AGGREGATES FOR LIME MORTARS - THINKING OVER TIME. LITERATURE REVIEW.

It has been the norm in the conservation and lime world over recent decades for the sands used to be sharp but also coarsely so, with what is sold as 'concreting sand' being commonly used. Whilst it has also been the norm to demand 'well-graded' sands, very many available sands are not, in fact, well-graded. 'Well-graded' sands tend to display a bell-curve of particle size, the most dominant particle sizes being 'coarse fine' and 'fine coarse', with smaller volumes of very fine sand and silt and of particularly coarse. such sands are the norm in North America, its building patterns often informed by 17th and 18th C British and European practice. The pattern of using sands with a high proportion of coarse aggregate conflicts with observed aggregate sizes in the majority of traditional building mortars, in which, whilst typically (although not always) sharp, the aggregates tend to be fine. In some regions, coarser aggregates were, indeed, more common, reflecting local geology and access to local aggregates. The general predominance of finer sharp aggregates is so whether the aggregate is sand or limestone or other stone. Also in modern practice, with portland cement or, indeed, with natural hydraulic limes, soft yellow building sand - which is fine, with rounded, mono-sized grains - is common. Bryan Higgins condemned the usefulness of such sand as long ago as 1780. The preference of cement-masons and, indeed, of those using NHL is that such sands will improve the workability of mortars made with binders that deliver poorly workable mortars. Not only sands and stone dusts and loam (a mixture of clay, sand and silt, dominated by particularly fine particles, but ashes and kiln waste from a variety of industrial processes were used as aggregates, often without other addition besides lime; as often as component parts of mortars, delivering feeble pozzolanic reaction in the latter case, and a hydraulic set consistent with the volume of fine, amorphous particles able to combine with and consume twice the weight of free lime to form belite. Before Smeaton established that one third part of the aggregate as pozzolanic material was sufficient to allow such mortars to set underwater (and a 1 pure quicklime: 1 pozzolanic material: 2 sand mortar would lead to the consumption of all of the free lime, if all pozzolan combined with the available lime, mortars for underwater and water-retaining purposes were made with a graded pozzolanic aggregate (such as trass) forming the only aggregate content. Once more, the energy of the hydraulic potential would depend upon the proportion of the pozzolanic material that was fine enough to combine with the lime - much would remain as aggregate. As Smeaton significantly observed in 1756, most pozzolanic aggregates were themselves porous. It has been common in recent decades to place great emphasis upon the sand - and its relative volume to the lime - in terms of the breathability of the mortar. However, it is generally - and lest the aggregate itself is capillary-active, such as a limestone - the case that it is the lime that does the work - the sand added to a level that would not overly compromise performance of the binder - to cheapen the cost of the mortar. Historically - and before the 20thC - sand is not considered to add to the 'breathability' of a mortar and, indeed, to weaken a mortar that made of lime alone - whether fat lime or, indeed, natural hydraulic or natural cement, or even portland cement - would be stronger. The spectre of 'vapour permeability' being considered the definition of 'breathability' lurks behind such thinking about the influence of sands and, indeed, of mortars lean to very lean in binder compared to historic example and practice. Historically, it was commonly considered that the presence of earth or clay in an otherwise lime: sand mortar would compromise its performance - although it was generally acknowledged that 'dirty' sands were frequently used in craft practice and that the presence of some clay would enhance workability. Very few writing about lime gave consideration to the prevalence, until relatively recently, of earth-lime building and plastering mortars. In Thornton Dale, in North Yorkshire, we see - on analysis - masons *adding* clay to an otherwise sand and non-hydraulic lime mortar in the mid-18thC - when 'as dug' earth-lime mortars remained in common use in this region and across the UK. Langley suggests that such 'dirty' pit sand should be reserved for interior myths of brickwork, or interior walls, whilst exterior mortars should be made with the cleanest sharp sand. Clay-bearing subsoil - loam - may, in fact be considered the most commonly used aggregate for lime mortars over most of recorded history, only really falling from use - and variably across the world - from the earlier 19thC onwards, although the use of such mortars for bricklaying - as opposed to lime rich mortars made with lime and sand - had declined somewhat earlier than this. Boynton (1982) was certain that such mortars - as well as lime: sand mortars - enjoyed a very feebly hydraulic potential, the lime and clay reacting with one another to deliver this. Most others deny the possibility of such a reaction. The lime stabilised the clay, reducing its potential to swell and to shrink in wetting and drying cycles, this potential being the primary reason that many objected to its presence at all in an otherwise lime: sand mortar.

As generally in the lime world, there is some confusion and contradiction in modern thinking about aggregates for lime mortars. My own impression is that, although there will be 'optimal' sands and that, wherever locally available these should be preferred, in the case of fat lime-rich, typically hot mixed lime mortars, the reality is (and always was) that 'any sand or other aggregate' will work for most of the general purposes to which traditional mortars were - or should be - put, and that this is among the numerous practical (and pragmatic) reasons that the crafts themselves preferred pure or nearly pure lime and generally preferred to hot mix their mortars.

