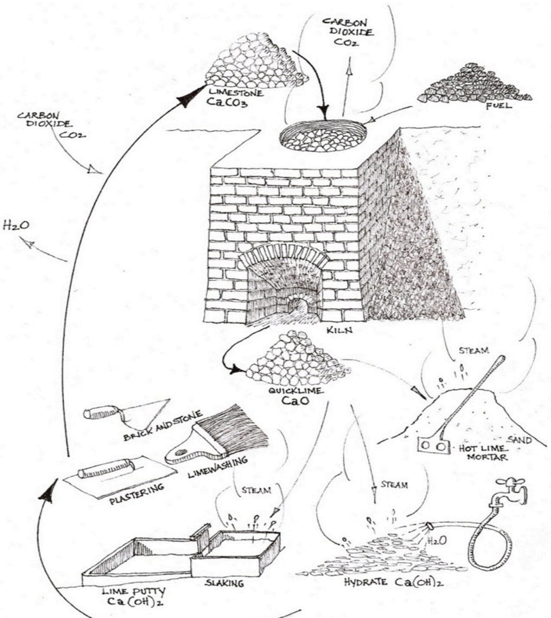

Figure 1. *The Lime Cycle.* (Courtesy Patrick McAfee).

4. PREVIOUS LITERATURE.

There have been very few reviews of historic literature regarding lime and its use in mortars. None has been extensive; a few have offered partial reviews of relatively few texts. Salzman (1952), Colvin (1971), Knoop and Jones (1933; 1936), and assorted individuals who were members of local history societies or groups, recognised the value of primary research into archived building accounts. Cowper (1927) prepared a limited literature review for the Building Research Establishment, focusing upon methods of mortar preparation, indicating, perhaps, an awareness that long-term and inherent understanding of such methods was already being eroded at this time. Sickels (1988) looked much more at the minutiae of organic additives that had been found in old mortars, reflecting a common enough preoccupation with such additives without an in-depth analysis of basic slaking procedures, or of the dominance of pure or nearly pure limes in craft practice, and sharing the dominant assumption over recent decades that lime putty had been the primary binder historically. Holmes (1993) reviewed architects specifications from the RIBA archive but these, as mentioned above, were limited in their scope, application and time-span; Lynch (1998) referred mostly to similarly late texts on the subject. Early editions of Lime News regularly featured excerpts from authors whose books remained available, but this was done in a relatively random fashion; no interpretation or synthesis of such sources was attempted. More recently, Marinowitz (2010) looked at practice in 15th to 17th Century Zurich and elsewhere through the lens of archived documents, concluding that hot mixing was the norm. Copsey has prepared an extensive literature review for Historic Environment Scotland, to be published in 2019, which is perhaps the first such review of readily available texts in English, French and Spanish and spanning a 2000 year period, with the greatest density of texts from the 18th Century onwards. Published transcriptions of archived building accounts were incorporated into this review. Copsey (2019) offered a literature review in *Hot Mixed Lime and Traditional Mortars* as part of a wider examination of traditional mortars and practical, best practice guidance. In a text that emerged during the course of this MA, Gibney (2017) sought to analyse the building trades in Dublin through the prism of surviving building accounts and specifications, as well as through pattern books and trade manuals and the buildings themselves, exploring many of the themes touched upon here and setting building practice within its particular social (and colonial) context. Gibney was an architect and was more particularly focused upon stylistic issues than upon materials or their manipulation, although, inevitably, any study of building accounts makes these difficult to avoid. Published posthumously, it represents an important contribution, asserting the essential nature and significance of craft practice, as well as exploring the dynamics of architect-craft relationships in the particular circumstance of urban Ireland. As with all such focused study, its intimate local understanding allows for plentiful generalisation across time and place. In similar spirit, Linda Clarke (1992) executed a thorough-going Marxist analysis of shifting relations of production and class struggle in late 18th and 19thC London, specifically in the Somers Town and St Pancras area, drawing extensively upon building accounts, maps and other documentary sources to illustrate the shifts in class power and the reduction in autonomy within the building trades evidenced by the movement away from measured rate valuations and towards wage labour, as well as the implications for this in terms of site organization (and scale), skill levels and rates of

exploitation incumbent upon the erosion of traditional bonds and apprenticeship systems within the construction industry.
A review of more recent literature concerning earth-lime and hot mixed lime mortars forms Appendix Two.

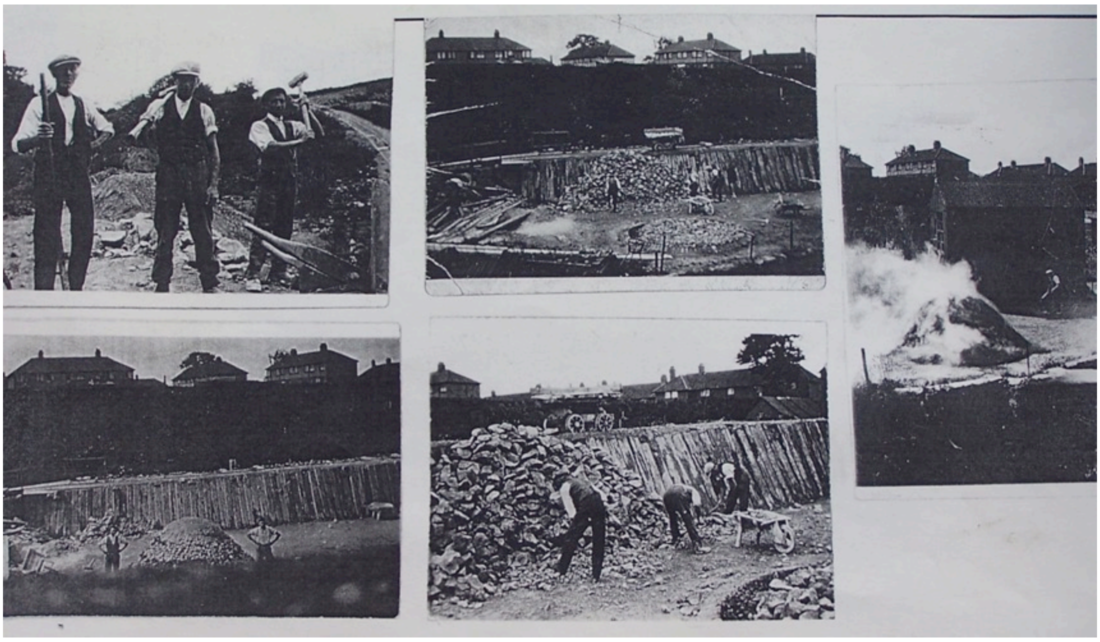

Figure 2 *Lime-burning at its most simple, Malton, 1930s***.** *This was used in the construction of social housing, some of it visible in the background.* (Image: Eric Blades).

Figure 3. *Traditional lime-burning, Norway* (image: Chris Pennock)

Figure 4. *Woral Smith lime-kiln, Fairbury, Nebraska, 1890s*

5. CONTEXT

5.1 Craft Practice, Fat Limes and Shifting Relations of Production: Reading Between the Lines, as well as the Lines Themselves.

This chapter provides an historical narrative of changing craft practice and embedded understandings of material performance, relating these to the author's own practical experience and general observations using quicklime mortars, as well as giving voice to the largely voiceless craftsmen routinely working with these mortars in the past. Many of these insights are to be gleaned from the published reflections and criticisms of craft practice by professionals, particularly by engineers (Hassenfratz 1825; Biston 1828; Vicat 1818; 1856; Burnell 1857; Scott 1862; Gillmore 1861; Lazell 1915).

It may be said that workability was the 'standard' against which the quality and utility, as well as the proper performance of a lime mortar, was judged in the past, particularly by craftspeople. Rather than seeing the incremental and steady set of earth-lime and fat lime mortars as a disadvantage, craftspeople valued these properties. They were unimpressed by rapid and hard setting alternatives (lest such properties were essential to their function), until social change and shifting relations of production began to transform the building industry. This changed in favour of mass, and fast-built, speculative construction executed by employed gangs of workers, of which rapid returns on investment were demanded. The change was coupled with the introduction of 'new' materials, outside the experience of traditional builders, such as steelwork, plumbing, electrics and the like. Alongside this, the associated increasing use of (and perceived need for) competitive tendering elevated the role of architects, and especially of quantity surveyors initially (Powell 1980), over and above traditional craftsmen in the building site hierarchy. Their role gradually superseded that of the craftsman in terms of material specification, valuation and, for the first time, in terms of mortar design. Discussing commonly held later 19th-century views about declining standards of workmanship, Powell (1980) summarises the issue thus:

> One origin of this was the erosion of autonomy of craftsmen by the growing practice of drawing up full details of buildings in advance of construction in order to aid estimating. The effect was to move decisions from site and workshop to the relatively remote designer's office. Hitherto, craftsmen had decided for themselves details of ornament and window, staircase and dormer, but now they were forced to yield responsibility to professional designers, often with different priorities. Another origin of concern for quality probably lay with the greatly increased volume of work carried out, much of it of low quality, as always (p33).

The latter point was especially so in circumstances of higher alienation and greater rates of exploitation once traditional patterns within the industry had been eroded by the development of industrial capitalist production, initially in the UK, and then globally. Clarke (1992) illustrated and analysed these shifts, as well as the erosion of traditional bonds within the building industry, which saw the dilution and ultimate elimination of 'guild-like' control and organisation and traditional apprenticeships in

London from the later 18thC onwards, a decline that facilitated and was compounded by the growing influx of less and unskilled labour, not only from other parts of the UK, but from Ireland, particularly after 1830. On the face of it, the switch to wage labour and casual or more permanent employment by larger contractors and speculative builders, might seem to have led to greater security, but it represented a significant erosion of autonomy and independence, as well as creating the conditions in which the rate of exploitation – the ready generation of surplus value – might be reliably increased, as well as inviting significant de-skilling within the industry. Measured rates, where these endured, declined in value for the first time.

> A key to the importance of different labour processes to valorization is given in the relation of different wage forms to time and output. Piece-work, for example, is rarely used in labour processes crucial to increasing surplus value, not only because of the difficulties for employers in controlling and reproducing such labour but also because…labour itself tends to reap the benefits of its own greater productivity. In contrast, with time rates, gains from improvements are entirely the employers' (Clarke 1992 57).

Outside of urban centres, many of the traditionally constructed buildings that today receive the attentions of conservators or of conservation repair were constructed within a very different social context and according to different, less exploitative relations of production. Very few were built by competitive tender: this form of contract began to become more common as buildings became more complex and building companies larger and more generalised in response to industry and technical demands, as well as rapid population growth. Competitive tendering, with contracts invariably awarded to the lowest tender, became the norm by the last quarter of the 19th century even in more rural situations (see Appendix Six). The building stock had expanded dramatically in the UK during the 19th century - the housing stock growing from around 1,889,000 dwellings in 1811 to at least 7,550,000 in 1911 (Powell 1980, 4) - with many civic buildings, mills and factories built besides. However, despite the shift to new tendering practice, this unprecedented growth was largely achieved using hot mixed air and feebly hydraulic lime mortars, prepared mainly on site and frequently used on the day of mixing.

So long as it had been that craftspeople designed the mortars of their trade, they had chosen to use eminently workable, relatively soft, inexpensive and efficiently prepared earth-lime and fat lime mortars. The former were generally only displaced as bedding mortars when access to raw materials became restricted, such as by enclosure of the remaining common lands in England by the end of the 18thC. The burgesses of New Malton (North Yorkshire), for example, had enjoyed the right and privilege of taking stone and earth for 'building and edification' from the 'wastes on either side of the town' since 'withowten Man's Membrance or mynde' before then (Hudleston (1962) 111-115).

Architects generally preferred 'standard', readily quantified materials, and the same socio-economic forces that had diminished the power of artisans had also generated technologies to produce such materials on an industrial scale (Powell 1980). Prehydrated air lime, Portland cement and, on occasions when its inherent variability might be ignored, bagged, pre-slaked NHL (after 1896, although NHL quicklime was generally preferred by craftsmen as late as the 1951 British Standard Code of Conduct) were materials that came quickly into use in a variety of combinations, after an initial embrace of neat cement: sand mortars was adjudged to have been a mistake (US Bureau of Standards 1924; Schaeffer 1932). The removal of inevitable, if often minimal, variability in traditional limes, to be responded to on site, also represented a significant de-skilling of the masonry and plastering crafts, just as the sudden embrace of structural steel did for the carpenter. These shifts were compounded by industrialized warfare and its consequences. World War One represented a brutal cull of young, fit, economically active, mainly working class men from Europe and far beyond, of all trades and none, and its conditions precipitated and magnified an even greater cull of particularly younger adults across the world by the 'Spanish Flu'.

Ideological shifts followed upon these deep changes in available materials and often skilled and experienced manpower, as well as within the relations of production. It rapidly became the norm to assert – after an initial acceptance that modern mortars were pale by comparison to traditional mortars, but that they had been forced upon the industry by circumstance (Thomas 1937) – that harder, faster-setting mortars were 'better' and that air lime mortars were simply inadequate and inappropriate. Such shifts were uneven across the world, and continue at the margins today, but always mirrored the ascendancy and then the hegemony of industrial capitalist production and the collapse of relatively independent artisans and building craftspeople with the loss of their historically generally higher and more independent status.

5.2 What are Mortars For? What Properties Do They Require?

Reflecting the tension that had existed even then between engineers seduced by hardness and apparent durability, and craft traditions, Biston complained in 1828 that

> Sometimes, the workers reject….types of lime which would be preferable to the ones they are accustomed to using. 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….(203-204)

By contrast, in France, as late as 1914, Champly asserted millennium-old traditional understanding and craft practice:

> We differentiate mortars thus: fat lime, used for raising walls, hydraulic lime for foundations, substructures, basement and works meant to be immersed. Slow (Portland) or prompt (natural) cement for underwater works or in very humid places. (Champly 1910-1914, 54)

Masons and plasterers generally preferred fat lime mortars (Smeaton 1791; Biston 1828; Gwilt 1839; Wright 1845; Sloan 1852; Vicat 1856; Hitchcock 1841 & 1861; Scott

1862; Hassenfratz 1825; Kidder 1920; Searle 1935) for their efficiency of preparation, their higher sand-carrying capacity (Smeaton 1791) and their gradual, steady set (Sutcliffe 1899), that allowed for the even settlement of traditional buildings without cracking or loss of bond. They were viewed as providing an excellent and durable bond between building units and mortars (US Bureau of Standards 1924; Boynton & Gutschick 1964), whilst being resilient to compromising jarring and disturbance during construction. They had been proven since time out of mind to produce dry and thermally efficient structures (Ritchie 1955), but also for their relative economy, both in raw materials and in production and use. A pure or nearly pure, or a feebly hydraulic, lime was observed to slake with urgency and general predictability. It would carry more sand than a more energetically hydraulic lime, or a magnesian lime, in both of which late-slaking was much more of an issue than in a fat lime (Rees 1829), and which expanded in volume much less upon slaking. More sand equated to lesser overall cost. A pure or nearly pure quicklime would substantially complete its slake within minutes (Miller 1960), allowing almost immediate engagement of slaked lime and sand. It took advantage of thermo-dynamically created particle sizes (Miller 1960) and bonds between lime, aggregate and water, so that a hot mixed mortar presented no free water to run down a wall, staining the stone or brickwork and a maximum of cohesiveness and adhesiveness. Its cohesiveness and adhesiveness allowed for precise and efficient application of the material, incurring little waste, and its reliance upon four main factors to begin its set – the porosity of the building unit; the porosity of the original mortar (in repair work), both of which applied suction to the freshly laid – but eminently water retentive - new mortar; the wind and the relative humidity.

A hot mixed earth-lime or lime: sand mortar stiffened readily in use (and the more readily if used hot), becoming structurally load-bearing very quickly and rarely inhibiting sound and on-going construction; it was eminently adhesive and its inherent water-retentivity all but guaranteed good and lasting bond (Boynton & Gutschick 1964). It was eminently cohesive, with all of the 'tenacity' that was a prized mortar quality, as well as being the most commonly deployed term to describe the best quality of a good mortar. Cementitious mortars, including natural hydraulic lime mortars, displayed few of these characteristics; they were harsh-working and not very water-retentive (Johnson 1926). Overly lean lime putties were workable, but lacked water retentivity, as well as durability, being generally considered weak in their binding qualities (Wright 1845).

Cementitious mortars used above-ground were inherently unstable, expanding and contracting in each wetting and drying cycle and ultimately shrinking away from building units or simply, as re-pointing, working loose over time (typically over a 20 year period). These are generally incompatible with older, traditional substrates, whether with the stone or brick, or with the original bedding mortars of earth, earth-lime or lime, particularly in terms of brittleness and effective porosity. Shrinkage after hardening was an inherent property of cementitious materials, whereas initial shrinkage in a lime rich air lime mortar was a one-off event, readily addressed during normal aftercare (National Lime Association 1934) and whilst the mortar remained plastic.

Nor did a typically lime rich mortar require the same levels of aftercare, or even of preparation of substrates by abundant pre-wetting (though some was still required): they were much more inclined to look after themselves, beyond initial attention to shrinkage (Sutcliffe 1899: Richardson 1897). All the water necessary for them to set up was given to them during slaking and mixing, and in excess during the latter procedure (Higgins 1780; Richardson 1897). In most conditions, they needed no more – quite unlike the more hydraulic limes and cements, which require ample and on-going hydration after placement, and well beyond their initial set, as well as physical protection against over-rapid drying out, once more, unlike pure lime-rich mortars, which require such protection only in exceptional circumstances.

The priority was to prevent the ingress of water into the top of an unfinished (and therefore, as yet undetailed) wall. This would undermine the slow and steady release of excess moisture from a lime rich mortar into porous substrates and the atmosphere; it might cause the leeching of as yet uncarbonated lime from the depth of the wall, and, most particularly, facilitate frost damage of saturated mortars and even stone, on occasion.

"In the winter season, so soon as frosty and stormy weather set in, cover your wall with straw or boards; the first is best, if well secured; as it protects the top of the wall, in some measure, from frost, which is very prejudicial, particularly when it succeeds much rain; for the rain penetrates to the heart of the wall, and the frost, by converting the water into ice, expands it, and causes the mortar to assume a short and crumbly nature, and altogether destroys its tenacity" (Kelly 1823 306)

5.3 The Shift Towards 'Hard & Fast' Binders

Most of the above narrative contradicts the received wisdom not only of the conservation industry, but of most academic and industry research over the last 40 years. Both have focused upon the preferred use and properties of lime putty or, more recently, over the last 22 years, of natural hydraulic lime.

Until around 1919 in the British Isles, at least, the majority of mortars were prepared from pure or nearly pure quicklime and were typically hot mixed (see Appendix Ten), although 'hot mixing' is a modern term. Hydraulic limes for underground and underwater use were also typically hot mixed before this date, or were, if particularly hydraulic, sand-slaked from quicklime and mixed cold, or else the quicklime would be dry-slaked initially on its own and set aside before mixing.

Natural cement was a particularly eminently hydraulic NHL but which had no free lime left after burning and had to be finely ground to set in contact with water, 'slaking' upon mixing without heat generation. The hydraulic compounds generated were di-calcium silicates and aluminates, as are developed within pozzolanic lime mortars. Tri-calcium silicates and aluminates, present in Portland cement, as well as in most modern NHLs (Figuieredo 2018) were generally absent. Natural cement was used historically for water works and for some external renders, as well as for the production of pre-cast architectural mouldings, rarely as a building mortar, except when gauged into a lime-rich common mortar on occasion (Totten, 1842; Wright 1845; Gillmore

1886), mainly to accelerate initial set at depth and sometimes for repointing (Pasley 1838). In common with numerous binders patented in the late 18th and 19th centuries, some of them based upon NHL and gypsum ('Scott's cement'), or borax ('Keene's cement'), its use as an external render was generally unsuccessful and it was most often displaced subsequently by the even more problematic application of Portland cement renders.

Portland cement use became established from the 1860s onwards, although mostly in these early years for flooring and for footings, as well as for drains and underground works, displacing the use of natural hydraulic lime or natural cement for these (relatively novel) purposes, and being, at this time, little stronger than an eminently hydraulic lime (Brocklebank 2012). Hot-mixed lime concrete (or floor plaster) is one of the earliest evidenced uses for lime, being found in the Neolithic period for dwelling house floors (Karkanas & Stratouli 2008; Zacharopoulou 1998; Papayianni 2013; Dikshit 1938).

It was commonly used in the Roman Empire, usually in association with pozzolanic aggregates (Vitruvius 1999). After this, whilst perhaps never as common as earthen floors, fat lime concretes were deployed within dwellings and ancillary buildings, particularly farms (Marshall 1788; 1796), until the use of hot mixed hydraulic concretes was revived, initially in London, after 1815 (Pasley 1826). Feebly hydraulic grey chalk lime, and then often moderately hydraulic blue lias lime, was the basis of such concrete throughout the remainder of the century, but displacement by Portland cement occurred early in the 20thC, although mixed as leanly as had been Blue Lias (1:7 or 1:8) (see Appendix Three). Building standards from London (1875, Dibdin 1911) and New York City (1871, Powell 1889), continued to treat of fat quicklime and sand mortars for general use, but also of Portland cement mortars mixed at 1:4 for some uses, such as below ground construction and drains. By the 20th century routine Portland cement use was becoming much more common and, at least initially, mortar proportions reflected traditional practice, the cement being mixed at 1:2 or 1:3 with sand.

By 1934, Schaeffer at the BRE noted the tendency for such mortars to promote dampness and decay in traditional masonry structures. In the USA, where cavity wall construction was rare, it had been noticed by the 1920s that buildings constructed with Portland cement mortars and less porous bricks were routinely letting in water. Research by the US Bureau of Standards (Johnson 1926; Palmer & Parsons 1934; Wells et al 1936; Building Code Committee 1924) identified the harsh working and very poor water retention and, therefore, the poor bond, and extent of bond, of such mortars as being the cause of failure, as well as their discouragement of and impediment to good workmanship. They tested and then recommended the use of cement-lime mortars in their stead – identifying the free lime content as the determinant of improved workability and bond and also the compromised bond that might be induced by the addition of air entrainer. 1:2:9 cement: lime: sand, along with 1:3:12 and 1:1:6 became the recommendation, according to exposure, although the Bureau did not rule out the use of straight air lime mortars for masonry walls thicker than 8″, and considered them entirely fit for purpose in situations where fast-setting was not a priority (US Building

Code Committee 1923), as did Searle in the UK, in 1935. Somewhat later, and without reference to US research, Richie (1955), for the National Research Council in Canada, examined similar problems in Newfoundland and Nova Scotia, noting that buildings constructed of air lime and more porous bricks remained dry; whilst those constructed since using higher-fired, less porous bricks and cement mortars were routinely wet and leaked. They interviewed architects and masons locally. Almost without exception, the professionals blamed poor workmanship for the problem. It took an older mason to point out that it was the character of both bricks and mortar that was its source, both having high porosity (Richie 1955). The NRC ultimately settled upon a mortar of 1 Portland cement: 2 ½ high calcium lime: 8 sharp sand as the most appropriate modern mortar for construction and for the repair of traditional buildings; a recommendation that still prevails, although Portland cements are significantly more powerful today. The relative success of such cement-lime mortars – when used for new build, not always for the conservation of existing fabric – is evidenced in Figures 5-16. The buildings shown are dry and have suffered no decay of either mortars or building units.

At craft level, small additions of Portland cement might be made to otherwise hot mixed air lime mortars (Revie, Calgary Mortar Analysis 2017, see Appendix Eleven No.10), again in situations where more rapid hardening was demanded. As late as 1951, Sawyer, a plasterer, indicated one-fifteenth or one-twentieth part of Portland cement for this purpose. Also at craft level, those masons that could, tended to ignore this trend. Wealthy suburbs of Chicago were built using straight hot mixed air lime mortars well into the 1930s (Pers comm Mario Machnicki 07.02.2018), and such continued routine use of air limes remained common internationally, and certainly in the absence of industrial capitalist development and beyond the normal reach of its associated trade.

At the same time, and for similar reasons, it became more common for gypsum or small volumes of cement to be added to more than ‘hard finish’ plaster coats, an idea frowned upon, in the case of gypsum, by Vitruvius (1999), who was wary of differential and competing setting properties. It was first suggested in the more modern age by Gillmore (1864), albeit, once again, only where rapid initial set was considered essential. Portland cement in these periods, however, was much less strong than after WWII and has only continued to increase in power since then. An 1875 Portland cement might be adjudged to be around the strength of a ‘normal’ NHL 5.0 today (Brocklebank 2012). Prior to 1870, when production methods changed, it had been considered to be of similar variability and unreliability as NHLs (Burnell 1857).

In this same period, it became common for the first time in history to routinely run quicklime to putty for use as a binder, despite the historic reputation of this method for inherent weakness (Vicat 1818; Wright 1845). This assumed an understanding that interior plasters would be gauged with gypsum or Portland cement and exterior mortars with Portland cement, compensating for any weakness (Thomas 1937; Mitchell’s Construction 1912; 1947; Ministry of Works 1950; British Standard Code of Conduct 121-201, 1951; Newbold & Lucas 1950). The same perception had led already to the adoption of 1 binder to 3 aggregate ratios (as in 1:2:9), for the first time, the additional power of Portland cement, as well, perhaps, as cost, seeming to make this allowable. In these early years of transition, at least in part because craftspeople familiar with traditional materials and methods remained, there was no sense that these modern renditions of building mortars were 'better' or 'superior'. On the contrary, they were considered inferior in usefulness and performance (Thomas 1937) and, unless Portland cement was added as more than 40% of the binder (as in 1:1:6), as having a lesser tenacity than a traditionally proportioned air lime mortar, albeit after 90 days (Palmer & Parsons 1934), something confirmed by the Smeaton Report (Teutonico et al 1993). Ray Waverley, a retired lime plasterer from North Yorkshire, who was trained in his trade by his father, refused throughout his working life to use or to add cement or gypsum, and would walk off a job if its use was demanded. He states still today that sandstone and limestone buildings locally should be repaired 'with lime only' and that old buildings in general should be repaired with the same materials of which they were built, regularly using earth daub backing coats for this reason (pers comm 23.05.2019).

Searle pointed out in 1935:

> A greater strength can be used by replacing some or all of the lime by Portland cement, but where such additional strength is wholly unnecessary there is no object in securing it, and lime mortar has ample strength for all ordinary buildings.… Some builders add a small proportion (15 per cent.) of Portland cement to lime mortar in order that it may set quickly enough for the bricklayers to work rapidly, as in many modern steel skeleton structures with brickwork panels (Searle 1935 585)

Cement-lime mortars were, however, being routinely specified by architects and engineers – particularly as walls became slimmer and were more 'scientifically' designed (Powell 1980) to minimize 'waste' and, at the same time, the volume of stone – as opposed to relatively thin-walled brick – buildings went into almost terminal decline (Powell 1980).

As late as 1935, Searle, again, noted that 'fat limes are preferred' for general building in the UK and notably defined NHL as a 'weak cement-lime' binder.

Giles Gilbert Scott reflecting the prevailing view of most professionals in 1938 asserted that:

> We cannot expect to get the best results from either a definite lime mortar or a definite cement mortar, but that a mixture of cement, lime and sand is likely to produce the most satisfactory material for our purpose (Report included in Richie 1955 A16).

Whatever they might think (or know), the crafts had increasingly lost the ability and the context to resist these changes. The ideological pursuit of 'hardness' and water resistance over water management, as well as the increasing affordability of Portland cement after the heavy Government subsidy of its production during WWII, saw the almost complete erosion of trust in air limes for modern construction. This accelerated closure of local lime kilns, their burners unable to compete with 'big business' cement producers, some of whom also produced NHLs and bagged air lime hydrates.

Where small-scale quicklime production endured, such as in Pickering, North Yorkshire, until the 1980s, then local builders would use this in preference to bagged hydrate, but would deploy it in cement-lime mortars (pers comm Alan Kendall, builder, Thornton Dale 10.12.2017), which Geeson had counted as optional, instead of lime hydrate, in 1952. As the skills and the understanding of lime and its normal behaviour continued to decline, then such cement-lime mortars were routinely deployed not just for new construction, which was generally successful in performance terms (see Figures 5 -16 below), having a typically high free lime content (Wiggins 2019), good bond and relative softness and steadiness of set over 90 days (Figueiredo 2018), but for the repair of traditional buildings as well. This invited all manner of compromised performance and decay, depending upon the relative volume of air lime, and it was into this environment that the 'lime revival' emerged.

Meanwhile, the wider building industry moved even further away from the use of lime, with lime added only as a 'plasticizer' to an otherwise cement mortar, its function in workability, bond and bond strength entirely forgotten. Cement: sand mortars became the norm for new build, which remains the case. The most commonly used mortar in the UK today is 1 part Portland cement to 5 parts sand: a mix that, even when cements were much less aggressive than today, the US Bureau of Standards had concluded was the worst possible mortar of construction, offering the worst of all worlds in terms of workability, water retentivity, bond and extent of bond, and therefore of water-tightness.

In this context, of course, with 1:3:12 and 1:2:9 falling from use and 1:1:6 or cement: sand mixes becoming the norm, even NHL seemed a preferable, more workable and softer option. This appeared to be affirmed in the context of earlier English Heritage indications (Ashurst & Ashurst 1988) that 1:1:6 was an appropriate conservation mortar, despite its having been reserved for the most exposed environments in the recent past (Mitchell's 1947; Ministry of Works 1951). All this contributed to the willingness of its embrace, not only for conservation, but for some new build, at least. The use of lime putty became largely confined to 'specialist conservators', considered to have the knowledge and the patience to use them successfully, which many continued to do until competition from habitual users of NHL – and liberal procurement policies, as well as a general shallowness of understanding amongst specifiers – made it very difficult for such specialists to compete without themselves switching to NHL.

Figures, cement-lime mortars

Figure 5

Figure 6

Figure 7

Figure 8

Figures 5-8: First Plymouth Congregational Church, Lincoln, Nebraska, 1931

Figure 9: *Auditorium, Wayne, Nebraska, 1935*

Figure 10

Figure 11

Memorial Park Library, Calgary, Alberta, 1909. Hot mixed lime mortar with minimal Portland cement addition (see Appendix 12 No 9).

Figure 12

Figure 13

House in York, 1910. 1:2:9 mortars.

Figure 14

Figure 15

Coventry Cathedral. 1956-62. 1:2:9 mortar.

Figure 16 *Cathedral of St Luke the Redeemer, 1905-06, Calgary, Alberta (see Appendix Eleven No.10). Hot mixed lime mortar with small volumes of Portland cement added.*

6. REVIEW OF HISTORIC TEXTS

The texts consulted for this research (see Appendix Nine) range in date from 160 BCE (Cato) until 1952 CE (Geeson). The majority dealing with lime and lime mortars were published during the 18th, 19th and earlier 20th centuries, many of these being written by military engineers, some chemists and, occasionally, by craftsmen themselves, as well as by construction industry professionals, such as architects.

Overall, these show a great consistency of understanding concerning the basics of slaking and mortar preparation, with variations determined by the character and properties of the lime used, the logistics of transportation (quicklime could not travel far without beginning to air slake) and building site and available or preferred aggregates. The primary variable, within clear parameters, was individual craft preference (Neve 1726 198-204). The localised diversity of lime and earth-lime mortars resides far more in the aggregate choices (and, therefore, geology) than it does in either the lime, the slaking method or the mixing procedure. These latter were universal wherever pure or nearly pure lime was used, as well as when feebly or even more energetically hydraulic limes were deployed, although the sequencing of the slaking methods might vary according to the hydraulicity of the quicklime. Rondelet put this very well in 1803:

> In all the regions of France and Italy I have traveled to study the way of building, I questioned workers, the ones who seemed the smartest. I found that their knowledge came, from a practical side, from use and experience. There are

> many differences in materials; it is not possible to prescribe specific methods, because every rule requires uniform qualities and properties in the materials, which does not happen. A worker of long experience knows how to judge if the mortar is fat enough, beaten enough, if it has the right consistency - he almost never makes a mistake; he crushes and mixes the different materials until it feels right. This is why it is not enough to propose methods, we need to train workers to understand and modify them on account of the materials and buildings intended to be built. There is an infinity of things that cannot be said nor prescribed in advance. We can only indicate the general precautions to take for the most important operations, which are the methods of slaking lime and the methods of mixing it with sand and cement *(pozzolans)* to make a good mortar. (Rondelet 1803, 301)

Pure and nearly pure quicklimes were the preference of most craftspeople, as well as the most widely accessible form of lime globally, and were the primary forms of lime used from the Neolithic period onwards, and across the world in all periods. As Smeaton rationalised the situation (1791), and others confirmed (Marshall (1788); Hassenfratz (1825), Biston (1828), Gwilt (1839); Hitchcock (1861); Scott (1862), Champly (1910); Searle (1935), purer limes were preferred by the crafts, as is also illustrated by a multitude of 19th-century advertisements for building limes issued by lime-burners and suppliers (Rolando 1992):

> 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 (Smeaton 1791, 108).

6.1 Predictability, workability and set

Relatively pure quicklime was predictable in its behaviour – providing it had been properly burned – and this behaviour could be modified in predictable ways by an experienced craftsperson. It slaked with alacrity; it expanded in volume by around two times as it slaked (most authors agree on this); it accepted the most sand or other aggregate into the mix without compromising workability or performance (Pasley 1838).

Quicklime also offered efficient methods of manipulation and a mortar that possessed optimum properties of effective porosity, workability, cohesiveness, adhesiveness, water retentivity, bond strength and extent of bond, whether this mortar was of earth-lime or lime: sand or other aggregate, such as limestone. It suffered initial shrinkage, but this happened whilst the mortar remained pliable, so that such initial shrinkage might be readily closed down, and such shrinkage rarely compromised bond with the substrates. After this, an earth-lime or a lime-rich mortar would suffer no further shrinkage (the addition of lime to an earth stabilised the potential expansion and contraction of the clay component (Boyton 1980). In contrast, more hydraulic or cementitious mortars would shrink by up to 4 times as much as air limes over the course of their life-times, but after the mortar had set hard (National Lime Association (USA) Bulletin 321(1934)) allowing for no remediation. There were ways of reducing, if not entirely eliminating initial shrinkage in a lime-rich mortar – aggregate choices and blends, beating of the mortars, which allowed the same workability to be delivered with less water, the addition of hair or other fibrous material, or proteins, as well as the addition of low volumes of pozzolanic material, such as wood ash.

Earth-lime and lime rich mortars generally set slowly, but stiffened to a load-bearing initial set within short order of placement, especially when the building units were porous, or when the mortars were placed hot, promoting the early evaporation of the excess water necessary to produce a workable mortar.

> 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….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) quoted in Kidder 1909, 134).

The slow and steady set of a lime rich mortar was not considered to be a problem or a handicap before the late 19thC – it is rarely, if ever, mentioned in texts before the 20thC, with F H Baddely, a Royal Engineer working in Canada, expressing what was probably the prevalent attitude in 1838:

> I do not think that the fact of a cement being sufficiently soft to yield to the pressure of the nail after one week's exposure to the air any proof of unsoundness, for I would trust more to the circumstance of an observed increase in the hardness, when examined from time to time, than to the quantity of that increase; and it is always, in my opinion, a safe sign when the hardness slowly but certainly increases (Baddely 1838 147).

A little shrinkage was considered the 'price' worth paying for mortars of eminent workability and usefulness; it was 'normal' and to be expected, and had no long-term ill-effect upon proper performance (National Lime Association 1934).

The slowness of ultimate set, by either drying and feeble pozzolanic reaction, in the case of earth-lime mortars, or by drying and carbonation, in a pure lime mortar, or by initial feebly hydraulic set followed by the slow carbonation of the high volumes of free lime in the case of a feebly hydraulic lime, allowed the mortars to remain deformable as the building settled, or as green timbers dried in situ, few traditional buildings having had deep or rigid footings before the rising use of concretes for footings during the 19thC. Even these footings offered initial deformability, being typically mixed at 1:7 hydraulic lime: sand and larger aggregate, the set of which underground might be relatively slow, especially when free lime content was high, as in Blue Lias lime; or with pozzolans the full effect of which might take weeks, or months, to fully develop. If mortars were energetically hydraulic and set hard and fast, settlement, as well as their tendency to expand and contract in each wetting and drying cycle, would lead to cracking in the context not only of settlement but of slight seasonal movement.

> Mortar ought to serve at least three purposes: it ought to form a soft but gradually hardening bed to receive the various building-materials, so that these shall obtain an uniform bearing notwithstanding the irregularity of their surfaces; in the second place, it ought to prevent the passage of wind and rain through the joint of the walling; and, lastly, it ought to have adhesive and cohesive strength enough to bind the component parts of the wall into one solid mass (Sutcliffe 1899 116)

Sutcliffe expressed the prevailing understanding at this time. It took much investigation by the US Bureau of Standards, in particular, during the 1920s and 1930s and then by the National Lime Association (US) in the 1960s, to fully express the significance of these requirements scientifically, and the role that relatively soft, porous and slow-setting lime-rich mortars played in keeping buildings water-tight and inherently dry.

> (Palmer) contended that the most frost resistant materials are usually the most dense, but that they tend to remain excessively wet in the wall. " The most weather-resistant wall is one that remains relatively dry even though the materials composing it have poor records in laboratory freezing and thawing tests"…the analogy between freezing a saturated mortar cube and a monolithic wall structure is ridiculous (Boynton & Gutschick 1964 Strength Considerations in Mortar and Masonry).

In the UK, Searle listed the advantages of fat lime mortar as late as 1935: bricks might be laid more rapidly and more easily than with cement; fat limes were the only mortars that might be mixed and stored in bulk in advance. Fat limes delivered the most economic mortar, the material cost being low, and fat lime has the highest sand-carrying capacity; 'the natural plasticity of the lime decreases the cost of mixing the mortar, of spreading the mortar and of placing the bricks; there is no waste, as it can be used indefinitely' and 'the only droppings are due to trimming the joints'; no delays, as 'lime mortar is always ready for use and so increases the efficiency of the entire force and makes maintenance of construction schedules easy' (Searle 1935 574). He attached the same advantages to fat limes for plastering, with the additional benefit that lime mortar was 'an ideal base for colours and decoration' as well as having the greatest covering power. For exterior renders, Searle says that a fat lime plaster is as 'equally durable' as a Portland cement render. Putty for fat lime renders and plasters, he says, should be laid down for 'at least a week' although preferably for several months to avoid blistering, having been pushed through a sieve when first made (p591). The commonality of high calcium, non-hydraulic limes, used on their own or supplemented by small volumes of pozzolan is demonstrated by analyses of mortars spanning almost 2000 years included in Appendix Eleven.

6.2 Pozzolans and feeble hydraulicity

The addition of small volumes of pozzolan to a pure lime mortar to modify its properties somewhat, particularly in terms of more rapid initial set and particularly within the depth of a wall, did not necessarily invite higher compressive strength or any significant diminution of deformability. In 1911, Dibdin tested a range of air, feebly and moderately hydraulic limes mixed with a variety of aggregate types. The differences in 'crushing strength' between mortars made with pure chalk lime and feebly hydraulic grey chalk lime were minimal, in general. Out of five combinations, three of the pure lime mortars had a greater compressive strength than the feebly hydraulic mortars after curing. When brick dust was the aggregate, the pure lime variety possessed almost twice the compressive strength, and with fine sand the grey chalk mortar had less than half the compressive strength of the pure lime version. It was only when blue lias was the binder that the compressive strength climbed much above 300 psi (2 MPa), being generally around twice this. Even so, a blue lias lime with fine sand aggregate was weaker than a pure lime with the same aggregate (Dibdin 1911, reproduced in Beare 1997 77).

COMPOSITION AND STRENGTH OF MORTARS TABLE IV Results of two years tests				
PROPORTION OF LIME SAND	1 to 2		1 to 3	
	tensile	crushing	tensile	crushing
Without clay				
White chalk & standard sand	43	218	53	240
White chalk & fine Charlton sand	53	300	55	260
White chalk & pit sand	73	247	50	253
White chalk & Thames sand	100	297	68	202
White chalk & ground brick	60	213	40	312
Dorking greystone & Standard sand	97	257	103	228
Dorking greystone & fine Charlton sand	50	143	35	140
Dorking greystone & Pit sand	62	333	75	200
Dorking greystone & Thames sand	88	243	58	228
Dorking greystone & ground brick	38	123	27	162
Blue lias & standard sand	58	538	38	188
Blue lias & fine Charlton sand	40	257	26	156
Blue lias & pit sand	75	605	77	650
Blue lias & Thames sand	80	785	102	507
Blue lias & ground brick	133	910	87	657
With 5% clay				
White chalk & standard sand	-	-	50	230
White chalk & fine Charltoin sand	-	-	35	70
White chalk & pit sand	-	-	57	163
Dorking greystone & standard sand	-	-	48	177
Dorking greystone & fine Charlton sand	-	-	20	82
Dorking greystone & Pit sand	-	-	67	140
Blue lias & standard sand	-	-	168	876
Blue lias & fine Charlton sand	-	-	34	79
Blue lias & pit sand	-	-	121	550

Figure 17. *Comparative strengths of different limes with different aggregates,* Dibdin (Beare 1997 77).

The most commonly used pozzolans in vernacular practice (evidenced by consulted building accounts, see Appendices One & Five) were wood ash, brick or tile dust, smithy ashes, or even volcanic ashes, such as trass, the most frequently used underwater pozzolan in British practice historically, as well as for laying stone floors, due largely to its ready availability from Holland.

The full gamut of 'vernacular' pozzolans were used in Georgia, USA, as evidenced by comprehensive analyses carried out by Dawn Chapman (2012). These were also relatively slow in their strength development and much less powerful than pozzolans commonly used today in Portland cement concretes and air lime mortars, such as micro-silica or meta-kaolin (Walker & Pavia 2016). Reflection on analyses of mortars made with pozzolanic aggregates, in this case calcined ironstone and associated fuel ash (see Appendix Eleven, numbers 9 &10), indicates that they retain a high free lime content and a well-connected pore structure consistent with a high degree of effective porosity, that they are rarely brittle and generally deformable but have been generally durable. This functional performance differs significantly, therefore, from that of an NHL mortar, which offers lower deformability, greater brittleness, relatively low free lime content and relatively low effective porosity (Wiggins 2019). Smeaton observed in 1775 and 1791 that all pozzolans were themselves porous.

6.3 Set and moisture retention

Vitruvius had entertained the idea that solid walls were stronger as their mortars were setting than they became once that set was complete, after which the mortars might be brittle and less adherent (Rowland & Noble Howe translation 1999).

The excellent water retentivity of a lime rich mortar meant that the mortars were reluctant to allow more than their excess of mixing water to flee into porous building units or into the air, thus preserving bond with the substrates (Boynton & Gutschick 1964). This was a major advantage, which could be enhanced by the addition of wood ash, which acts as an efficient water retainer itself (Revie 2018, unpublished preliminary investigations 2018). It meant that assiduous protection of new work was generally unnecessary - except at the height of the summer in more southerly, and the depths of winter in more northerly, climes. In available historic images of building sites, walls hung with protection against frost or rapid drying are nowhere in evidence. The priority of any protection of new works was to prevent the ingress of water into the top and into the core of a wall under construction. This is evident in building accounts, where wall-tops are routinely thatched in the autumn months, as at Sadborow House (See Appendix Five, DHS02) and at Bolsover Castle (Knoop and Jones 1938), for example, or when work continues through the winter, as at the Rockingham Mausoleum in 1785-87 (Appendix Five SA02), where a tarpaulin is purchased as winter sets in.

Without such measures, initial and ongoing set would be slowed or even arrested; it might lead to the leeching out of as yet uncarbonated free lime; it might allow frost to gain traction, disrupting new mortars inside and to the face of the wall. This covering was of the wall tops, not the faces – moisture needed to continue to evaporate from the wall face to facilitate carbonation. Facing mortar was unlikely to be frost-vulnerable except, perhaps, in conditions of strongly wind-driven rain, immediately followed by severe frost. The facing mortars of a newly-built wall are most unlikely to dry too fast, if these are rich in lime, as the excess moisture from the mortars of the wall core will pass out of the wall from its face and particularly from its facing mortars, so long as these are porous. Protection is rarely, if ever, mentioned or discussed in old texts about lime, mortars, or building practice, before the mid-19thC, when on-going hydration and protection are insisted on by military engineers in the USA using natural cements, as either the sole binder or as an ingredient in an otherwise air lime mortar (Totten 1838; Wright 1845; Gillmore 1864). Similar is insisted upon during the relatively brief window at the turn of the 19th and 20th centuries when natural hydraulic limes were being more routinely used for above-ground construction:

> 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. (Sutcliffe 1899 120)

Sutcliffe further remarks that "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 1899 120).

Burnell (1857) points out that "Vicat asserts that (mortars) lose 4/5 of their strength if allowed to dry very rapidly" (p69), and 2/5 if too much water is used to make them (p68). "He recommends…that the masonry be watered during the summer months, in all constructions of importance, to guard against this danger." (p69). Vicat, of course, was talking about hydraulic limes used in the air.

Higgins (1780), assuming the use of air limes, had a somewhat different perspective, whilst also indicating the prudence of protection, at least on occasion and according to the prevailing weather conditions:

> That mortar which is not suffered to dry, or which is supplied with moisture as fast as its proper water exhales, does not harden, or hardens only to a small degree…(So, a mortar that sets soonest and to highest degree and makes best cement)…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….(Higgins 1780 pp 73-74).

In optimal conditions and situations, a lime rich air lime mortar will achieve a good extent of carbonation in around 3 months. If used for pointing alone, this might be achieved somewhat sooner than this; if significant masses of mortar are involved, or if a wall is very thick, this process might take much longer within the depth of a wall, although structural performance is most unlikely to be compromised in the meantime.

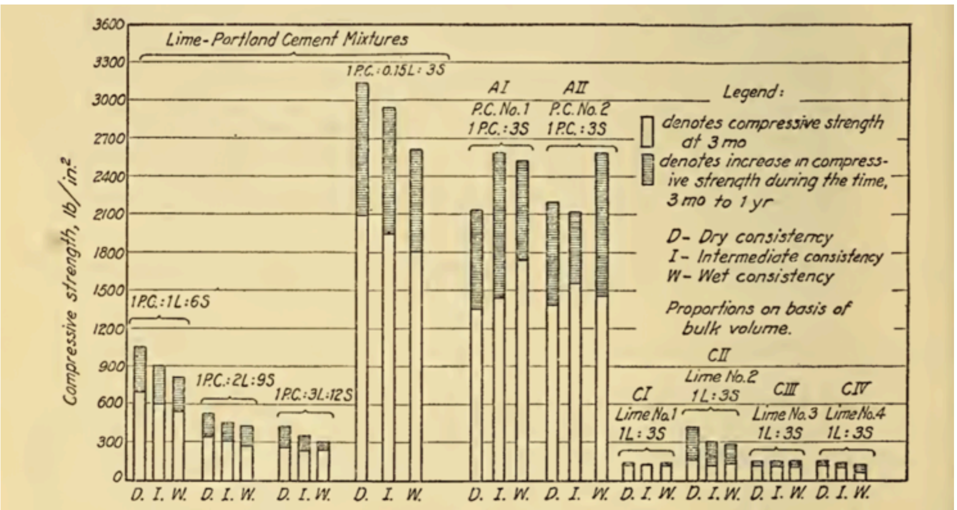

FIGURE 4.—*Average compressive strengths of 2-inch mortar cubes at 3 months and 1 year.*

Figure 18 *Relative compressive strengths of different binders when wet, initially and fully set* (Palmer & Parsons 1934, 662).