It would seem a worthwhile endeavour, therefore, to offer a review of writings and opinions about suitable aggregates for lime mortars in the past. Typically, these aggregates would be mixed with freshly slaked lime - sometimes with still slaking lime - at a proportion of 1 part quicklime to 2 or 3 parts aggregate. When pulverised quicklime - as opposed to lump lime - was used, the slaking of the quicklime would take place after initial mixing with this aggregate. With lump lime, the quicklime would be slaked within a ring of the aggregate or in mortar box or a pit and mixed promptly with the sand or other aggregate once it had substantially slaked and whilst still very hot. There is a general consensus that sands should be sharp, free of organic matter and earth (although earth inclusion was seen by some to confer some benefit and, at craft level, because this benefit was mainly in improving workability, adhesion and cohesion, there was probably much less concern about this. In North Yorkshire, and doubtless the length of the limestone belt, the most common aggregate was limestone dust, and, in East Anglia and other chalk geologies, chalk, with lesser volumes of fine sand, or, more often, no sand at all. Whilst 'coarse sharp sand' was commonly called for, it is highly probable (and confirmed by the vast majority of mortar analyses) that the definition of coarse differed from modern definitions, with 2-3mm tending to be the upper limit, when size ranges are mentioned. The majority of lime mortars - none of them deficient - that I have encountered in my practice were composed of fine sand and/or limestone aggregates, with relatively few coarsers grains. Indeed, the largest aggregate particles tend to be residual lime lumps, whether under- or over-burned lime, or, indeed, carbonated lumps of lime that were not fully broken down and remained unmixed at the time of placement. The only aggregate additions that might be comparable are the low level inclusion of brick chips or, indeed, again in the Vale of Pickering, larger grains of iron-rich jurassic sandstone from the North York Moors - both of these acting, like the lime lumps, as porous aggregate inclusions. Most sands were inert and, lest they were sandstone or limestone dusts, minimally porous - the porosity - expressed as the capillarity - of these mortars relied primarily upon the lime/calcium carbonate matrix - hence the desirability of lime richness. Both Wright (1845) and Gillmore (1864) insisted that it was insufficient to simply fill the voids between sand grains with lime, or cements, and that this threshold should be exceeded by adding 50% more binder than was necessary to fill the voids. Both suggested that adding fine sand to coarser sand such that the original volume of the coarser sand alone did not increase (simply reducing the voids between the coarser grains), would allow the use of less lime than if no fine sands were added at all. It would also, of course, reduce the 'resistance' of the mortar. Limestone or chalk aggregated mortars, of course, were ultimately very close to 100% calcium carbonate (oolitic limestones contain the tiny seed of shell fragment or silt around which each ooid was formed, and any sand will remain in the lime as aggregate, as might insoluble clay) and were, therefore, of optimal capillarity throughout. Such mortars, as also pure lime and hair pointing and plaster mortars, as commonly found, especially over earth-lime mortar-built masonry or earthen fabric, have proved remarkably durable and long-lasting, and numerous examples survive across much of rural North Yorkshire, at least.

Sand was not always easy to access. Rivers and the sea shore offered more ready access when known sand-pits were rare. Loam was very commonly used as aggregate in bedding and plastering mortars, with variable volumes of lime addition, the lime augmenting the binding qualities of the clay (a little lime could go a long way, although some earth-lime mortars might mirror lime: sand mortars in lime richness), the remainder of a loam being silt and sand, both reflecting local geology, and so frequently containing limestone aggregate, for example. Current international demand for sand, especially, perhaps, in China, is currently a source of environmental destruction and compromise, much of this sand being gathered from seashores, disrupting coastal environments and patterns of coast-line erosion. Historically, ashes, from iron or other kilns, from house fires and other coal-heavy industrial processes, were much used as aggregates, as, of course, was pulverised brick or tile (surkhi in India) and wood ash, however generated. Such mortars are generally tough and have been durable. In most cases, they have caused few of the problems that have been theorised on the basis of their use. There is currently little knowledge or understanding about how this kiln waste was processed prior to mixing with lime, either with freshly slaked quicklime or with already slaked dry hydrated lime. On the North York Moors, many 19thC aggregates used in buildings associated with the iron working industry during the 19thC were of calcined ironstone waste, which emerged in graded particle sizes. Only the finest ash or calcined ironstone acted pozzolanically, the remainder performing as sharp - and also porous - aggregate.