6.4 Compressive strength

The compressive strength of an initially set – even a just mixed – lime rich mortar, is not significantly less than the same once fully set (see Figure 18) and one-third of an MPa has long been considered sufficient to support a nine-storey building of traditional construction (Boynton & Gutschick 1964). Indeed, there was no building standard for compressive strength before 1938 (Stewart 1997), so little relevant was it considered to be in the context of traditional patterns of construction. Dibdin (1911) had said that no laboratory testing was rationally required to assess the quality of an existing mortar. He considered experienced observation and an inability to crush a sample between thumb and forefinger quite sufficient to establish its fitness for purpose. Compressive and flexural strength became more relevant as walls became much thinner, their capacities more 'scientifically' quantified, and as the construction industry became more driven by the use of as few volumes of material as possible. 1.3MPa remains the minimum demand for compressive strength (Beare 2015), after the application of 'factors of safety' and this is the typical strength attained by a 1:2 slaked lime: aggregate mortar after 3 months (Figueiredo 2018; Fusarde 2017, unpublished).

That said, modern research shows that compressive strength may be significantly enhanced by both the method of mixing (Fusarde 2017) as well as by aggregate choice. Lawrence (2006) and Scannel and Lawrence (2016) demonstrated such enhancement when limestone aggregates are used instead of sand aggregates with similar grain-size distributions. They show that coarseness of aggregate can lead to significant variations in compressive strength, as well as showing that such a mortar developed similar strength whatever the water content, unlike hydraulic mortars the compressive strengths of which will be reduced in proportion to the initial water content. (Lawrence & Walker 2008). Such enhancement of compressive strength was rarely necessary or even desirable in the past, but may be in the modern building industry where lime rich mortars might offer significant other advantages in terms of effective porosity and effective bond, as well as in terms of better workmanship. Limestone aggregates were at least as commonly used in the limestone districts of the UK, as well as in Spain, as silica sands, in the author's experience, but this reflects ready availability as well as the enhancement in workability offered and the perception of greater 'tenacity' in such mortars. Burnell (1857), a chemist, considered that limestone aggregates and lime were simply more 'compatible', more alike, and more chemically attractive to one another. De L'Orme (1567) felt that lime should be made from the same limestone of which buildings might be constructed, his logic indicating that aggregates might, too, be from the same source. The sub-soils in calcareous geologies of the UK also contained limestone aggregates, inevitably, and the earth and earth-lime mortars found in these regions often display greater cohesiveness and tenacity, and more durability than those from sandstone, igneous or metamorphic stone geologies, again, in the author's observation. There is some evidence that the use of limestone aggregates, particularly of those rich in iron minerals, may offer some very feeble hydraulic reaction when hot mixed, or, at least, may generate harder forms of calcium carbonate, such as aragonite, than calcite alone (Revie, pers comm 06.06.2014).

Mixing method can also influence compressive strength, although much more research into this factor is required, little having been considered necessary in the past, except by some military engineers:

> Of lime kept for three months after being slaked, before being made into mortar — the lime slaked into powder by sprinkling one-third of its bulk of water, gave the strongest mortar — represented by 250 lbs.; the lime slaked into cream gave the next strongest mortar — represented by 210 lbs., and the lime slaked spontaneously during three months, the weakest mortar, represented by 202 lbs… All these mortars being much inferior to that made of the same lime which had been carefully preserved from slaking by being sealed hermetically in a jar *[and hot mixed, therefore]*— this last mortar being represented by 364 lbs (Totten 1842 240).

Totten concludes that the last named lime must be feebly hydraulic, but this may not have been the case.

Early evidence is that hot mixing to traditional proportions, and when the minimum necessary temperature is achieved by slaking with traditionally understood volumes of water, will deliver greater – but by no means excessive - compressive strength, than will cold-mixing or sand-slaking methods where the quicklime is allowed to cool before engagement with the aggregates.

Table 2 Compressive Strength Development

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

Note: 1MPa = 145 psi

W1 1:3 Graymont kibbled quicklime from Quebec: Nesbitt sand
W2 1:3 Graymont powdered quicklime ditto; Nesbitt sand
W3 1:3 Indiana limestone fired on site: Nesbitt sand.

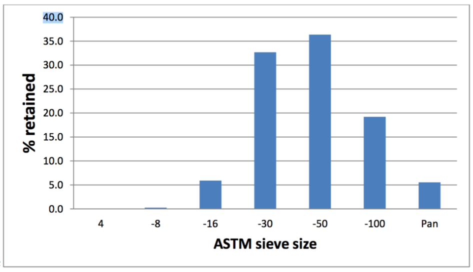

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Figure 19. *Compressive Strength Figures for hot mixed and sand-slaked lime mortars* (Truschik 2018).

In the above table, mortars P1 & P2 were 'hot mixed' by the sand slaking method, but left to cool before mixing, delivering compressive strengths of 1.01 and 1.20 after three months. Mortars W1, W2 and W3 were hot mixed by two different methods. W1 & W3 were slaked from lump lime by the ordinary method (see Figures 51-54), the substantially slaked lime mixed with the sand immediately and whilst still very hot; W2 was slaked from powdered quicklime, the sand and quicklime mixed together before the water was added incrementally. All three were mixed to a mortar consistency and sampled whilst still hot. All three delivered a compressive strength of around 2 MPa after 90 days, and of only just less than half this strength after 28 days (Truschik 2018). In other research, but of unknown slaking method, 1.3 MPa has been typical, but the three mortars sampled above are the only ones that may be vouched to have been mixed, to the author's certain knowledge, to traditional prescriptions.

The majority of this understanding and these expectations of a mortar were progressively lost to the building crafts as the 20th century wore on. Recipes were invented, involving dubious additives, to allow modern, natural hydraulic lime mortars to at least partially imitate the handling properties and performance characteristics that might be much more economically, but perhaps less profitably, achieved simply by hot mixing air lime/pozzolanic or feebly hydraulic limes to traditional proportions.

6.5 Hot mixed lime mortars – visual characterisation


Figures 20 & 21**:** *Roman lighthouse, Dover Castle.*


Figure 22: *mediaeval brick mortar, Hull*; Figure 23: *mortared brick from Frank Lloyd Wright house, Chicago, Both mortars slaked to a dry mix and screened*.


Figure 24: *hot mixed half-harling, Lindisfarne;* Figure 25: *hot mixed and placed internal plasters, ironstone workers houses, Rosedale, North Yorkshire (see Appendix Eleven No.11)*



Figure 26: *Dartmoor;* Figure 27: *Bronte House, Haworth, West Yorks*.



Figure 28: *Butte Creek Mill, Oregon*; Figure 29: *Cole Island, Vancouver Island*

Figures 30 & 31: *Farmhouse near Ripon, North Yorkshire*

Figures 32 & 33: *Napoleonic-era defences, Innis Oirr, Ireland.*

Figures 34 & 35: *Sompting Church, West Sussex.*

Figures 36 & 37: *Rideau Canal Building, Ottawa*

Figure 38: *Henry Best House, East Yorkshire;* Figure 39: *Seamen's Mission, Whitby, North Yorks*

Figures 40 & 41: *18thC farmhouse, Vale of York.*

Figures 42 & 43: *Boynton Hall, 16thC, East Yorkshire*

6.6 Slaking

> Lime which slakes the quickest and heats most in slaking is best, this also falls into the finest powder (Gwilt 1839 46).
>
> Let stone-lime be chosen, which heats the most in slaking, and slakes the quickest when duly watered; that which is the freshest made and closest kept; that which dissolves in distilled vinegar with the least effervescence, and leaves the smallest residue insoluble, and in the residue the smallest quantity of clay, gypsum, or martial matter" (Nicholson 1841 23).

The primary importance placed in the past upon the methodology of slaking lime for building purposes cannot be under-estimated. It was commonly understood that this should be achieved with the minimum necessary water to guarantee the optimum performance from the lime in terms of functional and mechanical behaviour as well as in terms of workability and usefulness. This might be with the lime slaked on its own to a dry hydrate or to a thick, dough-like paste. Either state might be initially achieved within a ring of sand, a shallow pit or a mortar-box, to be mixed with that sand as soon as the slake was substantially complete, or might be in more intimate association with the sand from the start of the slake.

The lime should be neither 'burned' by the addition of too little water in the first instance, which would lead to 'chilling' when more water was added (unless this water was very hot, Miller 1960) and to a 'short' mortar deficient in binder, nor should it be 'drowned', with too much water added in the first instance. The latter would block the outer pores of lump lime, slowing and reducing the temperature of the slake, and the temperature would be further reduced by the sheer disproportion of water to quicklime, as Miller demonstrated in 1960 in the only known (and incomplete) technical research into the effects of different water proportions upon the temperature of the slake (Miller 1960).

The volume of 'necessary' or 'sufficient' water might vary according to the lime. Gillmore (1864) says that this amount should be ascertained whenever a less familiar lime was used. The mixing of insufficient powdered quicklime with excessive and historically unprecedented volumes of sand can have a similarly inhibiting effect upon slaking temperature and may be the reason that it became universally accepted that more than three volumes of sand to one volume of quicklime (or more than two volumes of sand, depending upon the character of the lime, or its intended use) would compromise workability and performance (Pasley 1826). The ideal minimum temperature of the slake in the modern hydrated lime industry is considered to be 100 degrees Centigrade, although 80 degrees may be tolerated (Hassibi 2009), as may be up to 120 degrees, the higher temperature offering some particular advantages, depending upon the initial temperature of the slaking water, as Miller (1960) also recognised. The lowest water volume tested by Miller still exceeded that of traditional slaking methods, but showed that only this lower volume effectively guaranteed the necessary slaking temperature whatever the initial temperature of the slaking water (or ambient air temperature). It may be assumed that water volumes less than this, and typically one

volume of water to one volume of the quicklime to produce a dry hydrate, and 2 to 2 ½ volumes to produce a thick paste (Richardson 1897) would essentially guarantee the necessary slaking temperature whatever the initial temperature of the water or the ambient air temperature or time of year.
The preoccupation historically with the use of low slaking water volumes was accompanied by similar preoccupation with the retention of both heat and *steam* as the slaking proceeded. The modern, industrial slaking of dry hydrates is achieved with steam, not with liquid water, typically, and steam may generate bonds between materials that water alone may not. If slaking was by the 'ordinary method' in a basin of sand, then all instructions include the covering of the slaking lime with some of this sand and the closing down of the cracks that will appear in this sand as the lime expanded, to retain both heat *and* steam. If initial slaking was effected in a pit or in a mortar box, then covering of this somehow to the same end was always prescribed. If quicklime was slaked to a powder for more than immediate use, it was a routine requirement that the still slaking lime was placed into barrels and covered to retain heat and steam and to facilitate the 'cooking' of the lime (De la Faye 1778; Vicat 1856).
Moxon summarised these preoccupations – and understandings – more succinctly than most as early as 1703, and included the observation that lime and sand slaked intimately together produced a better mortar even than the 'ordinary method' whereby the lime was slaked initially on its own before full engagement with the sand, even though it was usually mixed whilst still very hot:

> 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. (Moxon 1703 258),

Moxon assumed dry-slaking, which would require 'sieves…to sift the lime and sand withal before they wet it into mortar or lime and hair'.

William Marshall (1788) took this observation further:

> Besides, another great advantage is obtained by slaking the lime, in this manner, with the sand with which it is intended to be incorporated. The two ingredients, by being repeatedly turned over, and by passing through the sieve together, necessarily become intimately blended; more intimately, perhaps, than they could be mixed by any other process, equally simple…. the labour of preparation is, by this method of slaking the lime, considerably lessened (Marshall 1788 122).

And this observation was shared by Semple (1750); Langley (1750) Dossie (1771), De la Faye (1777), Higgins (1780) Rondelet (1803), Martin (1828), Pasley (1826 & 1838) and Totten (1842), as well as by all those using roller mills or 'edge-runners', which made this intimate mixture of aggregates and quicklime almost inevitable, as well as easy. The lump lime was first pulverized in the mortar mill, before the addition of water and aggregate, or of aggregate and water in prompt succession. Similar had been detailed by Vitruvius for the production of 'concrete masonry' c60BC. This became the method for making concretes (with grey chalk or blue lias limes) during the 19th century, particularly in the UK, the sand and coarser aggregates being mixed dry with typically pre-pulverised hydraulic quicklime before being wetted up and launched into trenches or laid as floors whilst slaking was still underway (see Pasley (1838), referencing Smirke, who introduced the method around 1815; Davy (1839); Bartholomew (1840); Barry (Accounts and Papers etc 1847); Brees (1852); Burnell (1857); Austin (1862); Hammond (1890) and Benton (1893). The latter detailed the use of kankar, a feeble to moderate traditionally used hydraulic lime in India, in similar fashion.

The 'ordinary' or 'common' method, meanwhile, was detailed through time and explicitly by De L'Orme (1567); Ware (1738); Langley (1750, for the mixing of pozzolanic mortars), Semple (1750), Raucourt (1778), Higgins (1780); Marshall (1788); Rondelet (1803); Cleland (1810); Rees (1819); Kelly (1823); Hassenfratz (1825); Biston (1828); Martin (1829); Gwilt (1839); Totten (1842); Treussart (1842); Webster (1844); Wright (1845); Brees (1852); Vicat (1856); Espinosa (1859); Scott (1862); Gillmore (1864); Heath (1893); Millar (1897); Sutcliffe (1898); Richards (1901), for hydraulic limes used immediately; Lazell (1915); Graham & Emery (1924) and into the 20th century for hydraulic lime mortars for immediate use (Frost (1925); Ministry of Works (1950); Newbold & Lucas (1950); British Standard Code of Conduct 121-201 (1951). Most also set out slaking to a hydrate by immersion or aspersion, as well as air or 'wind-slaking' as traditional slaking methods. On site, the ordinary method may be considered to have been effectively universal where mortars were mixed by hand or from lump lime – the basic purpose of this method was to reduce lump lime to a scale that would allow the easy mixing of the lime and the sand, whether this lime was taken initially to a dry slake or to a thick paste.

> Enough water is thrown on the lime to slake it to a powder, and then sand is heaped over it to cover it all up and retain the warmth and moisture. The quantity of water necessary to bring the ingredients to a paste is added subsequently (Scott 1862 71).

6.7 Lime pit slaking, for preservation and removal of lime lumps:

Lime pit slaking, for preservation and removal of lime lumps, is referred to by many historical authors and, for some, at least, is within living memory, albeit in a modern form.

De L'Orme (1567), Ware (1738) and others (Alberti (1460); Palladio (1570); Loriot (1769); Marshall (1788), although preferring mixing sand and unslaked lime; Vicat (1818), although critically, saying it could lead to drowning in incapable hands. Partington (1825) saw the placing of lump lime in a deep pit before covering it with a deep layer of sand, the necessary water evenly applied through this insulating layer of sand, as the best way of producing a lime paste of necessary tenacity, adhesiveness and cohesiveness precisely because of the heat and moisture retention afforded by the sand (or earth) with which it was covered. Vitruvius detailed similar (2009). The sand also prevented premature drying out and carbonation, keeping the paste 'unctuous'. The sand was not typically then mixed with the lime, but was not so lacking in power when this was done – which of course it was on occasion and, perhaps, in places, typically.

Storage in the form of dry hydrate or thick paste was not always demanded by intended purpose, but quicklime could not be kept long before it would begin to air slake, losing power and usefulness. Great virtue was always placed upon slaking quicklime as fresh from the kiln as possible, ideally whilst still hot from the kiln, which would accelerate the set and even improve its efficiency. In most cases, it would be 'hot mixed' for immediate use or to produce a coarse-stuff or a dry hydrate for later use, especially when it was for building works. Lime for plastering would also be hot mixed to a coarse stuff, laid down for late slaking to occur (Higgins 1780), but was often used on its own, as a finish in association with earth or earth-lime structures of pise or adobe or wattle and daub, or of earth and earth-lime mortared masonry. It had perforce to be processed on its own with as little loss of cohesion and adhesion, and workability as possible.

Lime was placed into pits to preserve it in a good and workable condition; to prevent its drying out or carbonating; and when quicklime could not be kept for fear of air-slaking. It was also the Roman method of 'lump removal'. The lime was generally for use on its own as a mortar – for plastering over earth, finely jointed brick or stonework, finish plasters, or with small volumes of limestone or marble dust (see Appendix Eleven No.1 and No.12). Such pits became more common at the end of the 19thC and into the 20th, when fat lime was more typically run to putty for use as a binder. De L'Orme offered the clearest description in 1567:

> The method is this: when you take the lime from the kiln, you will put it in a (pit) with a depth of 2 or 3 feet and of any length and width you would like. You will put a good quantity of pit or river sand of about one or two feet of depth over it….You will then well water the surface, in such a way that the sand is so wet that the lime beneath cannot fuse, nor burn. If you see cracks in the sand and see vapours emerging, you will close those cracks in order to prevent their escape. With the sand well wetted, all the lump lime will convert into a mass of fat which may be used in 2, 3, 10 years - it will be as a cream cheese and the material will be so fat and sticky that it will be almost impossible to use the larry and will consume great quantities of sand and will be such a good mortar that it will stick to stones as if it was a real and good cement. (De L'Orme 1567 29)

That the sand (or earth) covering was not intended to be mixed with the lime is indicated by Hassenfratz in his discussion of the method:

> Because it is essential that the sand should not be mixed with the lime, we place in between them withy panels *(claies d'osier)* or straw or cane mats. When we wish to use it, we uncover it and take the quantity needed and cover it back up immediately (Hassenfratz 1825 153-154).

The building account for Sadborow House, Somerset (Appendix Six DHS02) details the presence of a lime pit, as well as the carriage of branches of fir trees to the same, perhaps to maintain separation of lime and sand.

De L'Orme advertised the indefinitely preservative aspects of the method. Later, in association with sieves and grills to extract the lumps, lime remained in these pits for a much shorter period, the priority being simply to allow time for the slaking of residual lumps:

> Consequently, in order to obtain a perfect kind of plaister that will remain smooth on the surface and free of Blisters, there is an absolute necessity to allow the lime to lie for a considerable time macerating or souring in water, before it is worked up. And the same sort of process is necessary for the lime when intended for use as mortar, though not so absolutely.
>
> Great care is, however, required in the management in this respect; the principal things being the getting of well-burnt lime, and the allowing it to macerate or sour with the water for only a very short time before it is used; but that which is the best burnt will require the maceration of some days in the water before it is sufficiently slaked in the whole for this purpose." (Rees 1829 386)

This reflects 20thC practice and the more routine slaking of lime to a putty to be mixed with sand in this century is explained by Champly in France in 1910, whilst also advertising prompt use of the material in general:

> Lime slaking - fat lime is placed in a basin formed of planks, masonry or even a simple hole dug in clay soil. We water the lime with a spray, the burnt stones crack, expand and melt into a beautiful white, cohesive and creamy paste *ready to make a mortar*. This slaked lime can be conserved from one year to the next by covering it with a good layer of sand and a roof that will keep the rain water away from it, the sand that covers the lime needing to be kept moist….(Champly 1910 54)

6.8 Lime putty mainly for use on its own, as a mortar.

See Figures 44-48 which illustrate the use of putty mortar as well as its durability.

The proportion of 1 hair to 6 lime is given by Neve (1726 201) for the 'white mortar' used as a finish over earth mortars. It was also used for pointing over earth and earth-lime mortars, although analysis of such a pointing mortar in Thornton Dale, that had survived intact since 1656, showed that it was two parts of lime to one part of fine limestone aggregate, with added hair, and that it had been hot mixed (Revie 2019, see Appendix Eleven No.1). The addition of fine chalk aggregate seems to have been common for such finishes anywhere where chalk was readily available. This is precisely the kind of lime putty or lime putty mortar, effectively, that might be held in mortar pits prior to use. For many uses, however, the lime was slaked to putty and used immediately, whilst still hot:

> 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 small 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*… It is only proper for gauged brickwork, or for the ornamental outside work of brick walls (*tuck pointing)*…. (Pasley 1826 9).

The unifying factor in all uses for lime putty, either neat or with small volumes of fine aggregate, and if it was not used immediately, was the necessary absence of unslaked lime lumps. This had always been the reason to lay down lime slaked to a putty or run to a putty from sieved dry-slaked hydrate. When sieves removed the larger lumps that were the least likely to slake easily, even with time, then the period of repose might be less than two weeks. Sieves do not seem to have been used in antiquity, so that the lime had to be laid down for longer for even the larger lumps to slake. That this was the purpose is made plain by Vitruvius (2009), Pliny (2015) and, later, by Alberti (1460) and by a myriad of particularly French writers who deconstructed the reasons for laying down lime over a long period, as well as the specific purposes to which this was intended to be put (De la Faye 1777, Loriot 1769; Biston 1828).

> Lime (for plastering) ought not to be soaked by a single dousing, but ought to be dampened gradually with several sprinklings, until it is evenly saturated. It should then be left on its own, mixed with nothing else, in a damp shady place with nothing but a layer of sand to protect it, until the process of time has fermented it into a more fluid paste. It is certain that this lengthy fermentation greatly improves the lime….<u>Lime prepared in this way requires twice the sand as when mixed freshly slaked</u> (author's emphasis) (Alberti 1460 55)

The slaking procedure, however, in Rome as much as in 19th-century France, was very similar:

> 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. If there is not enough, we will have to wait until the gruel has cooled down before adding any more water, otherwise, the lime will become lazy, will remain grainy and resistant to mixing (Biston 1828, 200).

The requirement of an 'earth pit' would be to allow the percolation of excess water from the lime, as well as to retain necessary moisture, and small lime pits are regularly discovered on former building sites during archaeological excavation, as in Norton-on-Derwent, North Yorkshire in 2017 (pers comm John Buglass 18.01.2017).

On the other hand, a pure or nearly pure quicklime slaked to the above prescription (or even by that of the BS Code of Conduct 121-201) and mixed with aggregate whilst still very hot, will deliver a mortar as workable, cohesive and adhesive as one mixed by other hot mix methods. It will be mouldable and water retentive, feeling much like window putty - from which similarity its name almost certainly derives - and will probably have fewer unslaked lime lumps, even when used straight away. Alternatively, such lime might be slaked to a dry hydrate and stored in this form:

> In the work-yards, *(or on sites)* rich limes slaked by the ordinary process, are preserved by placing them in trenches nearly impermeable, and covering them over with 30 or 40 cm of sand or fresh earth. When slaked by immersion, or spontaneously, they may be kept without change for a tolerably long time, either in casks or under sheds, in large bins covered with cloths, or with straw. (Vicat 1837 32)

These historical accounts can be set alongside more near-contemporary experience. James Edgar, a scaffolder working around Liverpool during the 1950s and 60s recalls lime pits on sites all over the UK in the 50s, the lump lime run into 10 feet deep pits and used after around 2 weeks, often still hot, as a binder by bricklayers and plasterers. Stonemasons, however, were still hot mixing from lump lime (Edgar, pers. comm 10.01.2018).