Road scrapings were commonly used for aggregates, particularly, perhaps, in limestone districts. Marshall noted such use in Gloucestershire in 1796, for example. Marshall observed and recorded craft practices, as well as material use across much of England and Scotland, and was free of 'engineer-think', one might suggest. Higgins (1780) references the frequent use of old mortars as aggregate in London in his time, the old mortars pulverised for re-use, and a combination of sands and calcium carbonate evolved from the original lime of construction.

River sands might frequently enjoy minimal particle size variation, yet such aggregates were often used in mortars that remain entirely fit for purpose centuries after placement, such as in 60 Goodramgate, York (see analysis below).

Vitruvius (30-20 BC) *Ten Books on Architecture*. Translated by Rowland I D; eds Rowland I D & Howe T N (1999) Cambridge University Press.

P36. Chapter 4. Sand for Concrete Masonry

1. In concrete structures one must first enquire into the sand, so that it will be suitable for mixing the mortar and not have any earth mixed in with it...the type that crackles when a few grains are rubbed together in the hand will be the best, for earthy sand will not be rough enough.

(pit sand is the best; river sand next; beach sand the least good, mortars made with it being slow to set up and if used for walls and then plastered, the wall will 'give off salt and dissolve the surface)...

2. Excavated sands, on the other hand, dry quickly in construction, and the plastering stays in place...(but should be freshly quarried) (p37)...But even though newly excavated sands have so many virtues in construction, they are not useful for plaster precisely because in mixing with lime, because of its own density, and with **straw,** it cannot dry without cracks, it is too intense. Although its fine grain makes it useless in construction..., river sand, when flattened down by the action of a plaster float, acquires firmness for plasterwork.

Chapter 5: Lime for Concrete Masonry

1. Now that everything has been clarified about supplies of sand, then we must be careful about our lime, and whether it has been cooked down from limestone or silex (hard limestone). And that which is made from denser and harder stone will be useful in construction, and that made from porous stone, for plaster *[this notion, that the durability of lime was in direct relationship with that of the limestone from which it was made was accepted by all writers on lime hereafter, until Smeaton disproved it. As an idea, it persisted even then]*. **When it has been slaked, then the materials should be mixed so that if we are using excavated sand, three parts of sand and one of lime should be poured together.** *[Is this proportioned before slaking – when mixed by the 'ordinary' methods, this would be so, as Pasley insists it always should be, in 1826]*. If, on

the other hand, it is river or sea sand, **two parts of sand** should be thrown in with one of lime. In this way the rate of mixture will be properly calibrated. Furthermore, if one is using river or sea sand, then **potsherds**, **pounded and sifted,** and added to the mixture as a **third part,** will make the composition of the mortar better to use.

Chapter 6: Pozzalana for Concrete Masonry.

1. There is also a type of powder that brings about marvellous things naturally. It occurs in the region of Baiae and in the countryside that belongs to the towns around Mount Vesuvius. Mixed with lime and rubble, it lends strength to all the other sorts of construction, but in addition, when moles (employing this powder) are built into the sea, they solidify underwater. (Supposes this effect due to their having been affected by 'huge fires' beneath)...Hence, when these three ingredients (lime, fired rubble and pozzalana), forged in similar fashion by fire's intensity, **meet in a single mixture, when this mixture is put into contact with water, the ingredients cling together as one and , stiffened by water, quickly solidify.** Neither waves nor the force of water can dissolve them. *{Once again, this reads as a description of hot mixing of lime concrete, with brick aggregate and pozzalanic sands].*

….**4.** [In building with pozzalana underwater] unlike and unequal entities that have been forcibly separated **are brought together all at once.** Then the moisture-starved heat latent in these types of ingredients, **when satiated by water, boils together, and makes them combine. (38)**

Chapter 4 Plasterwork in Damp Locations.

...For rooms on ground level, instead of sand mortar, terracotta sherds should be rough plastered and applied up to a height of three feet above pavement level, so that these parts of the plaster will not be damaged by moisture.

(If constantly damp, then a cavity wall should be built with a drainage channel at its base and weep holes to the outside and ventilation holes higher up.)...

Then the walls should be whitewashed with lime dissolved in water, so that they will not reject the terracotta rough plastering, for because of the dryness induced in the tiles by baking them in the furnace, they cannot absorb the rough plastering nor hold it in place unless the addition of (p91) lime glues each component together and forces them to join. Once the rough plastering has been laid on, with broken terracotta in place of sand, then everything else should be completed as has already been described in the instructions for plastering.

De L'Orme P. (1567) Le premier tome de l'architecture (The first book of architecture) Paris. Frederic Morel. Translated by Emma Michel 2018.

We say the best stone to make mortars is the hardest, because it is fattier and more glutinous. Mortars made from marble or stones similar in nature are wonderfully good. **So that when used hot, as straight out of the kiln, and mixed with small gravel and sharp river sand which carries other small gravel, (the lime)adheresand thickens (*conglutiner = the idea of a liquid becoming viscous*) very well with time, such that the whole becomes a rock, a mass of a single piece...**You would admit that the best lime is the heaviest and when hit, it sounds like a earth pot well burnt.

….As for the sand, we need good supply, whether to preserve the lime or to mix with it to make a mortar....I would like to advise that sands have different natures, and different qualities: some sands mix better with lime than others. Some are so fat that it needs five parts, even seven, for one part of lime. **Some can be mixed with two or three parts and some are so bad that they need as much lime as sand**. Some sands are good and adequate for walls above ground, others for underground work; some for plasters, some to make cement or to be used as real cement along with a pozzolan - a black sand used in Rome - which has the nature of a true cement.

Consider Pliny's work about the diversity of earths, the sand of Putzuoli and of several sorts of earths which harden like stone. The best sand in this country (France) and in other places is pit sand...because it is taken from the middle of a field inland, much better than that from rivers, and makes a noise when handled due to sharp grains like little rocks, which is the reason it makes a good mortar.

[...] Sands have various colours, white, yellow, red and black. You will know their quality when they are wet as they do not soil a sheet as mud does and do not dirty the hands as bad sands do. Have a look at Vitruve's writings on the subject.

Palladio A The Four Books of Architecture (1570) (Ware translation, 1738). Dover Press.

Chap. IV Of Sand

There are three sorts of sand commonly found: pit, river and sea sand. The best of all is pit sand, and is either black, white, red or ash-coloured, which last is a kind of earth calcined by sunterranean fires pent up in the mountains, and taken out of pits in Tuscany.

They also dig out of the earth in Terra di Lavoro...a sort of sand called Pozzolana by Vitruvius, which immediately cements in the water, and makes buildings very strong...The best river sand is that which is found in rapid streams, and under water-falls, because it is the most purged. Sea-sand, although the worst, ought to be of a blackish colour, and shine like glass; that which is large-grained and nearest to the shore is best. Pit sand, being fattest, makes, for that reason, the most tenacious cement, and is therefore employed in walls and long vaults; but it is apt to crack.

River sand is very fit for covering and rough-casting of walls. Sea sand soon wets and soon dries, and wastes by reason of its salt, which makes it very unfit to sustain any considerable weight.

Every kind of sand will be good that feels crisp when handled, and, if laid upon white clothes, will neither stain or leave earth behind it. But that sand is bad, which, being mix'd with water, makes it turbid and dirty…

Moxon (1703) Mechanic Exercises or the Doctrine of Handy-Works etc. London. Midwinter & Leigh.

Of Lime

There are two sorts, one made of stone, which is the strongest, and the other of Chalk, both sorts being burnt in a kiln *(Moxon here takes his lead from Vitruvius, who asserted that the harder the limestone, the tougher would be the mortar made of it, and writes before Smeaton demonstrated that chalk lime little different from stone lime - lest the stone itself contained clay or other forms of silica).*
The lime that is made of soft stone or chalk is useful for plastering of seedlings and walls within doors, or on the inside of houses; and that made of hard stone, is fit for structures or buildings, and plastering without doors, or in the outside of buildings that lie in the weather; and that which is made of greasy clammy

stone, is stronger than that made of lean poor stone; and that which is made of spongy stone is lighter than that made of firm and close stone….
And the fire in lime burnt, assuages not, but lies hid, so that it appears to be cold, but water excites it again, whereby it slacks and falls to a fine powder….

Lime mixed with sand is much used in buildings; and Vitruvius says that you may put three parts of sand that is digged (or pit sand) and one part of lime to make mortar; but if the sand be taken out of a river, or out of the sea, then two parts thereof and one of lime; as also to river or sea-sand, if you put a third part of powder of tiles or bricks…it works better. **But Vitruvius, his proportion of sand seems too much, altho' he should mean the lime before it is slacked; for one bushel of lime before it is slacked will be five pecks after tis slacked. Here at London, where for the most part our lime is made of chalk, we put about 36 bushels of pit sand, to 25 bushels of quicklime (244), that is about one bushel and half of sand, to one bushel of lime.** And lime mixt with sand, and made into mortar, if it lye in an heap two or three years before tis used, it will be the stronger and better…Moreover, there is a mortar used in making water-courses, cisterns, fish-ponds etc which is very hard and durable…which is called Maltha, from a kind of bitumen dug there (Rome); for as they build most walls thereof naturally (doubtful), so they use it in making of cisterns to hold water, and all manner of waterworks, and also in finishing or plastering of fronts to represent stone.
And I find two kinds of artifices used by the antients, both of which are compounded of lime and hog's grease, but to one is added the juice of figs, and to the other liquid pitch; and the lumps of lime are first wet or slacked with wine, then pounded or beat with hogs grease, and juice of figs, or with the same pitch…that which is plastered with this Terrace, is done over with linseed oil. (243)

….Whereas (bricklayers) make use of the sharpest sand they can get (that being best) for mortar, (244) to lay bricks or tiles in; so they chose a fat loamy or greasy sand for inside plastering, by reason it sticks together, and is no is subject to fall asunder when they lay it in feelings or walls (245)

Neve R (1726) The City and Country Purchaser and Builder's Dictionary.