Ray Waverley, a retired lime plasterer from North Yorkshire, but who worked across the UK, used to slake his own lime putty from lump lime, in a pit, adding the lump lime to water, in keeping with 20th-century practice, but would use it after one or two days, as soon as it had 'lost its fire'. He expressed bemusement at the notion of 'maturing' it for a minimum of three months (pers comm Waverley 23.05.2019), wondering how this could work on a building site, as it would require the lime slakers to arrive a long time before everyone else, particularly before there were lime suppliers 'maturing' lime putty off-site – a relatively recent phenomenon. Waverley's prescription accords exactly with that of Abraham Rees (1829).

6.9 Lime putty as a mortar – extant examples.

Figures 44 & 45. *Aldby Park, Buttercrambe, North Yorkshire*. 1726.


Figures 46 & 47: *Montrose, Scotland, 1893*

Figure 48*: gauged brickwork, York.*

6.10 Lime Putty - summary

Slaking lime to a putty is not typically listed as a 'traditional' slaking method, except sometimes in France, as a preliminary to hot mixing, where it is often termed 'slaking by drowning'. Although it was a common enough criticism of masons that they would routinely drown the lime during the 'ordinary method' of slaking, this was also considered the greatest hazard when making lime putty as well. This assumed drowning was probably the primary reason that lime putty was distrusted as a binder and considered inherently weak in its binding properties (De L'Orme 1567; De La Faye 1778; Rondelet 1803; Vicat 1818; Rees 1819; Biston 1828; Totten 1842; Wright 1845; Gillmore 1864; Radford 1909; Pulver 1922; Searle 1935).

This need not be so, if lime is made to putty by traditional methods and is subsequently mixed at a real proportion of 1:2. Even a dense lime putty will be composed of 30% free water, and so gauging must take account of this to avoid undue leanness.

Traditionally, water would be added to lump lime in just sufficient quantity to deliver a thick, dough-like paste, usually no more, and often somewhat less than 3 volumes of water to the volume of quicklime. This would be stirred to evenly distribute the water and to avoid 'hot spots' in which the lime might burn, as well as over-wet spots, inviting localised drowning. Stirring would also help to break down the lumps. It was uncommon to add lump lime into water before the 20th century, and even then, as evidenced by the 1951 BS Code of Conduct, one volume of quicklime was added to 2-3 volumes of water only, producing the necessary slaking temperature. Hot lime grouts and limewashes were prepared in similar fashion to lime putty traditionally: the water always being added to the quicklime in the first instance, dilution, as necessary, coming later and after the lime had cooled. Because the 'lime revival' has emphasised the use of lime putty as a binder, and because the lime putties sold by suppliers in general seem over-thin and dilute, as well as being lacking in the characteristics of a traditionally slaked putty, it has seemed essential to quote directly from a number of historic sources describing the making of putty for different purposes.

Distinction must therefore be made between lime slaked to a thick, dough-like paste beneath sand, for preservation and future use on its own (most typically in association with earth substrates) or as a binder, and lime run to putty either from quicklime or previously dry-slaked powder for immediate or prompt use after, at most, a short period of repose. Crucial to the proper performance of both was the method of preparation.

6.11 Hot Mixing of Lime Mortars

See Figures 20 – 43; Figure 49, illustrating the variety, as well as the similarity between hot mixed mortars, which will normally display 'lime lumps'. Larger lumps might be screened out where the joints were relatively fine.

There were a number of hot mixing methods for mortars in use historically, each chosen according to purpose and according to the form of the quicklime available, as well as to the preferences of the craftspeople involved.

Asturian stonemason, Santiago Gonzalez, working from the 1960s, when asked if he used to hot mix his mortars, shrugged and exclaimed 'why would we do anything else?' (pers comm 05.05. 2017)


Figure 49. *Hot mixing and hot use, Sweden 17thC.* (Pennock 2017)

6.12 The Common or Ordinary Method

The most widespread and universal – as the name suggests – was the 'common' or 'ordinary' method. It is thus called in France, Spain, the UK and North America. It appears in all texts, explicitly or implicitly, from the 18th and 19th centuries, as well, along with sand-slaking of more hydraulic limes, in building texts published as recently as 1950 in the UK (Newbold and Lucas 1950; British Standard Code of Conduct 121 (1951); Ministry of Works Lime Mortar Guide (1950).

Lump lime – the cheapest and most common form of quicklime, used as fresh from the kiln as possible – was placed in a ring of the sand which was to form the mortar, at a typical gauge of 1 quicklime to 3 aggregate or of 1:2. The sand formed a basin to retain both lime and water. The quicklime could be – and was not uncommonly – slaked initially on its own, in a mortar box (see Figure 50) or a pit, and then mixed with the sand whilst still very hot but substantially slaked. Alternatively, and as detailed by Moxon (1703), the sand and lump lime could be arranged in alternate layers before watering. Water was added to the lump lime in quantities just sufficient to slake the lime to either a dry powder or to a thick paste, or something in-between. The necessary water was added in one go, or in a steady flow. A high calcium quicklime will begin to slake immediately or very soon after contact with water and will approach 100 degrees Centigrade within seconds of the slake beginning. The majority of the quicklime will slake within minutes of this onset. As soon as the water was added, therefore, the lime would be covered with sand, or with sacking or even tarpaulin, to retain the heat. It became more common in the 20thC to leave even a high calcium lime in this state for some hours, probably to reduce the volume of unslaked lumps in the absence of the assiduous beating that was 'de rigueur' historically, and because this method had become the norm – and was essential - for more slow-slaking hydraulic limes.

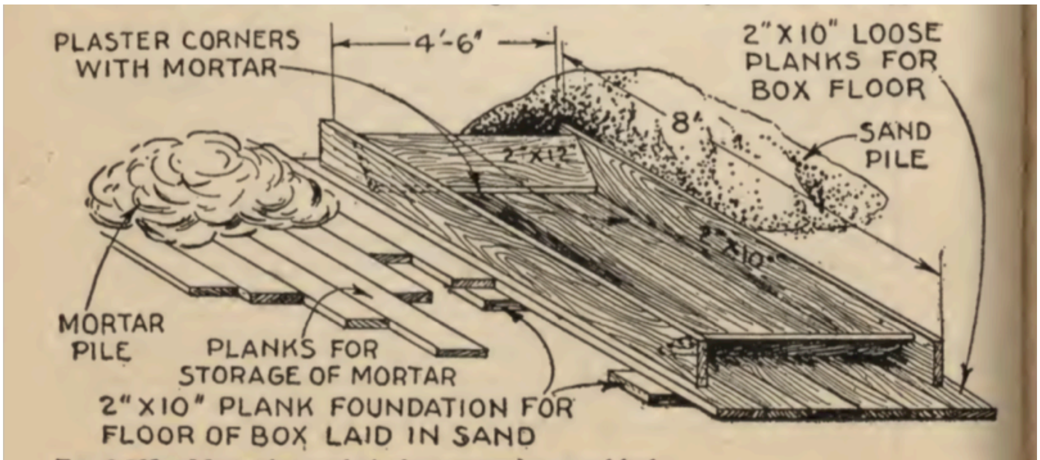


FIG. 3,866.—Mortar box and platform erected on sand bed.

Figure 50. Graham & Emery 1924 Fig 3,866. 1,610-64

In general, however, mortars slaked by the ordinary method would be mixed, to a coarse stuff, if not for immediate use within minutes, not hours. There is a widespread consensus in historical texts that all lime mortars should be used promptly– either on the day of mixing, the next day, or within a week of preparation (Neve 1726; Langley 1750; Dossie 1771; Higgins 1780; Marshall 1788; Wilkins 1799; Hassenfratz 1825, within 8 days; Treussart 1842; Gwilt 1839; Burnell 1857; Walsh 1858; Millar 1897; Radford 1909). In specifications, the requirement is usually made explicit. Barry required that no more mortar should be mixed in one day than could be used the same day, for the building of the Palace of Westminster after 1847. Fuller and Jones (1859) went further, insisting that the mortars, for both stone and brickwork, should be used 'as hot as possible' upon the Canadian Parliament building in Ottawa after 1849. Rees (1819) extended this to putty lime, as did others – whilst accepting that a period of laying down of either lime putty or coarse stuff was required, he insisted that this should be kept to a minimum of up to two weeks, typically. Pasley (1826) said for 'some days'. In New York City in 1915, Lazell bemoaned the fact that mortars were placed 'between bricks' or onto walls as plaster 'within hours' of slaking, but Rees

(1819) had also observed that the more pure was the lime the less likely would be late slaking.





Figures 51-54: *the ordinary method.* Figure 55: *the mortar in place*

Even when the laying down of such mortars was demanded, this was rarely for more than a few days (Moxon 1703; Neve 1726) and most commonly for bricklaying or for plastering, the mortars becoming somewhat less 'tacky', although no less adhesive, and somewhat more 'elastic' when they have cooled.

Hot mixing by the ordinary method could be to a dry hydrate, to be mixed with the sand and then screened along with it to remove larger lime lumps, or to a thick paste, or to a mixture of the two. Many of the mortars made during the medieval period would seem to have been made this way – sieves appearing in numerous building accounts from the period – or else the lime was slaked initially on its own to a hydrate, before mixing with the screened sand. Alternatively, the mortar was hot mixed directly to a wet state. This was as common in the 18th and 19th centuries and several writers maintained that slaking to a paste was the 'best' method (Burnell 1857), and it was the dominant, if not quite the ubiquitous method in North America (Gillmore 1864). Miller (1960) showed that lime made initially to paste had a greater surface area and porosity than lime made to a dry powder, something that slaking to a thick paste took advantage of, and lime first slaked to a dry hydrate is less 'sticky' than lime made to a paste, which some trades, such as bricklayers, might have preferred. Powdered quicklime slaked by hot mixing and then run to a paste as the mixing proceeds offers the finest particle size (and greatest surface area) of all (Hassibi 2011). Davy (1839) offers more nuance about these options than most, although his reasoning (and observation) should be conditioned by craft preference and local practice, and not by logistics alone:

> 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 (Davy 1839, 159).

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 159-160).

Whilst it may be true that a dry slaked lime retains more lime lumps than a wet-slaked lime – hence, in part, the common demand that dry-slaked limes should be sieved or screened before use – the prevalence of lime lumps will be as determined by extent of beating and speed of use, as well as by their composition. The residual lumps found in traditional lime mortars are under- or over-burned lime, or, if the mortar was placed hot, or very soon after mixing, lumps that were never mixed in and which carbonated in situ (see Appendix Eight, Binder Identification).

Once the necessary water was added, the sand would be banked over the slaking lime and left for the slake to substantially complete. Cracks in the sand prompted by the expansion of the slaking lime would be closed up to retain heat and steam. The slake of a pure or nearly pure lime takes a matter of minutes (it can be up to 12 hours for an eminently hydraulic lime), and the sand and the lime would be mixed immediately, the lime remaining very hot (much less so for a more hydraulic lime). If the slake was to a dry powder, the mixture might be thrown through a screen to remove larger lime lumps and larger particles of aggregate. Whilst this mortar might be stored, it would more commonly have been mixed to a mortar consistency after this and used immediately or within a week.

Otherwise, the mixture of dry-slaked or wet-slaked material would be taken straight to a mortar consistency, just sufficient water for this being added, and the mortar would be well-beaten to improve workability and to engage more of the residual lime lumps as binder (see Figures 51-53).

6.13 Slaking Lime With the Aggregate

Perhaps as a result of the experience of mortar mill mixing, from the 18th century onwards, numerous texts indicate that use of powdered or pulverised quicklime is advantageous. If mixed immediately with the sand or other aggregate before slaking and mixed through to a mortar by the incremental addition of necessary water – or even by the immediate addition of the necessary volume – the resulting mortar enjoys greater tenacity and strength and is particularly cohesive and adhesive. If one begins with powdered quicklime, it will fall to an even finer powder on slaking, maximising surface area and porosity, which will enhance the bond within the mortar as well as its bond to a variety of substrates (Hassibi 2009). A similar effect is achieved when hot water is used for the slake, and slaking will begin more promptly in otherwise slower slaking limes (Pasley 1826; Miller 1960). If the quicklime remained hot from the kiln (a common aspiration), this would also potentially accelerate the slake, or enhance its efficiency. The use of hot water, as well as of pulverised quicklime, was common for hydraulic limes, accelerating the slake, but Pasley observes in 1826 that the use of pulverised quicklime had become common enough by that time for the fat limes as well. It was inevitable when mortar mills were used:

"Mortar Mills - The lime is slaked under the wheel, and ground until, with suitable additions of water, it has become a homogeneous paste sufficiently dilute to make mortar of the ordinary consistency. The requisite quantity of sand is then gradually sprinkled in, as the wheel is in motion". (Totten 1842 230)

The use of powdered quicklime has been the method of most of those hot mixing in the UK today, although kibbled, 5mm down quicklime remains the mainstay of Scottish practice. The latter has the advantage of leaving residual lime lumps, which may yet be shown to offer performance benefits to the mortar, such as assisting in the process of deeper carbonation. This is also the method – using either of these forms of quicklime, powder or kibbled - that is best adapted to mixing in modern pan or forced action mixers, most firms having disposed of their roller pan mixers long ago. The use of powdered quicklime all but eliminates any risk of late-slaking, so that plaster mortars are as easily mixed for swift use by this method as are bedding mortars, and may be used hot or soon after mixing without fear of late-slaking. The more hydraulic the lime, the greater the risk of late-slaking, so that, when made from quicklime – which it still was well into the 1950s in the UK – NHL mortars were laid down for up to ten days before use, the only water added having been that necessary to slake the free lime and insufficient to begin the hydration of the hydraulic compounds (see 6.15). This latter requirement was problematic, of course, given the inherent variability in the composition of NHLs. How much water was just enough on any given occasion? Treussart says typically one quarter the volume of quicklime in water.

Other slaking methods were also employed.

6.14 Slaking by Immersion or Aspersion

The quicklime might be slaked alone to a dry hydrate: a basket of lump lime would be held underwater for a few minutes, until it had absorbed sufficient water to fill its pores, when it would 'stop whistling' (Del Rio 1859). It would then be tipped out onto a platform or into a barrel, where it would 'cook' and fall to a fine powder. The lump lime might first be reduced to egg or walnut-sized lumps to promote an even slaking.

> You will put this (fresh quicklime) on a dry, covered, swept floor.
>
> In that same place, you will have dry barrels, and a big tub three quarters full of river water… You will only need two workers for this operation. One will break the limestone with a hatchet until the lumps are the size of an egg. The other will take a shovel and fill a flat basket. He will put the basket in the water until the surface starts to boil, then removing the basket, leaving it for a few moments and then pouring this soaked lime into the barrel. He will do this same operation until all of the lime is in the barrel. This lime will heat up considerably and will give off steam, opens its pores and falls into powder and finally loses its heat. (De la Faye 1777 34)

Alternatively, the just-slaked dry hydrate might be immediately sieved and mixed with sand whilst still hot, to make either a coarse stuff or a mortar for immediate use.

Alternatively water might be sprinkled in sufficient quantity over the lump lime with a watering can, a method commonly termed 'slaking by aspersion' (Treussart 1842). This could then be sieved and stored, or sieved and mixed immediately with sand. It was typical when lime had to be shipped long distances, during which time quicklime might begin to air slake. John Smeaton, at least, preferred to use lime slaked to a powder, rather than quicklime or paste, for his pozzolanic mortars. Such mortars, however, require extensive beating (up to a day for two men) to attain good workability (Smeaton 1791)

> The lime, when slaked, must be passed through a sieve so as to leave only a fine powder; this is usually performed by means of a screen made of wire, set at an inclination to the horizon, against which the lumps of slaked lime are thrown…. For mortar the core must be entirely rejected… The sifted or screened lime is now added to the sand… It is however most important that the lime and sand be well tempered and beat together after the water is added to them, and the better this is effected the smaller will be the necessary consumption of lime… <u>When mortar is made, it should be used immediately, that is, supposing the lime to have been well burned….</u> (Gwilt 1839 48)

Nicholson (1819 concurs): after sieving, lime 'should be used instantly or kept in air-tight vessels'.

Slaking initially to a dry hydrate – if not initially hot mixing a coarse stuff to be laid down – was common plastering practice until the 20thC. This guaranteed the necessary slaking temperature, which running straight to putty might not. This hydrate was then run to a putty, or to a paste, prior to mixing with sand or with hair. Nicholson explains this explicitly in 1841:

> (For plastering) the safest mode of preparing lime 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 1841 179).

6.15 Air Slaking

Another method was to air slake (or 'wind-slake') the quicklime, laying it out in six inch layers on platforms within an open-sided shed and leaving it for up to a year to fall to a fine powder, a very slight sprinkling of water given on occasion to promote the initiation of the slake. This was usually condemned as impractical and unreliable, as when might slaking complete and when might carbonation begin? This method produced little palpable heat, and this may have been a source of suspicion also. It would seem to have been most common for the more hydraulic limes and one of the most complete descriptions concerns the slaking of blue lias lime:

> In the immediate neighbourhood, 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 (Davy 1839 102).

Hydraulic limes, for use as 'water limes' – and particularly those with a good reputation and relatively high free lime content, like those from the blue lias formations and from Charlestown in Fife, travelled more frequently out of their regions, and would be slaked to a dry hydrate and put into barrels to facilitate longer distance transport than would be feasible without air slaking of quicklime (SLCT 2006). Both were carried across the

Atlantic during the 19th century, to North America and the Caribbean (SLCT 2006; Cuming 1837). Wherever possible, however, masons on site preferred to use hydraulic limes in the form of quicklime, even in 1950, allowing them to remove tri-calcium silicate (alite) clinker and to modify the mixes according to perceived reactivity and hydraulic energy, which was well known to be variable according to the balance of free and 'compounded' lime. Slaking hydraulic lime from lump would also potentially reduce effective hydraulic power, as this latter relied much upon being ground to a fine powder. As Geeson pointed out in 1952:

> The degree of burning is more important than with other types of lime, for clinkering and fusion occur more readily and a much higher proportion of clinker may be formed. This clinker is comparatively inert unless the particle size is reduced by grinding; if it is extremely finely ground, a 'natural' cement results. (Gleeson 1952 9).

Lafarge developed the method for reliably pre-slaking more hydraulic limes for sale after 1896. In this process, tri-calcium silicate and aluminate clinker – termed 'grappiers', which would set up hard and fast if ground before slaking, were removed and ground separately, to be sold – as they were also in the USA (Pulver 1922; Eckel 1932) – as 'grappier cement'. Some of the ground grappiers might be put back into the bags of dry hydrated hydraulic lime to boost hydraulicity where necessary, and to assist in the production of a more consistent material (Searle 1935).

6.16 Sand-slaking

Sand-slaking has, on the face of it, great similarity with hot mixing by the ordinary method and has often been confused with hot mixing.

In common with the ordinary method, lump lime was placed in a ring or circular 'wall' of sand before being slaked by the addition of necessary water, the sand banked over the slaking lime to retain heat. In hot mixing versions of this, when the free lime content was significant, the sand and the lime would be engaged promptly, as soon as the slake was substantially complete, and either used or set aside as a coarse stuff for later use (still with a minimum of water content, so as not to significantly activate the hydraulic set).

In typical sand-slaking procedure, however, the slake was allowed to continue for longer and the lime and sand were not mixed until after the slaked lime had cooled. This tended to give a 'shorter', leaner mortar, although its workability could be much improved by rigorous beating. However, the water would be less 'locked in' than when the materials were mixed hot; the mortar might be less water retentive, less cohesive and less immediately adhesive.

This diminution might be compounded by the general use of the sand-slaking method for the processing of more hydraulic quicklimes, themselves somewhat lower in free lime than other limes, and therefore less inherently workable.

Whilst it became more common during the 20th century to allow slaked air lime to cool before mixing with sand or other aggregate (Frost 1925), this seems to have been a preference mainly confined to bricklayers. It reflected the growing use of more energetically hydraulic limes for above-ground construction, the efficient slaking of which demanded the sand-slaking method to mitigate the greater tendency of hydraulic limes to be both slow-slaking and more prone than pure or nearly pure limes to late-slaking after placement.

> Hydraulic limestone is calcined with difficulty to the proper degree, and when not sufficiently burned, the resulting lime slakes badly. The mortar, made with it in such a state, is less tenacious, and is moreover apt to swell after being used, to the great injury of the masonry. To ensure thorough slaking, it should generally be allowed, after extinction, to remain twelve hours or more before it is employed, but it is best in every case to ascertain approximately the time required for this purpose, by experimenting in a small way. Hydraulic lime becomes hard, however, in a short time after being converted into paste, and should never be slaked in greater quantity than will suffice for two days' consumption at most…. (Wright 1845 paragraph 40).

Wright indicates a delay of at least 12 hours; however, this might not be long enough, depending upon the hydraulic lime. The BS Code of Conduct, 1951, says 36 hours of repose within the sand-covering.

Other authors (Treussart 1842; Cowper 1927), indicate that the water sufficient only to slake the free lime should be added to the quicklime in its ring of sand. To add more water than this would initiate the hydraulic set. Quite how masons were able to ascertain the always variable free lime content of an NHL, can only be surmised. Familiarity with a particular NHL, from a particular quarry, might assist this judgment, but there would be variation between batches even so. Almost inevitably, some initiation of the hydraulic set would occur over even a 12 hour period. NHLs were notoriously slow slaking, not reacting at all with water for as long as 12 hours, although usually less time than this. After the initial period of slaking, a further period was usually required – the sand and the slaked lime would be mixed together and then banked to allow more slaking time and to allow its completion. The usual requirement is that this banking should be for no longer than 8 to 10 days (Treussart 1842; Cowper 1927).

Except for the making of concrete (when the ingredients were mixed before slaking, the quicklime often pulverized before mixing to accelerate the slake (Pasley 1826)), and perhaps for the filling of wall cores, immediate use after mixing of the lime and aggregate, might be fraught with the hazard of blistering. In extreme cases, it risked the disruption of building units by the expansion of larger unslaked lumps which might, at the least, break bonds between mortar and brick or stone. Sand slaking was deployed for the manipulation of feebly hydraulic limes, on occasion, but most often these were slaked by the ordinary method and were used immediately, or soon afterwards, as at the Palace of Westminster in 1847 (Barry 1847).

If the quicklime was less energetically hydraulic, the quicklime might be left beneath and within its covering of sand overnight, and mixed and used the next day, when it would retain some heat, at least, passed through the roller mill for tempering. Treussart (1842) describes this process at great length, referring to site practice with feebly hydraulic limes used at Strasbourg Cathedral. More energetic hydraulic limes were also used at Strasbourg, and these were left to 'stew' for up to 10 days at most, before being mixed with the *mortar* with which it had been surrounded. Treussart's use of the term 'mortars' would suggest the gauging of common mortars with hydraulic lime. He goes on to say that the sand-slaking method – the lime left undisturbed within the sand covering for several days, if not months, was common enough, in the warmer parts of Europe, the pure or nearly pure lime being sprinkled and:

> formed into heaps of a suitable size, with one-fourth to one-third of their volumes of water. This should be applied from the rose of a finely gauged watering-pot, after which the lime should be immediately covered with the sand to be used in the mortar. In this condition it should not be disturbed for at least a day or two, and the opinion prevails in the southern portions of Europe that the quality of the lime is improved by allowing the heaps to remain several months, without any other protection from the inclemency of the weather than an ordinary shed, open on the sides. In the vicinity of Lyons this custom very generally obtains, the autumn being usually selected for slaking all the lime required for the following season's operation. In Europe this method of slaking is applied to the fat and slightly hydraulic limes only, and not to those that are eminently hydraulic, upon which it seems to act disadvantageously, by depriving them, in a measure, of their hydraulic energy….(Treussart 1842 9).