(The use of sand) in Architecture is for making of Mortar. For this end, there are three sorts of Sand:

1 *Kinds of Sand.* Pit sand, river sand, and sea sand: Pit sand is inferior to river sand, because it is not purged; but of all pit sand, that which is whitest, is by long experience found to be the worst. Of all river sand, that which is found in

the falls of water is the best, because it is the most purged. The sea sand is the worst of all *(and perhaps the most commonly used in coastal regions. It also contains a lot of broken sea-shell, calcium carbonate).* The pit sand, because it is fat and tough, is used in walls and vaults. The river sand is very good for rough-casting of walls.

All sand is good in its kind, if, being squeezed and handled, it crackles; and if being put upon a white cloth, it neither stains nor makes it foul. The sand is bad, which mingled with water, makes it dirty and muddy, (262) and which has been a long time in the air, because it will retain much earth and rotten humour. And therefore some masons will wash their sand before they use it. (263)

Langley B (1750) The London Prices of Bricklayers Materials and Works, both of New Buildings and Repairs. London. Richard Adams and John Wren. Second Edition.

Sect. IV Of Sands

The kinds of sands used for buildings on London, are generally either Pit Sand or Thames Sand; unless by jobbing Bricklayers, who often use Glass Grinders Sand, after being done with by the Grinders.

Pit sand is generally either mixi with a small quantity of Loam, or entirely of a sharp grit. That which is mixi with loam requires less lime than the other, but then tis only fit for Inside Works. (31)

If the Various Kinds of CEMENTS, or MORTARS, used in buildings.

The several Kinds of Mortar used in Buildings are eight, viz

1 Inside and outside mortar, made of Lime and Sand

2 Terrace (trass) mortar, made of Lime and Terrace

3 Brick-dust mortar, made of red stock brick-dust and Lime

4 Bastard Terrace, made of Smith's 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 (32)

7 Plaister mortar, made of calcined Alabaster

8 Fine Mortar, called Putty, for rubbed and gaged works, made of lime only. (33)

1 Of Inside Mortar.

Inside mortar is used for vaulting, foundations, Partition and Party walls, insides of fronts, and other parts, which are hid from the eye and not exposed to the weather.

This kind of mortar is generally made with Pit Sand, which requires more or less Lime, as it abounds more or less with Loamy particles ; and therefore when Pit-sand is of a loamy fat nature, to 1 load (viz 24 heaped bushels) put 1 Hundred of lime; but when it is a clean sharp grit, as Thames sand, then to 1 load of sand put 1 1/2 Hundred of lime, which mix up together as the lime is slacked in small quantities. (33)

II of the Outside Mortar

Outside mortar for fronts, tiling etc exposed to the weather, should be made with the sharpest grit sand that can be had, as being best able to withstand the insults of rain etc, which loamy sand cannot so well do. The proportion that the lime should have to the sand is as 2 is to 1, viz 2 heaped bushels of unslaked lime to 1 (bushel) of sand….(37)

III Terrace Mortar. Is chiefly used in walls exposed to water, as to rivers, ponds, cisterns, bog-houses, cold baths etc.

The best Terrace mortar is made with two bushels etc of hot Lime and one bushel etc of Terrace, well incorporated by beating. And which quantity to beat well, is a good day's work for a labourer. (40)…

Bricklayers also sell Terrace dry, mixt with slacked lime, made ready for beating, which must be done near to the work where tis used, because of its setting very quick; which it will always do if tis good and well beaten, and therefore must be instantly used in small quantities as tis beat. In the beating of Terrace, great care should be taken not to over-wet it, but to beat it as stiff as can be, and the oftener tis beat, the stronger it is. (42)

IV Of Brick-dust Mortar.

This kind of mortar is exceeding good, and in some cases is better than Terrace mortar; for unless Terrace mortar is always wet, tis not better than common mortar made of lime and sand.

This kind of mortar is thus made, viz

To two heap'd bushels of hot Lime, put one heap'd bushel of Brick-dust made from red stock bricks, which mix, beat and work up, as before directed for Terrace. (43)

This is an excellent mortar for to lay Tiles or ten inch Tile Pavements in, on Floors which are naturally wet or damp; and for brick pavement and tiling, unless for glazed tiles, and then in the stead of brick-dust tis best to use Sea-coal ashes, with some unburnt small sea-coal dust mixi, in the stead of brick-dust. (44)

V Of Sea-coal Mortar, called Bastard Terrace.

This is also an exceeding good mortar for to lay the coping of walls in, for to point glazed pantiling, for to lay slating, Purbeck and Portland Pavement etc in; and many other uses, where the rains are required to be kept out.