Vicat elsewhere termed this the 'Lyonnaise method' (1818). Newbold and Lucas (1950) say that 'non-hydraulic lime mortar so treated will keep in good condition for a period of up to seven days." (p329).

The blue lias limestone that crops across the UK, from Lyme Regis to North Yorkshire, although rarely in accessible deposits north of Leicestershire, often had a relatively high free lime content. Unless specifically for water works, the eminently hydraulic beds might be avoided by the lime burner, as these would deliver a less than workable construction mortar – the period of repose might be less, therefore. Slaking could be accelerated by pulverising of the quicklime (easily done, when mortar mills were used), and, beyond this, by using hot water to effect the slake. In this scenario, use would be sooner, avoiding the hazard of the initiation of the hydraulic set:

> *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. (Mitchell 1912 12)

Once mixed with sufficient water, it was a common requirement that the mortar be used within four hours, or that, as soon as initial set had developed, that the mortar be discarded. It was well understood that the 'knocking-up' of a setting hydraulic lime mortar, robbed it of ultimate strength, for all that it might seem more workable for the knocking out of any hydraulic set that had been developed at this stage. Smeaton (1791) was alone in suggesting that a trass mortar gained ultimate strength for repeated knocking up after stiffening commenced.

6.17 Mortar Proportion

The typical proportion of slaked lime to aggregate, whether a pure or an hydraulic lime, during the 'Lime Revival' has been 1:3, sometimes 1:2 ½; occasionally 1:2.

It is clear from this research that a 1:3 binder to aggregate proportion has virtually no historic precedent before the 20th century, either in published texts, historical specifications or upon mortar analysis. Moreover, when lime putty is mixed at 1:3, it may be leaner than this in terms of actual binder, due to the significant volume of free water it contains (Boynton 1980).

One binder to three aggregate became the norm with the embrace of cement-lime mortars during the earlier 20th century, the additional power of Portland cement being considered sufficient to allow for this, and, in more recent years, the typical new build mortar is 1:5, illustrating the reach of this additional power, but without necessarily delivering a mortar of necessary tenacity or performance.

On analysis, and even allowing for residual lime lumps that should be characterised as porous aggregate, not binder, very few traditional lime mortars are leaner than 1 lime to 2 aggregate and whenever slaked lime was specified, this was the typical requirement (Vicat 1818; Pasley 1826; 1838) as illustrated below:

> The proportion most commonly used in the mixing of lime and sand is, to a bushel of lime a bushel and a half of sand, i.e. two parts of (slaked) lime and three of sand; though the common mortar, in and about London, has more sand in it than according to this proportion (Rees 1819 para 8 Mortar)

"Paris builders usually count two parts of slaked lime paste for one part of quicklime" (Hassenfratz 1825 154). Vicat (1837) concurred, as did all others who specified the use of already slaked lime. Vitruvius (1999) indicated 1:3 when loamy pit sand was used; 1:2 when the sand was river or sea sand, though he may have meant quick, rather than slaked lime, in fact.

Whenever 1:3 was specified, which was commonly, this assumed the use of quicklime, which would double in volume if it was of a pure or nearly pure lime. The expansion upon slaking of an hydraulic lime would be less than this and the less the more hydraulic the lime was, the proportion of free lime being lower. Hydraulic limes were mixed at 1 quicklime to 2, therefore, or at 1:1. Smeaton (1791) mixed one part of slaked blue lias lime to one part of Italian pozzolan for the Eddystone lighthouse, on account of its severe exposure to the sea. The more typical proportion for hydraulic limes for water works, made with trass or other pozzolan was 2 parts of trass or of brick-dust to 1 part of lime (Langley 1750). Langley said that this should be 'hot lime'; Smeaton preferred lime slaked to a dry hydrate (Smeaton 1775). Smeaton later settled upon a proportion of ingredients that would reliably set underwater that reduced the volume of trass, the most expensive ingredient, indicating 3 sharp sand:1 pozzolan: 2 slaked lime. He had worked this out by practical experiment, but, if all pozzolan combined with the lime, there would be no free lime left – entirely appropriately for underwater use, where the free lime contributes little to the necessary performance.

As reference to Langley (1750) and others demonstrates, lime mortars before the 19th century were frequently richer in lime than 1:2. His recommended 'inside mortar', which might include loam or clay sufficient to promote a very feeble hydraulic reaction, equates to 5: 6 *before slaking*. His suggested proportion for 'outside mortar', to be made with clean, sharp sand and lime was 2 bushels of unslaked lime to 1 bushel of sand, which might be 4 lime to 1 sand after slaking. Such mixes are impossible to use, in the author's experience, unless they are initially dry-slaked. However, pointing mortars over earth, on analysis, were typically 2 parts slaked lime to 1 aggregate, often limestone or chalk aggregate (see Appendix Eleven, No.1) and plaster mortars over earth might have even less aggregate than this. A regionally typical plaster finish over earth from York House in Malton had 10% limestone aggregate and very fine silica sand only, but a lot of horse and ox hair (see Appendix Eleven No.12).

Isaac Ware, writing around the same time as Langley, queried the excessive leanness – certainly for use in the British climate – of Palladio's recommendation of 1:3 slaked lime to pit sand, at least (Palladio was simply following Vitruvius, who had also recommended 1:2 for other than pit sand, and pit sand tended to contain clays). He suggested that two-thirds of a mortar should be of lime (2:1) for prudence sake, also pointing out that practitioners at the time tended to put even more lime than this,

> Palladio's proportion of sand is too great, at least for a mortar to be used in our climate, and…what we commonly allow is too little. (Ware 1758 84)

George Semple, writing in Dublin around the same time said that 'the proportion of sand to lime…(should) be not richer than four of Sand to one of roach lime (That is about 2 to 1 of slack); That, after it is riddled and turn'd up…it be allow'd as much time to soak as conveniently the Work will admit of.' (Semple 1750 National Library of Ireland, Ms. 2758.)

That the 'lime revival' might be based upon lime mortars with at least half the lime content as was considered essential historically is one of its more baffling features. The proclivity to specify 1:3 mortars was compounded by an over-reliance upon void tests to determine necessary binder content – water being poured into a measure of dry aggregate until it topped the aggregate, the volume of water used determining the necessary volume of binder to fill the voids between the aggregate particles. With a well-graded sand, this tends to be between 1:2 ¾ and 1:3.

Whilst Smeaton had invested time into the minimum proportions of lime, pozzolan and sand for use in water limes, all previous water limes having been based upon the use of just pozzolan and lime, with no sand, it took Higgins (1780) and then Pasley in 1826 to do the same for fat and feebly hydraulic limes.

Higgins performed numerous practical experiments, though he mixed his test mortars by weight, not volume. He concluded that 1 quicklime to 7 aggregate by weight was an ample proportion and displayed only minimal shrinkage. He felt that the craft habit of using too much lime had much to do with the quality of the lime (it had perhaps suffered significant air slaking before being used) and the failure to use it immediately after (hot-) mixing. Gwilt (1839) and Webster (1844) agreed with both of these propositions, pointing out that in London, at least, quicklime 'is received from Kent and Essex, and often lies at the different wharfs under open sheds long enough to lose every good property it originally possessed.' (Gwilt 1839 47).

Pasley, a military engineer, conscious of saving the government undue expense, and conscious also that "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' (p6), wondered what was the *most* sand that might be put to one quicklime without compromising workability or performance, sand being the cheapest ingredient. He concluded that for 'common mortar for the walls of buildings' one part of quicklime to two of sand, 'may be considered the maximum'; one quicklime to three of sand 'the minimum proportion of lime that ought to be used' (Pasley 1826 6), acknowledging the primary reason for excessive lime addition in later years, craft preference:

> A smaller proportion of sand such as 2 parts to 1 of (quick)lime is…often used, which the workmen generally prefer, although it does not by any means make such good mortar, 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 (Pasley 1838 6).

Pasley notes, however, that craft practice relied upon 'feel' and that precise gauging was rarely necessary:

> …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 (Pasley 1838 7)

Later again, Gillmore, another military engineer, sought to examine the reasons that mortars might require more lime than just that needed to fill the voids in an aggregate

> (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 1886 176)

Around the same time, Henry Scott of the Royal Engineers - a man wholly dismissive of craft knowledge and practice, in keeping with the increasing mood of his time, looked 'confidently forward to the day in which we shall feel quite independent, as respects mortar making, of the workman's traditions' (Scott 1862,) - sought to reconcile gauging by volume, as in site practice, and the variable bulk densities of different limes, to produce the appropriate proportions of sand and lime:

> …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…. (Scott 1862 81)

The lime mentioned was in the form of quicklime, so that, on the face of it, the recommended proportions accorded very well with Pasley's conclusions and with similar conclusions made in Spain, France and North America during the 19thC. 50lbs, however, is only just shy of 25kg, and it would seem impossible to squeeze almost a full bag of modern quicklime into a box of only 1 cubic foot. Scott's lime proportion, therefore, seems high. Scott was clear that the proportions above only applied to building above ground and that for water works and foundations using hydraulic lime the proportion should be 1:1. Similarly for natural cement, if this was used underwater, though 1:2 might be otherwise allowed.

Mortar analysis, however, arrives at similar proportions (1:2 or 1:1 ½ when inclusions are included as binder) in all periods, albeit with as many mortars that are 1:1 slaked lime: sand. 1:3 never appears (see Appendix Eleven).

The additional lime contents of traditional mortars would seem as critical to their usefulness and durability as is the slaking method, therefore, and should be ignored only when an especially sacrificial repair mortar is required. To continue to mix at 1 binder to three would be, as this research demonstrates, to ignore much of the wisdom evolved prior to the 20th century.

6.18 Earth and Earth-Lime Mortars

See Figures 56-91, illustrating the general appearance and character of earth-lime mortars, as well as their geographical spread, which has been substantially unrecognised or ignored by the conservation community.

In the UK, earth and earth-lime mortars are the most common mortars of masonry construction before the 18th century. Of the almost two million dwellings in Great Britain in 1811 (Powell 1980), most of those built of stone and most timber-frame buildings will have been effected using earth, or earth-lime mortars, supplemented by hot mixed lime or lime putty-based coatings (see Appendix Five). Two-thirds of the population was rural, and vernacular architecture and its materials were familiar to all. The majority of 19th century buildings, however, were in expanding urban centres, where hot mixed lime mortars will have been the norm after 1811. (Powell 1980).

Very few writers about mortars or architecture discussed earth or earth-lime mortars – the evidence of their common and routine use lies in the buildings themselves and in archived building accounts (See Appendices One, Two, Five, Ten & Eleven).

Cato (160BC), indicated the use of earth-lime mortars in Rome; Frontinus (40-103 AD) confirmed this in the context of aqueduct construction around Rome, and Vitruvius as well as Pliny the Elder spoke favourably about earthen construction, particularly of rammed earth and adobe. Alberti shared this favourable view of earth building, especially for their healthfulness, but also noting the use of earth mortars and offering some insight into their nature and use:

> Any stone to be smeared with a mortar of clay should be cut square, but most importantly it must be dry… Some assert that mud, if it is to be used as mortar, should be like bitumen, and they consider the best mud to be that which dissolves slowly in water, is difficult to wash off the hands, and contracts markedly on drying. Others prefer it to be sandy, being easier to mould. This sort of work ought to be coated on the outside with lime, and on the inside, if you wish, with gypsum, or even silver clay. In order to make it adhere better, fragments of earthenware should be inserted occasionally into the cracks between the blocks during construction, so that they project like teeth and support the rendering more firmly (Alberti 1460 77).

In the author's experience and observation, the first type of mortar described, whilst good for the laying of stones, its inevitable shrinkage mitigated by the compression of the build, for plastering and rendering this would likely shrink too much, lest lime and sand was added, and the sandier earth mortar would be preferred.

Alberti was less enamoured of more flimsy 'mud and stud'- type dwellings, but describes a basic pattern that continued around Europe, in Turkey, for example, until the 20th century, and which was also the essential pattern of timber-frame panel infills during the medieval period and before their routine replacement with brickwork and, sometimes, with stone, flints being common in chalk regions of England.

> The wickerwork is smeared with a mixture of mud and straw which has been kneaded for three days. It is then dressed…with either lime or gypsum, and finally adorned with pictures or reliefs. If you mix your gypsum two to one with crushed tiles, it will have less to fear from being splashed. If mixed with lime, its strength will be enhanced. In the damp, frost or cold, gypsum will be entirely useless.(Alberti 1460 78)

Although riven lath – both ‘sap-lath’ and ‘heart lath’ in different locations, inside and out, was generally preferred in the UK and in all periods, for the base of earth and earth-lime and later of lime plasters, reed was also used. In Spain, wild sugar cane was common and in the east, such as in Bhutan, bamboo.

Though Alberti does not say so, both adobe blocks and rammed earth in Spain typically contained 10 or 20% lime addition, according to analysis by Valencia University (Vegas, Mileto et al 2014).

The earliest British author to offer any insight into craft practice in this method was Henry Best, an East Yorkshire farmer:

> In summer-time wee usually fetch clottes out of the field to make morter on, but in winter wee eyther shoole up some dirte togeather, in some such place as is free from gravle and stones, or otherwise wee digge downe some olde clay or mudde-wall that is of noe use, or else grave up some earth, and water it, and tewe it. Morter neaver doeth well unlesse it bee well wrought in, viz.; except it bee well watered and tewed; and it is accounted soe much the better if it bee watered over night, and have nights time to steepe in. In makinge of morter, yow are first to breake the earth very small, and with your spade to throwe out all the stones yow can finde, and then to water it and tewe it well, till it bee soe soft that it will allmost runne; then lette it stande a while till the water sattle somethinge from it, and it will bee very good morter…. (Best 1641, 145).

Both Alberti and Best share the knowledge that beating and tempering were essential to a successful earth mortar. Best adds that it was used very close to its liquid limit. The need to let the mortar settle and lose some of its excess mixing water (necessary to fully engage the clays), is a delay that might be readily obviated by the addition of small volumes of quicklime, though Best does not mention the use of lime.

Plat (1653), writing in London, does include lime in the earth mortar equation, as well as ‘sope ashes’ (wood ash), advertising their successful use in the building of a brick house in Aldgate. The mortar, he said, was 2 parts ‘waste sope ashes’: one part lime (probably quicklime): 1 part loam and one part Woolwich sand.

Bailey and Worlidge (1726) promoted the utility of adobe construction, indicating that well-made and well-dried ‘unburned bricks’ should be laid up in a mortar of loam or brick-earth, into which some good lime should be mixed before ample tempering brought the mortar to a ‘tough, smooth and gluey’ consistency. After construction, and after a time to allow the fabric to dry, they advocated an exterior plaster made of the 'same earth the wall was made of, with a little more lime than was used for the wall,' very well tempered. 'If you would have it more beautiful, its only putting more lime to it, and less loam, and when this is dry, you may colour and paint it…' They further recommended the use of a roof tile bedding mortar of loam and horse dung over lime and hair for the same purpose, before discussing the measured rate for the daubing of 'a partition wall with Clay on both sides'.

Neve (1726) gives the clearest historic expression of the typical plastering system using earth and earth-lime mortars. He does not mention lime, but this does not at all mean that it was not used, depending upon the qualities of available loam:

> Lome: A sort of reddish earth, us'd in Buildings (when temper'd with Mud Gelly, straw and Water) for Plaistering of Walls in ordinary Houses…(194)
>
> White Mortar: this is used in plaistering of Walls and Ceilings, that are first plaister'd with Lome and is made of Ox or Cow-hair, well-mixed and tempered with Lime and Water (without any Sand). The common Allowance in making this kind of Mortar is one Bushel of Hair to six Bushels of Lime. (Neve 1726 201).

Neve indicates that the typical external finish over earth in Kent and Sussex was a roughcast lime render, sometimes finished with a lime and hair mortar as was used internally over earth or earth-lime backing coats. He describes the treatment of timber-frame infill panels: 'the walls being quartered and lathed between the Timber (or sometimes lathed over all) are Plaister'd with Lome…which being almost dry is Plaister'd over again with White Mortar' (Neve 1726), whilst criticizing the trend towards brick infills bedded in lime mortar, considering the latter to 'corrode and decay' the timbers, a common and persistent prejudice.

Campbell, writing about the 'London Trades' in 1747 indicates that whilst lime stucco was the norm for the plastering of walls, older patterns persisted for ceilings, where a backing coat of clay, with added hair or hay, was overlaid with a coat of 'fine plaister', which would typically have been of lime and hair.

Similarly, older ways still applied in London to the mortars for furnaces and ovens (and lime kilns), better resisting heat (and pollutants) and these should be 'well-chafed and beaten' similarly to the way 'outside mortar is done, and of such a consistency to work even' (Langley 1750 37). One hundred years later, Woolwich loam was used to similar purpose in the new Palace of Westminster (Barry, Accounts and Papers1847).

William Marshall, an individual of unique curiosity, as well as geographical range, noted the ubiquity of earth-lime mortars in the Vale of Pickering in 1788, whilst failing to notice their incorporation of lime in small quantities, "Formerly, ordinary stone buildings were carried up, entirely, with 'mortar'; that is, common earth beaten up with water, without the smallest admixture of lime"(p109) before going on to commend their tenacity and endurance in the walls of Pickering Castle (Marshall 1788, 111). Marshall analysed a variety of mortars from the castle, two of them very lime-rich pointing mortars, one of them, at least, an earth-lime mortar, although he interpreted the lime lumps as chalk aggregate – 'a sandy loam interspersed with specks of chalk some of them larger than peas. Its fragility similar to that of dried brick earth'. He attributed its weakness to the small proportion of lime. After the burning out of the lime, '100 grains…yield 30 grains of rough sand, and a few large fragments; 37 grains of silt and fine sand; 36 grains of calcareous earth.' (Marshall 1780). He further noted that an ammonia smell rose from some of his samples as these were wetted (the author has experienced similar from old earth-lime mortars in the region), which he put down to the addition of urine to the mortar, such addition being 'at present a practice among some plasterers'.

Marshall picked up a similar theme whilst in Gloucestershire (1796) advertising the use of road-scrapings for the making of mortar, their being 'levitated limestone, impregnated more or less with the dung and urine of the animals travelling upon them', which might be used with or without added lime. When lime was added this should be 'not more than one part lime (quicklime) to three of scrapings' and that these should be mixed by the ordinary method, organic debris fished out as possible. For brickwork, the material should first be screened or sieved (Marshall 1796 17-18)

The 'ordinary method' was probably the way that earth-lime mortars were mixed when the lime proportions were akin to those of a lime mortar. When the volumes were lower, the lime might be run to a putty just before mixing, or even added as pulverized quicklime to a wet mixed earth.

In Europe, earth and earth-lime mortars were ubiquitous for the construction of masonry buildings for much longer than they were in the UK, enclosure not having robbed the masons of ready access to their raw material.

In France, Cointeraux (1790)'s technical treatise on rammed earth construction advertised his conviction that 'houses built that way are solid, healthy to live in, cheap, and they last a long time even when left in a bad state' (32). He does not mention lime, except in the context of sealing the formwork against loss of soil (a practice that leaves a lime mortar fillet between each lift) and of finish plasters and limewash. Martin (1829) also mentions the 'bead' of lime mortar between lifts, and such is also common in Spain (Vegas et al 2014). Again, this does not mean that lime was not, or was never added. Rondelet (1803 237) writes about rammed earth with equal enthusiasm but says that when the available earth was 'dry and mediocre' in quality, and after 'beating it in the normal way' he would 'moisten it with milk of lime instead of pure water.' Martin (1829), also in France says that rammed earth buildings should be plastered with lime and sharp sand mortar at 1:3 proportion, the mortar 'not spread in water but…kneaded for a long time and…(so) softened' (Martin 1825 101). Whilst interior plasters might also be of lime and sand he says that 'We often substitute for the plaster, for economy, or for obtaining a lighter and warmer plaster *(enduit),* heavy soil, kneaded with care, mixed with a certain quantity of hair *(bourre)* and if we want, a fifth of old slaked lime,' which method is termed 'batifotage' (Martin 1829 103) It was typically finished with a distemper of size and crushed chalk.

Telford (1838), in contrast, seeing no benefit in earth-bound stone houses, which he terms ‘mud hovels’, celebrated their displacement by ‘enlightened’ land-owners by houses built with lime: sand mortars. He was out of step with some, at least, of his contemporaries who, like their peers in France, saw great advantage in earth-built dwellings for the rural poor, whether of rammed earth, adobe, cob or of earth mortared stone. Doyle concurred with Cointeraux, asserting that ‘clay walls, if properly constructed, and well plastered and dashed on the outside with lime mortar, are cheap, durable and warm’ and offered guidance for its mixing that might apply to all earth mortars –

> A sufficient quantity of cohesive clay, free from any stones, being collected, the labourer digs it thoroughly, and renders it as fine as possible; when well saturated with water, he works it with his shovel until it acquires the consistence and toughness of dough. After lying eight or ten days, it should be again wetted sufficiently for use, and a small quantity of sound chopped straw (for if this be long and stringy, the surface of the wall will not be easily dressed and polished afterwards) is to be intermixed through the mass…. The floor should be laid on a stone foundation, as well as the partition walls, and covered with tiles, bricks, or clay and lime mortar, well tempered and evenly laid. (Doyle 1844 161).

Loudon (1846) offered designs and specifications for houses of stone, brick and rammed earth masonry, placing equal structural value on these, but greater aesthetic value upon stone or brick, however an earth wall might be disguised by lime renders or limewash. He details methods of adobe construction in Cambridgeshire, noting that such buildings were lime plastered internally and rough-cast to their exteriors, as well as the methodology of cob construction in Devon, for which ‘the earth nearest at hand is generally used, and the more loamy the more suitable it is considered for the purpose.’

> Clay Floors, that is, floors formed of a mixture of clay and marl, were formerly a good deal used in Norfolk for barns, malt-houses, hay-lofts, cottages, &c. They are composed of clay and marl mixed with chopped straw, well trodden by horses, and mixed together in the manner clay lumps are to be made; and, when the mixture is to be used for malt-floors, bullock's blood is added. Much of the excellence of these floors depends on the thoroughly mixing and working of the material. (Loudon 1846 para 2461).

Loudon offers a number of regional recipes and methodologies for lime concrete and gypsum floors.

Scott Burn (1860) and Jacques (1860) and Bruce Allen (1886) mirror French authors in their advocacy of earth buildings, Scott Burn insisting that in the case of rammed earth, ‘ no valid objections have been raised against it’. Jacques favours adobe and says that the bedding of adobe blocks should be done with good brick mortar, whilst noting that the lime mortars generally used, whilst also of sand and lime are somewhat weaker than this. ‘Where lime is scarce, a mortar composed of three parts clay, one part sand

and two parts wood ashes, answers very well.' Bruce Allen advocates both rammed earth and cob construction, though Loudon had been somewhat contemptuous of the latter.

Champly (1910) discusses the methods and materials of rammed earth and cob construction, noting that 'it is customary in a few countries to spread a layer of mortar of lime and sand on the banchee already rammed', which should be 2 -3 cm thick. The year after construction, such buildings, he says should be coated with an earth-lime render:

"Make a clear but binding paste with one part of slaked lime, four parts of clay and some water. Add and mix into this paste, as much hair as it needs for the mix to be full of it… Apply the coating in the autumn on a well dried rammed earth wall with a big paint brush or by throwing it and then spreading it with a trowel."
(Champly 1910 131)

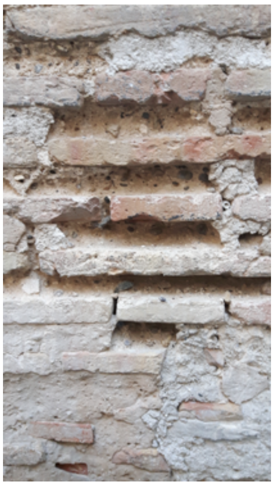
The little research into the properties of earth-lime mortars that has been carried out more recently would indicate that the pore size distribution of an earth-lime mortar is dominated by pores of around 0.8 microns. A lime mortar rich in lime will be dominated by pores of around 1 micron. Both are within the optimal range for efficient and active capillary movement of liquid phase water (Wiggins 2019). Each is compatible with the other. Importantly, however, the over-laying of an earth-lime bedding or base-coat plastering mortar with a mortar of a lesser effective porosity (such as a cement, cement-lime or, indeed, an NHL mortar of any designation), will be incompatible in this crucial regard; moisture will be trapped and will progressively accumulate within the fabric (Faria 2016). Other research found air lime: sand and air lime-earth renders to be equally compatible with rammed earth substrates (Faria, Silva et al 2013).

Characteristic traditional mortars – earth-lime


Figures 56 & 57 *California Farm, Thornton Dale, North Yorkshire*

Figures 58 & 59 *Pond Farm, Crambe, North Yorkshire, c1570.*

Figures 60 & 61 *17thC Merchant's House, Valencia Old Town*

Figures 62 & 63 *St Laurent de Condel, Calvados, Normandy*


Figures 64 & 65 *Asturias, Spain; clay mortar, hot mixed lime renders.*


Figures 66 & 67 *Busby Hall, Faceby, North Yorkshire. John Carr, architect 1767*


Figures 68 & 69 *St John the Baptist Witton, North Lincolnshire*


Figure 70 *Typical core mortars, Ryton, Malton* Figure 71 *Lincoln Cathedral Precinct wall*


Figure 72 *Lake District* Figure 73 *Oxfordshire*


Figures 74 & 75 *Barn, St Laurent de Condel, Normandy*


Figures 76 & 77 *High status barn, Calvados*

Figures 78 & 79 *Monastic Dovecot, Calvados, Normandy*

Figure 80 *Flint laid in earth-lime mortar. Calvados, Normandy.*

Figure 81 *Adobe construction, Calvados*

Figures 82 & 83 *York House, Malton, North Yorkshire; plaster cross-section and south, garden front.*

Figures 84 & 85 *York House, Malton; internal wall and north, town front*

Figures 86 & 87 *York House, Malton, plaster cross-sections*

Figures 88 & 89 *Tong Hall, Middleton-in-Rochdale*

Figures 90 & 91 *Ukrainian settler house, late 19thC, Northern Alberta*

6.19 Pozzolanic Additions

Most discussion of pozzolans in historic texts is in the context of water works or for masonry in constantly wet situations. See Figure 92.

In building accounts, we see the routine use of pozzolans, and particularly of trass, in mortars for the laying of masonry floors, or for the bedding and pointing of coping stones, and their occasional use in final pointing mortars or exterior renders (see Appendices One & Five). The historic exterior render upon Oxted church, Surrey, was mainly of a pure lime and limestone aggregate, but the 4 mm finish coat was grey, containing significant volumes of wood ash (Sandberg mortar analysis 2018). Numerous historic pointing mortars contain charcoal residues, whilst the bedding mortars behind them do not – clearly indicating the deliberate addition of wood ash, sometimes 'smithy ashes' (as above, Wilkins 1799, although apparently without attention to pozzolanic set, rather to 'match' existing mortars) or other ash. This is not 'dirty lime' – such lime would not be used on the face of a building; it is conscious addition, usually in small volumes. Such craft practice is little mentioned in old texts. Where a 'stone lime', which before Smeaton (1791) was taken to indicate a tougher lime than a chalk lime, not necessarily an hydraulic lime, was available, pozzolanic addition may not have been considered so necessary. Higgins (1780) paid more attention than most to craft knowledge and reported the usefulness of wood ash addition:

> The ashes of wood and sea coal are frequently mixed with water, or used in the place of sand, in laying tiled floors and even in external incrustations.
>
> Some workmen say they are used in the former case to save sand; others that they serve to resist moisture…and that they hasten the drying and induration and prevent the cracking of mortar which is laid very thick in order to fill the

depressions of walls which are to be stucco'd and that they are used in finer incrustations with the sole view of preventing cracks…After a great number of experiments…with the elixated ashes, I found that they rendered the mortar spongey, disposed it to dry and harden quickly, and prevented it from cracking, more effectively than the like additional quantity of sand would do it." (Higgins 1780, pp163-164)

Until the later 18th[th] century, there was but intuitive understanding of the mechanics and chemistry of hydraulic set with the addition of fired clays to a pure lime mortar, creating mortars of durability with the ability to set under water. Some limes were noted for this capacity, or were considered especially 'tough'. Such mortars, however, were known to 'work' and to be 'fit for purpose', although it had been common for many centuries to use just lime and pozzolanic aggregate, without any sand addition, to create such mortars, with only the finer particles reacting significantly, the remainder acting as aggregate, reacting minimally.

The use of brick dust aggregate for pozzolanic effect is first recorded in the Middle East around 1000BC (Zacharopoulou 1998), and such addition may be considered the most common and most widespread, alongside the use of wood ash, perhaps. Both are relatively weak pozzolans, but offered great advantage in relatively small, or in large proportions. They accelerated set, and depth of set, not only generating hydraulic compounds, but being porous as well; they reduced initial shrinkage but importantly did not set hard or even fast initially, preserving deformability and a relative steadiness of set. Small – and even large - volumes of pozzolanic addition will not adversely affect workability, which may be seen to have encouraged their preference by craftspeople over the harsher-working natural hydraulic limes, along with their general predictability.

Until brick and fired clay tile production became re-established across Britain, access to brick dust was limited. The pozzolans mentioned in the accounts of Westminster Palace 1532 indicate the use of 'black mortar' made with 'smythys dust' for the laying up of flint walls, but also the purchase of '100 Flemish tiles for making dust for the …cement' for a buttress which extended into the Thames, the cement also incorporating pitch (Salzman 1952). These were exceptional uses of pozzolanic material, not the norm in this period. Other cements, made with wax and resin were commonly deployed where there was excessive exposure, otherwise air lime mortars were used.

Langley (1750) offers the most comprehensive summary of pozzolanic mortars at the time, and makes clear that these were for water works, cisterns, pools etc, with air, or feebly hydraulic limes used for ordinary building above ground. He lists eight mortars as being 'the several mortars used in buildings', with brick dust, trass and smith's ashes (of sea-coal) the sole aggregates of pozzolanic mortars:

1. Inside and Outside mortar made of Lime and Sand
2. Terrace Mortar, made of Lime and Terrace (trass)
3. Brick-Dust Mortar, made of red Stock Brick dust and Lime

4. Bastard Terrace, made of a Smith's Forge Ashes and Lime
5. Pargetting Mortar, made of Lime and Horse-dung
6. Furnace Mortar, for Furnaces, Ovens, Kilns, etc made of Woolwich Loam or Windsor Loam only
7. Plaister Mortar, made of calcined Alabaster
8. Fine Mortar, called PUTTY, for rubbed and gaged Works**,** made of Lime only. (Langley 1750 32)

Trass and brick-dust mortars were to be mixed with 'hot lime' at 2:1; forge ash mortars were more complex: 'To 3 heap'd Pecks of a Smith's Forge Sea- Coal Ashes…intermix'd with the Iron Flakes put 1 heaped Peck of unburnt Sea-coal Dust and two heaped Bushels of hot slacked Lime which incorporate well by Beating' (Langley 1750 45)

Such pozzolanic aggregates were not ground to a powder, but were graded in particle size, and trass was distrusted (Smeaton 1791) for use other than underwater, becoming friable and crumbly in situations of wetting and drying cycles, or when used above ground, which wood ash mortars did not.

Smeaton revolutionized understanding of the source of hydraulic potential as well as refining understanding about the necessary proportions of pozzolanic addition for underwater working. He realized that it was fired clay, primarily, that offered hydraulic set, whether this was already contained in the limestone before burning, or was added to a fat lime. He also appreciated that, for maximum effectiveness, pozzolan should be ground to the finest possible powder, using mill-stones for this purpose. He preferred the use of dry-slaked lime, not unslaked or freshly slaked quicklime, as Langley had indicated. He first published a paper on the matter in 1775, and then much more in his account of the building of the Eddystone Lighthouse, which included detail of numerous empirical experiments, in 1791. He identified a range of pozzolans useful for engineering works: pumice stone (volcanic ash); terra puzzolana (ash from Mount Vesuvius); trass (volcanic ash); minions - calcined ironstone; coal cinders (coal ash); brick and tile dust and wood ash, as well as smith's forge ashes and iron filings. Beyond this, he proved that the proportions of pozzolan could be economically reduced, and even that pozzolanic mortars could accommodate inert sand without detriment to their performance underwater. Two measures of lime to one of true pozzolan was considered sufficient for the pointing of 'the faces of walls either stone or brick that are exposed to water, either continually, or subject to be wet and dry…' and he went further, suggesting that a mortar of 1 lime: 1 pozzolan: 3 sand would serve as well, so long as the lime was of good quality (Smeaton 1775).

Higgins wrote without Smeaton's insights, but understood the hazards of using 'water limes' in the air:

> A mortar made of terras powder and lime was used in water fences by the Romans, and it has been generally employed in such structures ever since…It is preferred before any other, for this use, because it sets quickly, and then is impenetrable to water: whence some people hastily conclude that it is the best

> kind of mortar for any purpose. But by experience I know that mortar made of lime and terras powder, whether coarse or fine, will not grow so hard as mortar made with lime and sand, nor endure the weather so well; but…is apt to crack and perish quickly in the open air. The efficacy of it in water fences is experienced only where it is kept always wet. (Higgins 1780 124)

It took some while for Smeaton's insights to percolate down into either practice or understanding. However, Barry's specification (Accounts & Papers 1847) for the mortars of the river wall of the Palace of Westminster was for '1 measure of the best fresh-burned Merstham, Dorking or other equal and approved lime, 1 measure of finely-ground genuine Italian pozzuolana, and 2 measures of sharp above-bridge river sand'. Martin (1829), who may have been referencing long-standing French experience and not necessarily Smeaton, said that 'ordinary mortar is of better quality when we replace one part of the sand with fragments of tile or powdered pottery' (Martin 1825 101-102) although this was for use in general construction.

Pozzolanic water lime mortars appear generally preferred over natural hydraulic limes (and Smeaton and others typically used pozzolans as well as Blue Lias, or other moderately hydraulic limes, for water works), while Wright (and Pasley) preferred natural cement, once these had become established:

> (Pozzolans and fired clays) offer very important advantages in the improvement of mortars, and deserve particular attention, because hydraulic cement is not always to be had, and hydraulic limes often give mediocre results, unless they are mingled with a certain proportion of pouzzolana; and the latter has, moreover, this advantage over the hydraulic limes — its qualities are scarcely at all impaired by exposure to the air and moisture…. (Wright 1845, 29

The use of pozzolanic mortars diminished through the 19th century, however, and almost entirely disappeared once reliable Portland cement became commonly available after 1870. The use of small volumes of pozzolanic addition particularly to putty lime mortars was revived by Professor Robert Baker at Wells Cathedral and Crowland Abbey (Copsey 2019 Baker's private notebook).

Totten, whilst indicating the routine use of pozzolans at Fort Adams after 1838, also indicated his preference for the 'pozzolanic' use of natural cement, recognizing some equivalence of effect:

> (At Fort Adams), hydraulic cement, or burnt clay, or brick dust, or some other similar matter is added to every kind of mortar made at the work, in proportions varying with the purpose to which the mortar is to be applied. The poorest mortar we make contains 1 barrel of hydraulic cement to 3 barrels of unslaked lime and about 15 barrels of sand; the cement being added before the sand, and while the lime is being reduced under the wheel (Totten 1842, 231)

When pozzolans were added, these would go into the aggregate from the start. When pozzolan formed the only aggregate, they were typically mixed by the 'ordinary' method. The heat of the mixing might promote greater reactivity in the pozzolan and may promote very feebly hydraulic reactions in some limestones and sandstones, depending upon their mineralogy. Most certainly, the set of lime-stabilised soil relies upon pozzolanic reactions between the lime and the clays, the intensity of this set varying according to the nature of the clay itself. When NHL was added as a gauge, as in Scotland over recent decades, or, much earlier, in early 20th-century Spain (Lopes del Vallado 2009), or, in the form of natural cement, in the USA from the mid-19th century, this was added into the previously hot mixed mortar just before use.

A recently analysed pozzolanic mortar from a Roman bath-house at Vindalanda, Northumberland, from circa 100AD (Revie 2017 See Appendix Eleven, No.2) shows a binder: aggregate ratio of 1 slaked lime to 1.36 parts aggregate, aggregate forming 47.6% of the mix, most of it being limestone, 10.1% lime inclusions, 2.4% quartz and 8% brick, of which 5.1% was fine enough to offer pozzolanic reaction. This mortar has lasted almost 2000 years, during many years of which it had been exposed to the elements, and yet it was found to be in excellent condition. This may be seen as the typical volume of pozzolanic addition for above-ground construction and effective despite the fact that brick dust has been calculated to be 89% less powerful than meta-kaolin, a modern pozzolan much used in the conservation industry since the onset of the 'lime revival', as well as than ground granulated blast furnace slag (Pavia & Walker 2013). Pavia & Walker found that amorphousness, as well as particle size, were the key determinants of pozzolanic power.

Figure 92. *Roman mortar from bath-house at Vindalandia*. See Appendix Eleven No.2)

6.20 Hot Lime Grouting

> Walls. With respect to their firmness, strength, and duration, much depends on the cement with which they are carried up. In erecting rough stone walls, liquid mortar is most eligible to be used, in the middles, and inner parts, of the walls. If the stones are small, or want length to bind the work firmly together, it should be the common practice of workmen to cover their work, every evening, with an entire sheet of flowing cement; to assist in preventing the wall from bursting, or parting in the middle, the ordinary failure of walls which are built of such materials (Marshall 1804, 270)

It was commonly understood in the past that a masonry wall should be solid and properly filled with rubble stone and mortar to be structurally sound and long-lasting. It was not always sufficient to lay the hearting stones into a bed of mortar, slapping wetter mortar around and upon them to create a uniformly bonded mass of mortar and infill, also bonded to the previously laid facing stones. This was the case whether the mortars were of earth, earth-lime or lime, although the arrival of harder, more hydraulic mortars, especially of Portland cement, coincided with the widespread use of cavity walling, which was not only of thin wall construction, but which made a virtue of voids within a masonry wall. Cavity walls offered a measure of insulation, but their primary advantage was commercial, consuming fewer materials and relying upon iron ties between two half-brick thick walls for their structural integrity. They excluded rain from the inner leaf of wall, but, depending upon the bond of the mortars used, the outer leaf and cavity may be routinely wet.

Iron cramps had been common enough in traditional masonry construction, and might allow the secure attachment of ashlar facing to otherwise rubble wall-cores. However, the essential integrity of a masonry wall of solid construction, its thickness observing established rules (typically 19 – 21 inches thick for ordinary buildings) of long-proven success, relied upon the solidity of construction and upon the quality of the bond between all elements – facing stone and core work and the mortars of both. The most effective 'insurance policy' was to pour a liquid grout into a wall core as building proceeded, and this was routine, as evidenced by building accounts and specifications and historic texts. Cavities and voids within the core of a wall will arrest the capillary movement of liquid phase water, which cannot cross the void except most inefficiently as water vapour (Wiggins 2019). This consideration is not referenced in old texts, but is arguably the reason beyond the optimum structural integrity why grouting might be considered appropriate.

> My Father (who was a Workman about the Year 1675) often told me, and my own repeated Observations convince me, that the Methods Masons practised in former Times, in building Churches. Abbeys, Castles or other sumptuous Edifices in this Country, was to this effect. After they laid the outside Courses with large Stones, laid on the flat in swimming Beds of Mortar, they hearted their Walls with their Spawls and smallest Stones, and as they laid them in, they poured in plenty of boiling Grout, or hot Lime-liquid among them, so as to incorporate them together, as if it were with melted Lead, whereby the heat of it exhausted the Moisture of the outside Mortar, and united most firmly both it and the Stones, and filled every Pore (which as the Masons term it) set, that is, grew hard immediately (Semple 1780 79)

Smeaton (1791), reflecting his preference for already dry-slaked lime, discusses grouting with a cold mixture of lime and sand 'to consolidate the upright joints by pouring in liquid mortar, commonly called *Grout* in so fluid a state, as to run into every cavity and crevice.' (p110). The pouring of cold grouts, however, relies largely upon suction from the stone or bricks to stiffen; it may be deficient in adhesiveness and may be very slow to gain its initial set. These issues were readily overcome by the pouring of just slaked and still slaking lime, with or without sand addition. The completion of the slake *in situ* would lead to some early stiffening of the grout independently of suction. Evaporation – particularly via effectively porous lime mortar joints and into the open air whilst succeeding facing courses were laid – would further assist early stiffening, and the tendency for hot lime to bond immediately with both porous and little-porous substrates was taken full advantage of. When a grout was used hot, stones were unlikely to begin to 'swim' (McAfee 2000), holding up the work.

The routine use of grouting also placed an onus on the proper filling of mortar joints – both bed and perpend joints - to the facework. The grout would find its way out of any deficiently mortared joints and run down and stain facework. In this scenario, under-burned and over-burned, or otherwise slower slaking lime lumps, would assist in prompt stiffening, as well, potentially, in deeper carbonation over time, in much the same way as would the use of a limestone aggregate. At the same time, hot lime 'flows' in a way that cooled lime does not, and does so whilst relatively viscous: it could be expected to find its way easily into open joints. For a cold grout to reach as far, it would need to be particularly liquid and would take much longer to reach an initial set, unless it was hydraulic. There is, however, little evidence for the use of more than feebly hydraulic lime for grouting. Blue Lias lime was used at Kirby Muxloe Castle, Leicester (Hamilton-Thompson 1920, although grouting is not specifically mentioned) and probably at Sadborow House, Somerset, where its production was continuous and there would undoubtedly have been an awareness that hydraulic lime grouts would stiffen well, and these *may* have been preferred for this purpose when available (Appendix Five, DHS02). An hydraulic lime would be considerably weakened used as a grout, however, for requiring so much water, whereas a pure lime, especially if mixed with limestone dust would not. On the whole, however, this was not necessary. Semple says that the lime for grouting should be 'pure and well-burned' (1780). A grout of lime and sea-sand was specified for the Edinburgh Exchange in 1754.

> The mortar for running into the upright joints of the courses, and for filling in the work sound, to consist of one part lime to four parts of small unscreened gravel, to be well mixed and beaten to a tough consistency, and liquefied in tubs or other vessels, to be properly adapted to run into and fill up all vacuities. The mortar to be used as hot as is consistent with the safety of the work (Davy 1839. 165-166)

Pasley (1826) and others recommended its use for brick walls as well, it being poured whilst still very hot every 3 or 4 courses of brick. His preferred recipe was 1 grey chalk lime to 4 sand, mixed and used hot, for brick walls; neat hot lime grout for stonework. He relates that Robert Smirke used grouts and then extended their logic into the pouring of hot lime concretes, for footings.

Partington (1825) shared Smeaton's preference for the use of cold, even somewhat matured lime for grouting, indicating that it would set the same day, if matured, much more slowly if this was neglected, though he does not explicitly attribute slow-setting to hot grout (Partington 1825).

Vicat (1818) considered grouting essential for finely jointed ashlar. Totten (1842) compared the strengths of common mortars and grouts, concluding that a liquid grout had only two-thirds of the compressive strength as a mortar made to a much stiffer consistency, consistent with a degree of hydraulicity. Scott (1862) was ambivalent about the benefit of grouting, suspecting that it might lead to short-cuts elsewhere in the building process and that a stiff mortar carefully applied should suffice.

Hot lime grouting is much mentioned by: Semple 1750 & 1780; Marshall 1791; Pasley 1826 & 1838; Kelly 1823; Shaw 1832; Cuming 1837; Davy 1839; Webster 1844; Wright 1845, although doubting it was a good alternative to properly mortared masonry; Brees 1852; Dempsey 1857; Espinosa 1859, Scott Burn 1860; Scott 1862; Austin 1862; Gillmore 1864; amongst others. It was required by both Barry (Accounts & Papers 1847) during the construction of the Palace of Westminster and by Fuller and Jones (1859) for the Canadian Parliament buildings.

Heath (1893) questioned the virtue and effectiveness of grouting dry laid hearting material, suggesting that …'a better method is to fill the shallow basin enclosed by the facework with comparatively stiff mortar, softened if need be with a little water, and remixed with a long-toothed rake called a 'larry'. The bricks or stones are then well bedded by hand in the pool of mortar paste' (p123), although it must be said that this should be best and normal practice even when grout was to be used.

Sutcliffe (1899) illustrates the tendency, as Portland cement use became more common, for practice with more traditional materials to be seamlessly transferred to the new, indicating the grouting of brickwork built with Portland cement mortars to be grouted with neat cement. He saw this combination as offering 'water-proofing' to a wall. As some building accounts from this same period make clear, the grouting of brick or tile floors with neat Portland cement also became common around this time, and Sutcliffe happily advocates the same.

Grouting tends to be much less mentioned hereafter, especially grouting with pure or nearly pure lime and has generally only been applied in the conservation industry retrospectively, for the stabilisation or consolidation of old buildings, the cores of which have been disrupted by uneven settlement or bulging of the wall face; or when insufficiently solid wall cores were left by the original builders.

6.21 Limewashes

Throughout most of building history, limewashes were the default finish for all types of buildings (see Figure 56; Figures 94 - 102) – for timber-framed buildings, extending across whole elevations, including the timbers themselves; for stone and brick buildings, although the latter might as often be colour-washed, with a mixture of pigment, alum and stale beer (Hammond 1890); for earth buildings of all iterations.

Figure 93 *Routine limewashing in Spain, earlier 20thC* (Museo de Cal de Moron)

Limewashes were applied to the outsides and to the insides of buildings of any status, wherever plastered walls and ceilings were the norm. Whilst their purpose might be seen as decorative, modern research (Brito & Diaz Goncalves 2013; Wiggins 2019) has shown them to be a very effective drier of fabric. The presence of coats of limewash will dry the most to the least porous substrate more efficiently and to greater depth than if the same substrate was bare (Brito & Goncalves 2013). Wiggins's research indicates an explanation – limewash is pure calcium carbonate after curing and is composed mainly of the 1 micron pores that are optimal for the capillary movement of liquid phase water (Wiggins 2019). Whilst such efficiency of functional behaviour was not understood historically, the drying effect of limewashes was observed and taken for granted. As in so many other aspects of traditional building practice, form followed function. Most stonemasons, when building a house, would expect that it would be rendered either with earth or earth-lime or, later, with lime-sand mortars in most cases, and limewashed, as a minimum in all cases; in the case of brickwork, coated with a colour wash, bound with alum, or a similar fixative and stale beer (Hammond 1890).