This mortar is thus made, viz

To 3 heap'd pecks of a Smith's forge sea-coal ashes…intermix'd with the iron flakes, put 1 heap'd peck of unburnt sea-coal dust, and two heap'd bushels of hot slacked lime; which incorporate by beating, as before said of Terrace mortar, and use it up as tis beat. (45)

VI Of Pargetting Mortar

This kind of mortar is chiefly used for to plaister the insides of the funnels of chimneys, and is also very good for to point common Pan-tiling etc and is thus made:

To 1 heaped bushel of fine screened clear Lime as about a 4th part of fresh horse-dung, clear from dirt and straw; which incorporate the lime by well beating it, as is said of Terrace mortar. (46)

VII Of Furnace or Fire Mortar.

This mortar is made either of Woolwich Loam or of Windsor Loam, viz loam brought from Woolwich in Kent or from the Brick Kiln at Jerrard's Cross, by way of Windsor.

Both these kinds of loam endure very great heats before they will vitrify.

The manner of making them into mortar is to well chaff and beat them, as outside common mortar is done, and of such a consistency as to work easy. (47)

Of Plaister Mortar.

Plaister prepared (vulgarly called plaister of Paris) when mixi with water, becomes a mortar or cement, that sets very soon and hard; and by Bricklayers is used for setting of Galley Tiles in the copings of chimneys, cold baths, pastries etc. And as common lime is made of chalk calcined, so plaister is made of Alabaster-stone or Talk calcined and pulverised; or first pulverised in the raw stone, and calcined afterwards in a Boiler. (47)

To calcine alabaster-stone, and to make plaister commonly called plaister of Paris:

Beat the stones to pieces, about the size of a hen's egg; then burn or bake it, until the shining quality within each piece (which is easily known by breaking some of them) be entirely gone, and they appear entirely white within, like chalk; then beat it on a flat Purbeck stone, enclosed within a frame, about 3 feet square, and sift it through a fine wire or lawn sieve into a tub for use.

To boil raw Plaister pulverised:

The raw alabaster being pulverised etc…and having an iron boiler fixed up in manner of a small washing copper, that will contain about 6, 8 gallons; fill it about half full, and having a good fire under it, keep it constantly stirring up from the bottom (where it will endeavour to coagulate or thicken) until the humidity of the pulverised stone is entirely evaporated, when it will boil, and may be stirred (which must be constantly done) with the same ease as so much water….(48) When the pulverised stone will no longer boil, but subsides, and becomes so heavy and compact, as not to be easily stirred, then tis done, and must be taken out with an iron ladle and put into tubs, and when cold, into brown paper bags, and kept dry and close from the air, for use. (49)…

(Alabaster) is sold wholesale in the stone by the Gainsborough Merchant-men, who bring it as ballast to London, at about 30s per tun, delivered at any part of the Town. (49)

1754 Contract of Agreement for Building an Exchange in the City of Edinburgh between the Magistrates and Edinburgh Town Council and the Tradesmen. Edinburgh Hamilton Balfour and Neill

Particularly touching the mason work, That all the foundations shall be so digged as to make them proper and safe for building upon, in order to prevent crevasses and rents in the walls, and that the walls to be built...and the whole work in the foundations shall be laid with out and in-band large flat bedded stones packed in a sufficient manner, and with **good mortar made of lime mixed, and made up with sea-sand** ...and as to the other parts of the said rubble-work, the bed of every stone shall be at least two inches broader than it is high, and in every other course the end of the stone shall be turned to the face of the wall, and the length of the stone shall be turned in through the wall: all which shall be sufficiently **bedded, grouted and filled up with mortar of lime and sea-sand, and the rubble walls shall be harled as they are carried up...**

(Paving in Piazza to be laid upon) a bed of till, at least six inches thick, over the whole vaults, composed of clay, lime and smiddy-culm, well and proportionally mixed and ramm'd, and the joints of the pavement, which is to be laid upon this till, to be secured with pan-cratch or terras sufficiently beat and prepared... (paving inside shops and kitchens) bedded in lime to prevent shifting...

Dossie R (1764) **The Handmaid to the Arts Vol 2** Second Edition, with considerable Additions and Improvements.London. J. Nourse,

Where a great quantity of cement is wanted for coarser uses, the coal-ash mortar (or Welsh tarras, as it is called) is the cheapest and best, and will hold extremely well, not only where it is constantly kept wet or dry, but even where it is sometimes dry and at others wet; but where it is liable to be exposed to wet and frost, this cement should, at its being laid on, be suffered to dry thoroughly before any moisture have access to it; and, in that case, it will likewise be a great improvement to temper it with the blood of any beast.
This mortar of Welsh tarras must be formed of one part lime and two parts of well-sifted coal-ashes, and they must be thoroughly mixt *(*P33) by being beaten together; for, on the perfect commixture of the ingredients, the goodness of the composition depends *[the coal will be anthracite, later to be preferred for burning hydraulic limes].* Where the cement is to remain continually under water, the true tarras is commonly used, and will very well answer the purpose.