> If it is only wanted for white-washing, the lime, after being well-slaked with water, should stick like glue. For this last purpose, however, the lime should only be slaked in lumps. (Pliny 2015 chapter 55)

Few of those using modern limewashes, mixed from cold, 'matured' lime putty would recognise Pliny's requirement that they should 'stick like glue'. Modern limewashes are 'water-thin' and are applied in 7 coats, slowly building up a suitable thickness. They have enjoyed a poor reputation for durability, expected to last perhaps 5 years in good order, whilst old limewashes have tended, where they survive, to have lasted very much longer than this.

Whenever limewashing, typically called 'lime-whiting' in the past, was specified, the demand was for 2 or 3 coats. Limewashes were made in the same manner as grouts and, indeed, lime putty – water was added to lump lime in the necessary quantity to preserve the temperature of the slake, plus a small surplus, the whole being stirred as slaking proceeded (Langley 1750; Pasley 1826). It is commonly referred to in building accounts and specifications (see Appendix One). It might be diluted somewhat after slaking was all but complete. For polite work, it would then be poured through a fine hair sieve; for less polite use – as upon sheds or farm buildings – sieving would not be so necessary – larger lumps would sink. Dilution would bring it to a 'mud-like consistency'; not so thin that a dipped brush would drip. Such limewash may not always be used hot, but very frequently was.

The method of slaking offered a material that could be applied quite thickly, without subsequent shrinkage; hot application reduced the risk of crazing even further. Good coverage (and intended colour) was immediate. As the lime wash approached a 'gelatinous' consistency on the wall, half way towards carbonation, it could be worked over and burnished with a dry brush, tightening the surface, which could be effectively polished. This consolidated surface would repel most received rainfall – the addition of tallow or of other oils and fats, although it was done, was not essential by any means, and would significantly compromise effective porosity (Wiggins 2018; 2019), although this would be counter-intuitive. Such additives might also encourage embrittlement of the limewash, compromising its longer-term attachment. The surface coating would be somewhat incompatible with the lime or earth mortars behind, in terms of breathability, at least, which might also lead to detachment. Salt was a common ingredient of traditional limewashes, as were sifted wood ashes. In England, at least, limewash fell from favour for purely ideological reasons – the same ideology that led during the later 19th century to the removal of countless plasters from church interiors, as well as from house exteriors. William Morris and others founded the Society for the Protection of Ancient Buildings – the 'Anti-Scrape' – in very specific response to the new 'archaeological' aesthetic that saw lime renders and colour washes as 'obscuring' the inherent character of ancient building fabric.

The vicar of Crambe St Michaels, near York, may be considered typical of his time, in justifying his wholesale removal of plasters and limewashes from the interior in 1895:

> Meanwhile the question arose of the treatment of the walls of the Nave, which were covered with white-washed plaster, presenting a very cold appearance. I had intended to obviate this by colouring them in a warm stone or other colour, but in the course of some necessary repairs to the wall, the possibility was revealed of rescuing the natural stone…
> The white plaster was stripped off, and the natural stone pointed *{with a hard Portland cement mortar}*, both in the Nave and the Bell Tower, any of the fine old white Hildenley stone *{carvings)* there being freed from the whitewash by which it was obscured, by the application of oxalic acid etc. (Ricketts, unpublished memoir, held at the Church).

This ideology held little sway outside of England – limewashes and renders remained the norm in Wales, Cornwall and Scotland, where the prevailing weather made such aesthetic luxury less willingly affordable. Except, perhaps, in France, it held little sway across much of the rest of the world, but, increasingly, during the 20thC, routinely applied limewash was displaced by modern paints of little or no breathability. These claimed to be much longer lasting, for all that they would be sufficient in themselves to compromise the proper performance of any traditional building to which they were applied, whether inside or out.

Limewash was so commonly used and so generally applied by 'unskilled' people (see Figure 93), and its 'rules' so widely understood, that its mode of preparation is barely ever detailed in old texts. However, Langley's description (1750) of the method of running lime to a putty applies equally to limewashes:

> 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 fit for Use. (Langley 1750. 132)

Figures 94 & 95: *Hot 'barn red' pigmented limewash, Amos Brown House, Whitingham, Vermont 2000.*

Figure 96: *Hot mixed aggregated limewash (sheltercoat) Crowland Abbey 2016*. Figure 97: *Hot limewash, All Saints, Foston, North Yorkshire 2018*

Figure 98 *hot limewash to interior of York House, Malton, 2010*. Figure 99 *Hot limewash to 20 Coney Street, York, 2018.*

Figures 100 & 101: *hot limewash to Old Lighthouse, Bridlington, 2016*

Figure 102: *hot mixed and applied lime sheltercoat, St Mary's priory church, Old Malton, 2011*

6.22 Concretes

It may be reasonably asserted that the use of mass concrete for flooring, as well as for walls (typically stone or brick-faced) was imported into Britain by the Romans and substantially fell from use after the collapse of the Roman occupation. Thereafter, floors were typically of earth, modified with the addition of organic matter and with proteins, such as bull's blood. In higher status buildings, these earth floors would be overlaid with brick or with stone laid in mortars of earth, clay or, on occasion, of lime, or with a layer of 'lime ashes, or other ashes, between ground and flooring material, as evidenced by a number of archived building accounts (see Appendix One). The use of earth-lime and of lime mortars for floors, if this did diminish or die out after the Roman withdrawal, was re-imported by the Normans, very many of whose stone churches and fortifications were built with earth and earth-lime mortars. During the 19thC, in the UK, it became the norm to hot mix lime concretes for footings and floors using feebly and then moderately hydraulic lime. During the 20thC, this was displaced by Portland Cement. This briefest of summaries is expanded in Appendix Three.

6.23 Aggregates: Sands

The call for lime mortars to be made with clean, coarse aggregate is a constant through time, from Vitruvius onwards, although there was some similar acceptance that pit sands might contain clay or loam. Vitruvius put great store by the colour, as well as the provenance of building sands, and this was reflected in some medieval usage (see Appendices One and Five). Vitruvius placed pit sand over river sand and both over sea sand in usefulness, though his primary objection to the latter was the damage to surfaces that might be done by its salt content. Pit sand was generally considered superior to river or sea-sand, so long as it had been washed, although some reversed the preference.

After exhaustive testing, Totten (1842) concluded that the strongest mortar might be made with the finest sharp sand, but his opinion seems something of an outlier. Most concluded, Smeaton included, that 2 parts of coarse sharp sand to one of fine sand to one of quicklime gave the optimum tenacity. Dibdin's research in 1911 suggested that a fine sand made with air lime would be significantly stronger than the same with a feebly, and even a moderately hydraulic lime and recent practice has tended to see quite coarse sands used in association with Natural Hydraulic limes to best effect. The use of sands of such coarseness is not so necessary for fat limes hot mixed to a traditional proportion, it may be concluded, and this is confirmed by the author's experience. Higgins established in 1780 that sand of uniform size and rounded profile (the 'soft building sand' still sold and much used in Portland cement mortars today) was the worst possible, offering deficient tenacity. Few defined the coarseness of a sharp sand. Heath was the exception in 1893, saying that 'Fine sand may be defined as composed of fragments whose diameters range between 1/24 and 1/16 inch, coarse sand between 1/16 and 1/8 inch….' (p119) (i.e. the particle size distribution of a fine sand should be between 1.0 mm and 1.6 mm, and a coarse sand between 1.66mm and 3mm). Many sharp sands used in the UK for lime mortars are coarser than this, although most of those used in the USA are of this order, with the highest densities of particle-size mid-way between the two parameters. In the author's experience, historic mortars tend to consist of relatively fine aggregates, finer than most modern specifications call for. The dominant particle size of most earth-lime mortars are very fine, indeed, being mainly of clays and silts.

Moxon (1703), who observed craft practice in London, as well as reading Vitruvius and those that followed him, although not uncritically (he said that Vitruvius's 'proportion of sand seems too much, although he should mean the lime before it is slacked, ' for example), drew a distinction, later reiterated by Langley (1750), between sands for indoor and outdoor mortars,

> And whereas they make use of the sharpest sand they can get (that being best) for mortar to lay bricks and tiles in, so they choose a fat, loamy or greasy sand for inside plastering, by reason it sticks together and is not so subject to fall asunder when they lay it on seelings and walls (Moxon 1703 245)

He insisted that the best and sharpest sand should be washed up to 5 or 6 times before use. Others only insist upon such washing when sea-sand is used.

Higgins (1780) experimented extensively with sands, seeking to establish which blends prompted the least initial shrinkage in a lime mortar, as well as being the 'hardest and most durable'. He concluded that fine sand mortars were better than those composed mainly of coarse sand and that those comprising two parts of fine sand to 1 of coarse and 1 of quicklime were the best of any that included coarse sand at all. Translating this from volume to weight, he concluded that

> Of the specimens made with coarse sand, fine sand and lime, those were manifestly the best which consisted of 4 parts of coarse sand, 3 of fine and one part or a little more of lime: for, whilst fresh, they were more plastic than the others, and were easily made to acquire a smooth surface; they were not disposed to crack …; they were not at all injured by wet or freezing or thawing; they were pretty close in grain and they grew so hard, in the course of 9 or 10 months, as to resist the chisel…(Higgins 1780 93-94)

The fine sand had to be sharp, however, and graded – rounded, mono-sized sand was the worst performing of all and shrank dramatically when applied as a stucco. Smeaton (1791) concurred with Higgins, '…If the sand is not naturally a composition of fine and coarse, it should be rendered so by an admixture of different sorts….' (p123) Vicat (1837 pp87-88) looking at the best sands to use with different limes concluded that fine sand was best for eminently and moderately hydraulic limes, followed by coarse and fine sand blends and, lastly, coarse sand. For feebly hydraulic limes: blended coarse and fine sands, then fine sand and finally coarse sand. For rich limes, and contradicting Higgins, he placed coarse sand first, mixed, second and fine sand the least good. Quite why the hierarchy should vary so much between fat and feebly hydraulic limes is mysterious, to say the least. Treussart routinely accused Vicat of simply making things up. Burnell and Gillmore tended to agree:

> General Treussart, however, does not agree with Vicat, in supposing that the chalk, or rather the rich limes, cannot be rendered capable of setting by the mixture of pozzolanos; and, indeed, the experience of almost all builders would lead us to believe that Vicat has, in this case, been carried away by the love of theory (Burnell 1857 65).

Davy (1839), whilst dismissing the value of Pennine sandstone for building, commended the value of the same stone crushed for aggregate.

Totten (1842) supported Higgins's conclusions on sands after extensive experiments of his own: 'Sand freed from dust by washing and then pounded fine, gives much better mortars, than a sand composed of particles of every size from dust (no dirt) up to grains of ½ an inch diameter. In 21 comparisons, 2 exceptions,' and beyond this that 'it appears that coarse sand, or, rather, sand composed of coarse and fine particles, is a little inferior to sand that is all fine.'(p240)

A C Smeaton (1840) maintained that river sand should be preferred, it being the cleanest and free by default from clay or loam or salt.

The use of mixtures of fine and coarser sharp sand was the practical orthodoxy through most of the 19th-century. In London, sand and other aggregates dredged from the Thames were the norm. In truth, sands that could be readily sourced in any locality were used, whatever their theoretical quality. Volumes of lime (and of mixing water) would be varied accordingly. In many cases, this meant using crushed stone aggregate of various geologies.

Burnell challenged the orthodoxy that sands should always be sharp and clean, referencing the 'arenes' of parts of France that were 25-75% clay, mixed otherwise with chalk, and which were well known to set under water when mixed with fat lime, as well as the degraded granite sands of Devon, Brittany and Galicia, which he says yielded eminently useful building sands precisely because of their particular clay content (feldspar). In the author's experience, the Devon variety, 'Growan', much used on Dartmoor historically and typically around 18% clay makes a tenacious and swift-setting mortar and enjoys a feebly hydraulic set.

Espinosa (1859) attributed similar value to schist sands and others formed of degraded igneous rocks, as well as to limestone sands, seeing the mineral contamination of pit sands as a potential benefit in building, whilst insisting that plastering sands had to be clean and relatively fine. 'When dealing with mortars the grading/size of the sand is significant only according to the case and the end use'.

Scott (1862) felt that the addition of any sand to an hydraulic lime mortar – the only kind of which he approved - was to compromise its strength and performance and to reduce the expense. He concluded that the coarseness of the sand made little difference to ultimate strength and that 'those mortars must of necessity be the best, which have as much sand as they can carry without losing the toughness and plasticity which the workman has reason to prefer' (Scott 1862 48).

It might be suggested that Scott's attitude presaged a decline in concern about the quality and qualities of sands the more hydraulic binders became, and especially once Portland cement became the norm. Even the more technical publications on lime during the 20th century make little mention of sand, or of the types of sand that may be most appropriately used, according to the lime.

6.24 Limestone Aggregate

The presence of mainly limestone aggregate in traditional lime mortars is very commonly found, by observation and by analysis. This is most particularly so in limestone regions, but also in regions adjacent to limestone geology, into which lime and limestone were routinely imported. Unless from rivers, sand was not always easily found, but this is not, perhaps, the primary reason for the liberal addition of limestone aggregates. Calcium carbonate was frequently, perhaps always, included in sea or beach sand. Analysis by Karkeek, quoted by Isham showed that calcium carbonate content in Cornish beach sands ranged from between 25% (Porthreath) to 94% (Harlyn), with the sands from all but five of fourteen beaches sampled exceeding 64% (Isham 2000, 5). The use of such sands would have delivered very workable and effectively porous mortars, as well as potentially enhancing compressive strength (Lawrence 2006). The presence of limestone aggregates can often be disguised by unsophisticated acid digestion, which might also, thereby, inflate the apparent lime content.

Vitruvius saw great virtue in the use of marble dust aggregate in fine finish coats. Limestone and carbonated lime have a very similar pore size distribution, and comparably high concentrations of 1 micron pores (Wiggins 2019), so that, for all that the setting lime will be slower to carbonate, this carbonation and drying will, perhaps, be compatible in ways that they would not be if the aggregate is silica sand. Vitruvius extended the use of marble aggregates into the rougher base-coats of three-coat plaster schemes, with larger marble aggregates used in the first coat, medium-sized marble aggregates in the second, and the finest material in the finish coat, along with lime laid down sufficiently that it retained no residual lime lumps. The 'rough-coats' were likely prepared from freshly slaked quicklime, not with 'matured' lime putty. He also allowed for the base layers to be of 'sand coats', but the implication is that the best work was done with marble. He indicated the use of pulverised terracotta in place of sand in the base coats of lower sections of a wall, where these were inherently damp, the better to manage such moisture (Vitruvius 2009). Lime plasterers in East Anglia today prefer the use of graded chalk aggregates, which they insist shrinks only minimally, compared to lime-sand mortars, as well as adding chalk flour to limewashes to 'soften' them and make them less brittle (pers comm Joe Orsi).

The porosity of the aggregates was considered important, therefore, to the most reliable and successful performance.

Referencing De L'Orme, Henry Wotten (1624) notes his assertion that lime should be made from the same limestone of which the building will be built, 'as belike imagining that they sympathise and joyne the better by an Original kindred,'(p13) though Wotton counts this an unnecessary conceit.

Burnell ruminated upon the advantage of using limestone rubble in the manufacture of concrete:

> 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," but without extending this to lime mortars in general. (Burnell 1857 77).

6.25 Prompt or Later Use

> It was supposed, for many years, that the longer the lime was slaked before it was used, the better mortar it would make. Recent experiments prove, however, that this is not the case with mixtures of fat lime and sand only. Better results are obtained with such mortars, if the paste be mixed with the sand as soon as the slaked lime has become cold, and care should be taken to use no more water, in the process of extinction, than may be required to produce a thick pulp. (Wright 1845 para 152)

That fat lime mortars should be used promptly after being made – which is to say, within a week - is a view explicitly shared or expressed on behalf of others by Neve, Langley, Higgins, Dossie, Marshall, Rees, Hassenfratz, Guilt, Treussart, Burnell, Walsh and Radford. That others felt that mortar should be laid down before use is discussed by Moxon and Neve, but, even when building, as opposed to plastering, mortars were laid down, this was usually for days, and they were used within a week. Neve spoke to some craftsmen who felt that it could not be laid down long enough and that it improved indefinitely for being allowed to rest. Wilkins summarised the general consensus in 1799, at the same time offering a précis of general understanding at the time:

> In preserving the Ruins of Bayham Abbey the following Mortar Cement is Recommended.
>
> Stone lime – well burnt and new from the Kiln every two or three days – The lime to be slaked with <u>but little</u> water and no more mortar to be made up than can be used in the Day. To half a Bushel of slaked lime mix a Bushel of clean sharp road or wash(ed) sand which will be quantity sufficient for a Days use, this must be beaten in small quantities by two Labourers for three hours at Least & they must keep on beating it – in the same way that Tarriss (trass) is prepared for water; a small quantity of smiths ashes should likewise be added to give it the colour of the old mortar – and if any remains to be used when the Days work is nearly over, some of the larger stones may be laid with it when a greater quantity of cement may be used in a short time, because I consider the mortar as of no use the day after it is made – The grout which is designed for pouring into the loose walls should also be prepared in the same manner – that is: the same proportions of lime, sand & smiths ashes to be made of a consistence thin enough for running into & filling up the Interstices – the work as I have before observed should be previously pointed to prevent the Grout from running through & Smearing the face of the walls (William Wilkins Architect, Bayham Abbey 1799, Kent Archives U840)

Some of the concern over prompt use was doubtless informed by the difficulty of preserving mortars, or lime, from the air and from the onset of carbonation, hence the use of sand-covered lime pits when such preservation and storage was necessary. Other concerns attached to the notion that lime, whether on its own or in a mortar, simply lost 'power' the longer it was left before use (Rees 1829). The most obvious concern, however, although it was the least often explicitly expressed, was simple efficiency. Why handle a mortar more times than was necessary? Why spend time moving and protecting a coarse stuff when it would receive more than sufficient protection from drying out or from the weather generally once it was in or on a wall? The craftspeople themselves would feel this urgency and inefficiency the most, and so may be expected always to prefer prompt and efficient use of just-mixed mortars, just as they do today, although the hydraulicity of modern mortars makes this unavoidable. This is reflected in most 19th-century architects' specifications, which demand the use of building mortars on the day of mixing, or explicitly whilst still hot, whether or not the lime is a pure air lime or a feebly hydraulic lime (Accounts and Papers etc 1847; Fuller and Jones 1859). When the mortars were hydraulic in nature, prompt use was, of course, essential.

> (Worlige) tells us, That it is a great error in mason, bricklayers, etc to let the lime slacken and cool before they make up their mortar, and <u>also to let their mortar cool and die before they use it.</u> Therefore (says he) if you expect your work to be well done, and long to continue, work up your lime quick, and but a little at a time, that the mortar may not lie long before it be used…. (Neve 1726 200)

Higgins (1780), noting the fact that many builders liked to slake large quantities of lime in one go, and more than could be used immediately, as Moxon had recommended as 'improving' the mortar (1703), opted to test the performance of fresh and less fresh mortars -

> I found…mortar which had been used quite fresh, to be harder and to resist fracture and the separation of it from the bricks in a much greater degree than any other specimen….I concluded that mortar grows worse every hour that it is kept before it is used in building, and that we may reckon as another cause of the badness of common mortar, that the workmen make too much at once, and falsely imagine that it is not the worse, but better for being kept some time…. The plaisterers, who use a finer kind of mortar made of sand and lime, observe that their plaster or stucco blisters, when it contains 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 39-41)

Mortar should be mixed as soon as possible after the burning of the lime, and whilst the quicklime remained hot from the firing, it was commonly asserted, even if the mortar thus prepared might not be used immediately:

> In works of little duration or importance, one makes the mix (*la mezcla - vernacular for mortar*), by taking the lime as quickly as possible after it has slaked and heaping it with sand in the adopted proportion; sprinkling the surface of the heap - this forms a crust that preserves the interior. From here, one takes what is necessary, beating the mortar with water in a ring ('enclosure') which one forms out of sand. (Espinosa 1859 91)

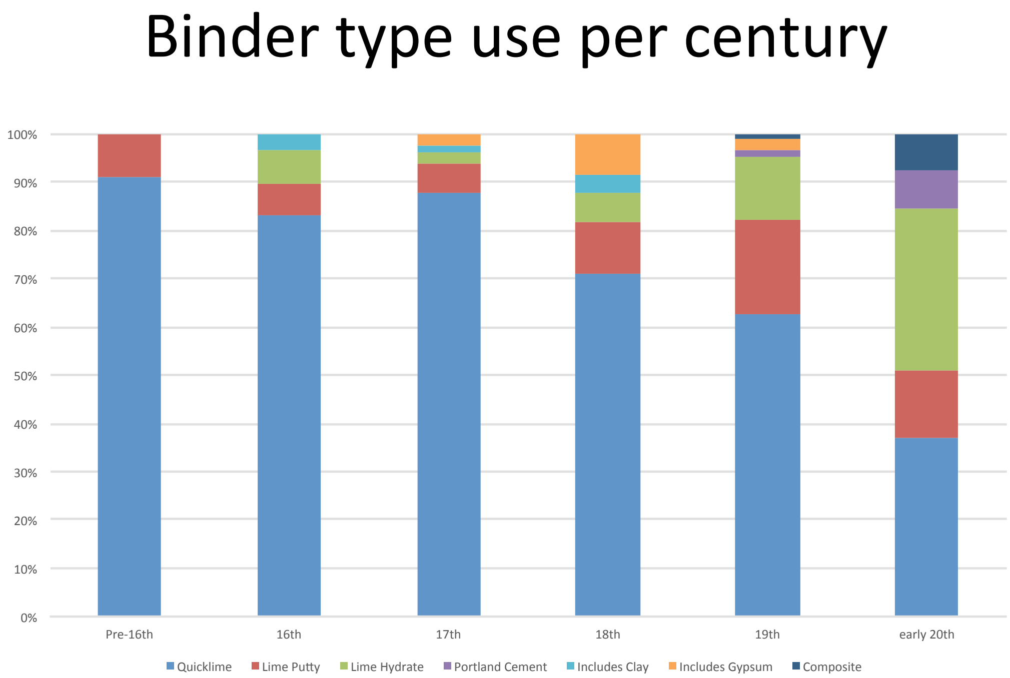
All of these options – hot use and cold – are attested to in the analyses contained in Appendix Eleven.

7.0 CONCLUSIONS

Drawing on the evidence from historic texts reviewed in Chapter 6, above, this concluding chapter seeks to draw together the good practice of centuries of craft experience in traditional construction of buildings in stone, earth and timber. See also Appendix Four, a Summary of Consensus Within Old Texts.

7.1 Hot mixed lime mortars

The great majority of traditional mortars were hot mixed, with lime as fresh as possible from the kiln, and were used either immediately or within days. This is clearly demonstrated by historic texts, as well as by a multitude of archived building accounts, and almost always in architects' specifications from the second half of 19th century, when these became more common. It is a routine demand that 'no more mortar should be mixed in a day than can be used in that day' (Barry, Accounts and Papers 1847), or, more explicitly, that the mortars should be 'used as hot as possible' (Fuller & Jones 1859). An as yet unpublished review of the data-base of mortar samples held at the Scottish Lime Centre Trust, carried out by Anne Schmidt on behalf of HES and examining some 4000 samples, clearly illustrates the pattern of lime and mortar use through the centuries (Figure 103). It mirrors the pattern illustrated by both this historic literature review and by archived building accounts. It may be seen as generally representative, although with some bias towards hot mixed moderately hydraulic limes due to both Scottish geology and climate, though even here, more than feebly hydraulic limes constitute only around 20% of the total. The analysis demonstrates that it was only during the 20th century that hot mixing produced less than 60% of mortars in the data-base and that, still in the 20thC (the earlier 20thC), hot mixing retained equivalence with the use of by then readily available dry slaked lime. Throughout, lime putty based mortars were used in less than 10% of mortars, and only 20% of mortars during the 19th century. Even these figures may be errors of interpretation, since a slaked and sieved lime putty was as often used immediately (Pasley 1826), whilst hot, or may have been run from a dry hydrated lime (Nicholson 1841) after sieving of the same, and would not present residual lime lumps on analysis. In terms of hydraulicity, the same research shows that at least two-thirds of the mortars analysed were fat or feebly hydraulic lime-based, only 15% moderately hydraulic and only 5% eminently hydraulic. This is a markedly different picture than that presented during the more recent 'lime revival'. (Schmidt HES TP 30).