Smeaton J (1775) Directions for preparing, making, and using Pozzelana Mortar, by John Smeaton, Engineer, in Reports of the Late J Smeaton FRS, made on various occasions in the course of his employment as a civil engineer, Vol II. 2nd Edition, Taylor, London 1837.

Pp421-423. The first thing that should be done, is to sift it through a coarse wire sieve, separating what will pass through the sieve from what will not, and then to sift what has passed through the first sieve through one of a finer sort. A wire sieve having about seven or eight meshes per inch running, will be of sufficient fineness, and all that will pass the second sieve will be fit for use; what will not pass the second sieve must be reserved for grinding, and what would not pass the first sieve must be broken to a size conformable to what would not pass the second, and then all ground together; but, in breaking the large that would not pass the first sieve, it will be proper to pick out a kind of gray stony matter, as well as other heterogeneous substances that get accidentally mixed therewith, and which will readily discover them selves from the true pozzelana, and which have no cementing quality, and render it more difficult to grind.

The true pozzelana is of a dark brown or dirty red colour, and the larger pieces being broken will readily discover themselves, especially with an ordinary magnifying glass, to be of a spongy substance, with innumerable little cavities, like a cinder, and not much harder. That part of it requiring grinding must first be got perfectly dry, either by the sun or by a drying kiln, otherwise it is apt to clog the mill-stones, and it is done by far the most completely by grinding it upon a pair of corn mill-stones, which will at one operation reduce it to a proper fineness without need of further sifting; French stones answer the purpose best, for, though it may be done by other kinds of mill stones, yet, being mixed with flinty matter, which cannot readily be picked out, no other kind of stones will stand the service, if wanted in any considerable quantity. The millers, however, are not very desirous of meddling with it, on account of its spoiling the colour of their stones. I have, therefore, in the larger kind of works that I have been concerned in, found it worth while to construct a mill on purpose, to go by water, wind, or horse, according to convenience.

In making mortar of it, it must be mixed with lime **in much the same manner and proportion that terras mortar is made**: it must be observed that the better and stronger the lime is, the better and stronger the cement will be; but, like terras, it may be used with any lime, and in making comparative trials with terras**, the same sort of lime should be used with both.**

The best kind of lime for water-works that I know of, is from Watchet, in Somersetshire, Aberthaw, in South Wales, and Barrow, in Leicestershire; and the strongest composition I know, is made **by an equal quantity of lime, striked measure in the dry powder, after being slaked and sifted, and of pozzelana**, ground and prepared as above, and, if put together with as little water as may be, and beaten till it comes to a tough consistence, like paste, it then may be immediately used; but if suffered to set, and it be afterwards beaten up a second time to a considerable degree of toughness as before, using a little moisture, if necessary, **it will set harder, but not so quick.** This composition is of excellent use in jointing the stones that form the lodgment for the heels of dock-gates and sluices, with their thresholds, &c. when of stone.

A second kind of mortar is made by using the same proportion of ingredients as terras mortar, that is, **two measures of lime to one of pozzelana beaten up in the same manner, and which, if used with common lime, will fully answer for the faces of walls either stone or brick that are exposed to water, either continually, or subject to be wet and dry**; in which last case the pozzelana greatly exceeds the terras, as also in its lying quiet in the joints as the trowel has left them, without growing as terras does.

As a piece of economy, I have found that if the mortar last mentioned is beaten up with a quantity of good sharp sand, it nowise impairs its durability, and increases the quantity. The quantity of sand to be added depends upon the quality of the lime, and is thus determined: if to the pozzelana considered as mortar, you add as much real sand as will make out the whole quantity, such as an experienced work man would allow to his lime to make good common mortar, this will shew the quantity to be added, that is, may be originally beaten up together; thus, if the lime is of such quality as to take two measures of sand to one of lime, then one measure of pozzelana and three measures of sand will satisfy two measures of lime.
The compositions above mentioned, are seldom used further than for six inches within the face of the stone, or, at most, for setting the stones and the bricks forming the face of the work, while the backing is wholly done with common mortar, and which, under water, never comes to the hardness and consistence of stone, or forms that bond of union which would arise from a stony hardness; I have therefore, found it preferable, where pozzelana can be had in plenty, to allow one bushel of pozzelana to eight bushels of the lime composing the mortar for backing. The first composition will assuredly acquire the hardness of stone under water, and in twelve months will be as hard as Portland.

The hardening of the second and third depends greatly upon the quality of the lime, as also that of the fourth; yet there is scarcely any lime with which the materials, well beaten up, in the proportion specified, will not acquire a very competent degree of hardness under water.