Research Anne Schmidt courtesy Jessica Snow, Historic Environment Scotland

Figure 103: *Summary by Century of common mortar binders. Schmidt unpublished Technical Paper. HES.*

The import of this research is readily confirmed by simple observation. The presence of small, typically pea-sized and below, angular lime lumps, often containing under-burned cores of the host limestone, or over-burned lime, but also of carbonated lime, is now generally accepted to be an indicator of hot mixing (see Appendix Two). It was not until 2001 (Hughes, Leslie, Callebaut 2001) that this analysis was accepted in the academic community. Masons familiar with hot mixing methods, or who had used hot mixes, had already made this deduction (McAfee 1997), since all quicklimes, apart from finely powdered quicklime, will – when hot mixed – leave variable volumes of lime lumps in the resultant mortar, even when efficiently burned, industrially produced quicklimes are used. Although poorly mixed lime putty may leave agglomerations of slaked lime, and dry hydrates may clump during mixing, leaving similar, these are of somewhat different character and much more 'fluffy' than the sharp, angular lumps left after hot mixing. Moreover, they will be fully carbonated. (Revie 2018, see Appendix Eight). Once the prevalence of such lumps was accepted as evidence for hot mixing, it became increasingly difficult for observers of traditional lime mortars to avoid the conclusion that the vast majority of traditional lime mortars – and most earth-lime mortars – were made from quicklime and were typically hot mixed, although the precise method might vary.

The implications of this deduction for like-for-like repair and conservation were substantially ignored, however, and challenged by poorly informed views (as evidenced by historic texts at least) on the 'inauthenticity' of pure lime, the high risks attached to hot mixing, and its impracticality on a modern building site (Ashurst 1988; Holmes, Lynch 1997). There was an insistence that 'dirty' historic limes were better reflected by

use of available natural hydraulic limes. This bias was accentuated in a lime market of suppliers who had become used to the hazards of putty lime in inexperienced hands, as well as the profitability of selling NHLs and associated 'added-value' products built around a base of NHL.
The only objectors to this new orthodoxy were craftspeople themselves, especially those with roots in the early lime revival (Carrington 1993; Durnan 1997; Swann (and Hughes) 1998). It took the experience and then the campaigning of such craftspeople after 2012 for this orthodoxy to be challenged and for the realization to begin to dawn that, in fact, the NHL emperor had no clothes (pers comm McAfee 2019).

It may be demonstrated, therefore, that mortars made with these materials, with pre-slaked NHL or with pre-slaked and long laid down lime putty, in both the processes of manipulation and in performance, do not represent a like-for-like response, in very many circumstances, and may, therefore, be unsuitable replacements or companions for original, historic mortars, although for starkly different reasons.

7.2 Lime Putty

The primary intent of slaking quicklime to a thick paste, prior to further dilution, as required, once the slake was complete, was to remove inevitable residual lime lumps (Vitruvius 60BC; Alberti 1460; Palladio, 1570; Ware, 1758; Loriot 1769; DelaFaye 1778; Rees 1829; Pasley 1826; Nicholson, 1841; Millar 1897). It was not to 'mature' the material – such 'maturing', if it happens at all, will happen in situ, after placement of the mortar, during the slow progress of carbonation, and in a mortar of greater inherent 'tenacity' for its having been made and used fresh and, ideally, with quicklime fresh from the kiln. The reduction and final removal of residual, unslaked lumps by laying down of lime putty was an early approach, also influenced by the need to preserve lime in good order and before it might begin to air-slake after having been burned to quicklime. In later centuries, the lime would be pressed through a sieve; or even – and very commonly – slaked initially to a dry hydrate, which might be sieved, before being run to a liquid form for use, and which guaranteed the necessary minimum temperature of the slake. It might, on occasion, be held in site lime pits, preserved beneath layers of sand or earth, although primarily for plastering or the bedding of very fine stone ashlar or for plasters and pointing over earthen substrates.

Lime putty was used for the final finish coats of plaster schemes throughout time; it was used on its own as a mortar for the most finely jointed ashlar or brickwork – all uses that would be compromised or rendered inefficient by the presence of even very small residual lime lumps and which did not demand maximum strength. Even so, the laying down was itself generally considered to diminish the binding properties of the lime, and this period was kept to the minimum necessary (Rees 1829). In the UK, at least, this period was rarely more than 2 weeks, and was preferably less time than this. It was a common and perennial assumption that a freshly mixed mortar should be used within a week to avoid diminishment of its 'power' (Neve 1726; Langley 1750; Semple 1750; Dossie 1771; Marshall 1788; Higgins 1780; Hassenfratz 1825; Gwilt 1839; Treussart 1842; Burnell 1857; Walsh 1858; Radford's 1909). However, there were always some who argued that it 'improved' and became 'tougher' for a period of repose, or who preferred to use it that way (Neve 1726). Building accounts routinely demonstrate quicklime, sand and/or earth for mortars being delivered at the same time and, although plasters might often be delivered already mixed, there is only occasional mention of lime pits and as little mention of the laying down of lime, though mortars might be laid down for a few days, being re-tempered before use (see Appendix Five).

An often-drowned lime putty, mixed at a lime: sand proportion with at least half the lime content as is routinely found in historic mortars on analysis (see below), will be much less tenacious than a similarly fat lime mortar from the past, though it may be of similar strength to numerous earth-lime bedding mortars. Its lime-deficiency will cause no immediate damage, but may allow greater water ingress (Malinowsky 2011) and the efficiency of its capillary function may be reduced. It will enjoy a lesser water retentivity, and will be more prone to over-rapid drying, or to the loss of necessary early moisture content to porous building units or existing, lime-rich mortars. It may be too sacrificial. It will exhibit 'free water' in use, which is uncommon in a hot mixed lime mortar (or a traditionally made lime putty) of traditional proportion. It will lack the tenacity of a traditionally proportioned lime mortar, but will display consistency of compressive and flexural strength and a good degree of workability. An NHL mortar will not.

7.3 Dry Hydrated Lime

For general use as a binder, lime slaked to a dry hydrate has as much historic precedence as slaking to a thick paste as a preliminary to hot mixing; for use as a binder after storage or transportation, it has more precedence than lime putty. Smeaton (1775; 1791) preferred to mix dry hydrated lime with pozzolanic aggregates and lime that had to be carried long distances was typically slaked first to a dry hydrate. Dry hydrate was traditionally prepared on site, or at the kilns, by immersion or aspersion, but modern, industrially produced versions – and contrary to prejudice against the use of this material during the 'Lime Revival' - represent a viable, reliable and useful binder option, so long as these are fresh, mixed to traditional lime: sand proportions and are processed in traditional ways – typically being run to a thick paste the day before use, to 'fatten' prior to mixing with aggregates. Dry hydrated lime has a coarser particle size unless extensively beaten, than lime putty of wet-slaked hot mixes. Pre-bagged dry hydrated lime was embraced by many in the early 20thC as avoiding the potential quality and potential late-slaking issues of hot mixed mortars, particularly by architects (Lazell 1915; Searle 1935). Dry hydrates were used extensively across the USA during the first half of the 20thC, with and without cement addition, and have proved durable, as well as having offered good functional behaviour.

7.4 Natural Hydraulic Limes

Le Sage, a French engineer, called for the prohibition of what we now term Natural Hydraulic Limes, as early as 1777, on the grounds of excessive variability and unreliability. Vicat (1818; 1837; 1856) concurred – whilst also calling for the prohibition of fat limes (which he may have confused with earth-lime mortars, in fact), and set about the commercial production of an artificial hydraulic lime, as well as lobbying for the use of the same in above-ground construction, in contradiction of craft practice, which largely continued to ignore his complaints. Treussart (1842) agreed, but doubted the utility of both NHL and Vicat's artificial hydraulic lime for either above ground or underwater construction. He tested all of these and concluded that the most predictable and reliable underwater mortar was made of fat lime and pozzolanic brick dust – a practice that dated back to at least 1000BC, where mortars were used in inherently wet situations (Karkanas and Stratouli 2008; Zacharopoulou G 1998).

The sheer variability of NHLs within and between types had been recognized by many over the centuries, as well as its excessive and impractical demand for long-term, ongoing hydration when used in the air, in the absence of which it would lack tenacity. NHLs might vary dramatically in compressive strength from one batch to another, inviting structural complication across any elevation built with mortars of variable strength. This variability remains the primary issue with NHLs, and even in the 20th century, despite numerous attempts, the inclusion of more than feebly hydraulic lime into building standards proved elusive until the parameters of the standard were drawn so widely (allowing up to three times the strength in any one category after 28 days without breaking the standard) as to be essentially meaningless, and mitigating against informed specification for other than producers. Toes had been dipped into NHL-clouded water on occasion – most especially at the end of the 19th century and into the early 20th century, when the use of Blue Lias NHL, already used increasingly for concretes and for some underwater and underground construction, extended into above-ground construction, particularly for thinner than traditional section brickwork. American engineer Quincy Adams Gillmore (1864), and chemist Edwin Eckel (1932) had both considered the Blue Lias a feebly hydraulic lime of limited usefulness in engineering projects, but, in truth, it could range from feebly to eminently hydraulic, depending from which strata the lime for the burn was extracted (pers comm Holmes). Even so, this extension of its use into above-ground construction was quickly discovered to have been a mistake and was discontinued for the most part before 1945. Its variability from different sources and even within the same source, that made a standard impossible to devise, being regretted by a Post-War RIBA Committee (1946).

As long ago as 1756, when looking for a suitable hydraulic lime for the Eddystone Lighthouse, John Smeaton had observed, as proof of its suitability, that when used for building Bath stone walls in Somerset, the mortar lasted longer than the stones themselves, the latter eroding readily, whilst the mortar joints remained intact. This lesson has been learned a number of times over the centuries, and is being learned again in parts of the UK today. It might be reasonably stated, however, that the first time in history that there was sustained and widespread demand for the use of NHLs 'in the air' was due to practices created by the conservation industry, initially in the UK and Scandinavia, and then, following the lead of particularly John Ashurst and English Heritage, across the world. This phenomenon continues to spread into parts of the world with no historic access to, or tradition of using NHLs for any purpose, such as North America (Canadian Parliament West Block 2015; Calgary City Hall, 2018; generally across the USA) and China (Shi-Bing Dai 2013).

The use of Natural Hydraulic Limes (NHL) and cement-lime mortars in the air has little historic precedence for use in above-ground construction prior to the end of the 19th century, except in circumstances where the only lime available locally, or with convenience, was itself hydraulic. Kirby Muxloe Castle is an exceptional example, where Barrow-on-Soar blue lias lime was used in the 1480s to build a fortified brick complex (Hamilton-Thompson 1920), although Marshall had acknowledged its exceptional 'toughness' in 1790, a reputation which will have commended itself for military construction.

The case that NHL use was never typical for above-ground construction may be extended into the use of NHLs in underwater or unduly wet situations. An hydraulic mortar was commonly and necessarily used in such applications historically, but hot mixed air lime mortars with pozzolanic addition (or an aggregate entirely composed of pozzolanic material) were almost always preferred by craftspeople and engineers for these uses. NHLs were seemingly distrusted due to their variability and unpredictability, which also over-complicated slaking procedures. The evidence in the UK, at least, is that the only purpose for which NHL binders were preferred, was for concretes – for building footings and floors. Moreover, this was only during the 19th century in England and Wales, during which Blue Lias was also imported into the Eastern USA and Canada to be used for similar ends (Fuller and Jones 1859; Gillmore 1881).

The clear picture offered by historic texts, from Vitruvius onwards, is that pozzolanic fat or feebly lime mortars were the norm for below ground and underwater construction. Pure and nearly pure limes were the predominant binders of above-ground construction, supplemented throughout most of building history by the clay content of earth-lime mortars. The use of the latter for masonry construction far outweighs the use of lime: sand mortars in terms of sheer volume and reach, in the UK and Ireland as much as elsewhere before the 19th century (Copsey 2019). Lime: sand mortars were always used, and generally in combination with earth or earth-lime mortars with fat lime finishes, whether for pointing, exterior renders or interior plaster finish-coats, and, of course, as limewashes, but not nearly so much as the primary building mortar, until relatively recently, as has been generally supposed by both academic research and the conservation industry. Earth and earth-lime mortars were the common mortars of masonry construction, whether of stone, brick or, indeed, of earth, across most of the world – across Europe, in China (Shi-Bing Dai 2013) and elsewhere in South-East Asia, as well as across the Americas.

Moreover, a review of historic texts covering the use of lime mortars suggests that the common assumptions of the 'Lime Revival' were based upon 20th-century practice. They lacked significant reference to traditional building practices, except insofar as these were elucidated by Vitruvius, and that readings of his text were heavily influenced by a presumption in favour of 'matured' lime putty having been the primary binder, subsequently mixed cold with aggregates.

The forms of lime used in the 20th century – industrially produced lime hydrates, some of them naturally hydraulic, and putty lime produced by the 'drowning' of quicklime in large volumes of water – had, it is clear, variable and often specific historic precedent.

Arguably site-produced, dry hydrate had more historic precedent than lime putty as a binder, and as a stage in the production of interior plasters and some hydraulic lime mortars for underwater use. Quicklime was made to a thick, dough-like putty throughout time, but for very particular uses, usually employed on its own as a mortar (Langley 1750; Pasley 1826) and rarely as a binder, for which it was generally distrusted and considered weak in its binding properties (Rondelet 1803; Vicat 1818; Rees 1819; Biston 1828; Treussart 1842; Totten 1838; Wright 1845; Gillmore 1864; Radford's 1909; Pulver 1922; Searle 1935).

The general conclusion of this review is unavoidably that many of the proscriptions and 'rules' of the lime revival were precisely that: proscriptions of the lime revival only. It appears to have been based on dubious foundations as regards attention to, awareness or understanding of historic practices and norms as well as upon forms of lime that had minimal precedence historically for the uses to which they were put. Hot mixed lime mortars, earth-lime mortars and lime slaked to a dry hydrate, the most commonly used forms of lime historically, were substantially ignored – even dismissed as inappropriate or in some way 'defective'. The material in this review challenges many of the core beliefs of the lime revival, but necessarily so in the light of historic texts and understandings and the author's (and numerous others') experience using and working with those materials in the context of traditional buildings.

Fundamentally, 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 may enhance tenacity, durabilty and speed of set without compromising workability or other essential characteristics, and may reduce initial shrinkage. This is why hot mixed pure or nearly pure lime mortars, and, before them, earth-lime mortars, were the preferred mortar of craftspeople. In the modern period, we may add to these qualities the fact that they offer high effective porosity, keeping building fabric dry and thermally efficient and reducing the need for repair or replacement of building elements, as well as the fact that in a period of accelerating climate chaos, traditional mortars, as well as traditional patterns of construction, offer more sustainable and much less polluting options for new build, as well as for compatible repair. Traditional pozzolanic mortars often incorporated 'waste' materials from other industrial activity, enhancing the sustainability of such mortars. Hot mixed mortars may be anticipated to last indefinitely in properly detailed buildings and in the absence of artificial decay mechanisms, whilst lean lime putty mortars led to an expected life-span of 25 years or so (though they may perform better than this) and growing evidence would suggest that a similar time-frame may apply to NHL mortars, especially when deployed by inexperienced or expedient hands. The proven longevity of traditional hot mixed, or lime-rich mortars, therefore, would significantly reduce the frequency of essential repair, further enhancing the sustainability of such repair.

By common consent, successful and substantially authentic building conservation relies upon the use of like-for-like and compatible materials. This is most effectively achieved by employing the same, or very similar materials to those used originally, processed in the same or similar ways and used to similar ends (Copsey 2019). It is to be hoped that this MA will contribute to the routine achievement of such success.

The primary limitation of this research beyond the relative adequacy of the author - is the relative geographic narrowness and Euro-centricity of its sources – it is to be hoped that this endeavour may encourage others, wherever they may be, to do similar with the historic resources available to them, to enhance and perhaps develop the story. Asian practice, in particular, is little represented in this account, other than secondhand, via British military engineers, although earth-lime and lime mortars were, of course, as widely used across China and India as they were elsewhere on the Continent. Similarly, the Middle East, repository of so many physical remains of all periods of earth, earth-lime and lime use in human history. Many texts remain to be processed in Spain, elsewhere in Europe and, of course, in Latin America and Africa. The author's suspicion, however, is that regional variations in additives and discreet ingredients apart, the story will be very much the same concerning the basics of lime manipulation, mortar-making and use.

The research posits a provisional base-line which may 're-set' many of the assumptions of the 'Lime Revival' upon which over coming years it will be possible to assemble a more reliable scaffold from which may be constructed a more nuanced and detailed assemblage for specification and practice with traditional mortars, and into which base may be incorporated regional diversity and variation. The foundation, however, must be solid and solidly based.

It is the author's conviction that this research provides sufficient knowledge, as derived from the old texts and more recent research and experience, for any competent and engaged craftsperson (or professional) to develop their own understanding of the primary traditional materials and to use them with confidence and success. Indeed, in the author's own observation over recent years - during which time the he has travelled the UK and beyond speaking to the content and conclusions of this research, demonstrating the mixing techniques discussed and providing people with the opportunity to 'have a go' with these materials - that good craftspeople will take such knowledge and run with it – that experiment and exploration of the possibilities of these materials – often within the local context in which they are used, incorporating regional and diverse ingredients – is the almost inevitable response. The provision of a rational and evidence-led narrative of mortar use – which cuts through the confusion and straightforward myth-making of the Lime Revival, and which is also a narrative of craft practice and of their own craft - delivered by an individual experienced and proficient in the use of these materials – has inspired many individuals not only to embrace traditional materials once more, but to take ownership of them and to actively experiment and develop our common understanding of them.

Much deeper research is required into the role of aggregates and pozzolans and these would represent fruitful avenues for further research – how does the functional performance of a pozzolanic lime mortar compare with that of an air lime and with an NHL mortar? Is there equivalence between an NHL mortar and one of similar hydraulicity made with a fat lime and a pozzolan? Comparative studies might be made between the character and performance of a hot mixed air lime; a lime putty mortar; a hydrated (builder's) lime mortar. Crucially, to be of real usefulness, the current and persistent academic habit of testing lime mortars at a proportion of 1 slaked lime to 3 aggregate, instead of at the historic proportion of 1:2, typically mixed at 1 quicklime to 3, or at 1 quicklime to 2, should cease. If scientific endeavour is to offer genuinely useful data that will inform and elucidate the good sense of traditional building technology and assist in compatible future repair, as well as informing options for a return to sustainable architecture in the face of climate chaos, it needs to respect traditional knowledge, not remain in a bubble the parameters of which are defined by modern materials and modern binder: aggregate proportions. In similar vein, the avenues for useful research into earth-lime mortars are multiple. With a few notable exceptions, research into the properties, character, composition and performance of earth-lime mortars has been minimal. The most common mortar of construction in terms of time-span and geographical reach – if not always in volume – has been almost entirely ignored by conservation and academic communities alike. Of all traditional mortars, these have the richest potential in the context of the shifts necessary to combat the climate emergency. They are long-proven.

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

Much research, therefore, is required to flesh out the real-world performance of traditional materials, mixed to traditional prescription and to traditional proportions, with and without pozzolanic addition.

One of the conclusions of this work is that NHLs have had minimal historic precedence for the uses to which they have been put over recent decades; that they have always been regarded as problematic, not only by masons but by engineers, primarily due to inherent and unavoidable variability, between and within 'brands'. Much work remains to be done in terms of establishing why; in establishing their true demands in use and into understanding their failure to meet up to expectations. How much on-going hydration do they require? For how long? When, actually, do they reach their final strength? Is this ever achieved, and, if so, with what consequence for their effective porosity and general compatibility? How different is an NHL mortar made to traditional, sand-slaking methods from lump lime to a mortar made from high-temperature-fired, ground, pre-slaked and bagged NHL? What are the structural implications of using a material of such routine variability in compressive strength and functional performance? Should expansion joints be introduced into structures new-built with NHL? Should NHLs be used at all for purposes they were rarely, if ever, used for in the past without later ruefulness or regret? What are the implications in terms of long-term performance of gauging air lime and NHLs in the production of mortars? Is this necessary? Is it desirable? Over what time period will these mortars achieve maximum strength? What are the implications of variability of strength of the NHL component? Or of the competition between hydraulic set and carbonation within the curing mortar?

In the case of hot mixed non- and feebly hydraulic lime mortars, research might focus upon the differences in mechanical and functional performance between mortars mixed and placed hot and mortars used after cooling, at the same time exploring the effect of time before such latter use. Similarly, for pozzolanic mortars. Tugce Busra Su is currently researching pozzolanic mortars at the University of Bath, supported by Historic England, the outcomes of which are eagerly awaited. Preliminary work has been done by HE and Lucie Fusarde into the difference in outcomes (porosity, compressive strength, etc) according to mix method – between dry-slaked and 'wet-slaked' hot mixes, compared to mortars made (to traditional proportion) with dry hydrated and with lime putty. Cecilia Pesce is studying the effects of slaking (powdered quicklime) with steam, as well as with hot water, at Northumbria University, again supported by Historic England.

Finally, procurement policies within the conservation sector require wholesale re-evaluation. Very many – indeed most – traditional buildings were built by small companies or by looser associations of independent craftspeople. Very many these days are repaired by large, disparate companies with priorities that frequently militate against best practice and considered workmanship and procurement policies favour the awarding of conservation contracts to such companies, which contracts then proceed according to inadequate and ill-informed specifications which are generally hostile to amendment or change in response to discovered fabric, lest at considerable additional expense. Many such companies employ large gangs of workers in generally exploitative and frequently insecure conditions, once more militating against good workmanship. Most use predominantly 'lowest-price' sub-contract labour in similarly unequal and dis-empowering relationships – ways should be found to successfully cut out the 'middle man' and to engage craftspeople in the design process from the beginning as more equal partners. NHL-use, for example, is preferred by such companies, being (erroneously) seen to require less skill in its application and because it allows for the short-term ignoring of best practice guidelines, many of which are not even known, since the embrace of NHL led to a general suspension of critical thinking within the industry. NHL use has mimicked Portland cement use insofar as poor practice – not wetting substrates, not giving on-going hydration during curing, etc – may be 'got away with' in the short-term; its consequences – wetting of general fabric due to absent bond or due to inadequate actual set within the mortars at depth – becoming evident some time after the completion of a contract and its snagging period, but contributing – like over-lean lime putty mortar use before it - to the general impression that lime 'doesn't last' or causes problems for building fabric. The evidence of recent practice with lime-rich, hot mixed lime mortars has demonstrated that they are easy and efficient in use, that they encourage good craftsmanship and contribute not only to the on-going health of traditional building fabric, but to the good health of its occupants.

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