Austhorpe, 23d September, 1775. J. SMEATON.

Higgins B (1780) Experiments and Observations made with the view of improving the art of composing and applying Calcareous Cements and of Preparing Quicklime. London. Cadell.

P86 I next endeavoured to ascertain the mixture of coarse and fine sand, (which most reduces the voids, therefore requiring less lime to fill these and) promises to make the hardest and most durable cement.

Series of experiments with different sands in combination

P90 The mixtures of rubble and mixed in any proportion greater than 5:1 were not fat enough, when fresh, to be conveniently used in building or stuccoing...Those which had the smaller quantities of lime in them were very rough on the surface, coarse in the grain, spongey and easily broken...those which contained more lime were not so bad in these respects. 1:5 optimum with 'rubble'.

P92 I was persuaded that a better cement can be composed with such sand as I call fine, than with a coarser sand whose grains are all larger than all those in my fine sand...

p93 Of the specimens made with rubble and fine sand, that was the best in which the fine sand was twice the quantity of the rubble...(but did not seem better than those made with fine sand alone)

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 (p94) they grew so hard, in the course of 9 or 10 months, as to resist the chisel... (the best mortar he had made or tested).

...In stuccoing walls, the rubble promised to be useful in pointing and in the first coat; because a roughness of this coat makes the finer exterior coat adhere more firmly.

(Experiments with fine 'house sand' commonly used in London and much finer than the sharp fine Thames sand).

Mortar containing the quantity of lime necessary to the plasticity and other desirable properties of it, or a greater quantity of lime, is the more liable to crack in drying, as the sand if it is finer.

Mortar made with this finest sand and lime does not grow so hard, or resist fracture so forcibly, as that made with my fine Thames sand and lime. ...

P99 Mortar composed of lime, my fine (but sharp) Thames sand and the finest sand is the worse as the quantity of finest sand is greater...

(Notes that the roundness of the grains of the finest sand is the problem). P109

In great cities, where gravel cannot be procured so cheap as the rubbish of old walls, which the workmen lay in the streets to be ground to powder by the passing carriages, they use this rubbish screened, in the place of sand or gravel, in making mortar. It consists of the gross powder of bricks, and of mortar indurated, as much as bad mortar can be, by time; and some builders affirm that it is (p110) better than sand or gravel for mortar. It is certainly eligible when the price is chiefly considered; in any other view, it is not so.

(So, made some trials....)

I found that less lime was required to make fat lime mortar with this ground rubbish, than with my best mixtures of sand...but the mortar made with this rubbish appeared in every stage of induration, and in every comparison except that of the plasticity, to be greatly inferior to that made with mixed sand and lime in the same proportions.

If the workmen would confine their opinion to the comparison of such rubbish mortar (p111) with that in which clayey gravel is used, or with the cements made with the ashes and ordure of the town, dug out in preparing foundations for houses...they might maintain it on divers grounds...but otherwise it is erroneous.

p117 To guard a recent incrustation from the rain, and to secure it from cracking...I proposed **the expedient of hanging sail cloth on the cornices and scaffolding**; but the expense of this measure, and the danger of it in windy weather, are strong objections.

p124 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.

Experiments shewing the Effects of common Wood-ashes, calcined or purer Wood-ashes, elixated Ashes, Charcoal Powder, Sea Coal-ashes, and powdered Coak, in Mortar...

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.

P164. 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.

p168

From these experiments, I conclude that...these powders are eligible in this order: elixated wood-ashes freed from the finest powder in washing, first; powdered coak or sea-coal cinders, next; charcoal powder next; rough wood ashes powdered, last.

Semple G (1780) A Treatise on Building in Water in Two Parts. Second Edition. London Longman

I HAVE from my Childhood, been well acquainted with the Nature of Lime and Sand made in Mortar, of all sorts, that have been used in Buildings in these

Countries, and tried numerous Experiments with them; on which, together with what I have observed and learned from old experienced Workmen, during the Course of upwards of sixty Years, I think, I can safely affirm, that good Mortar, that is, Mortar made of **pure and well-burnt Limestone**, and properly made up with sharp, clean Sand, free from any sort of Earth, Loam or Mud, will within some considerable Time actually petrify, and as it were, turn to the Consistence of a Stone. I remember I had one of my Remarks from an old Scotch Mason, which I shall give you in his own identical Words, that is,

"When a hundred Years are past and gane.
Then gude Mortar is grown to a Stain (or a Stone.)"

Marshall W (1789) The Rural Economy of Gloucestershire; Including Its Dairy: Together with the Dairy Management of North Wiltshire; and the Management of Orchards and Fruit Liquor, in Herefordshire, Volume 1. Gloucester. R. Raikes

The Cotswolds.

CEMENT. Lime is excessively dear; and sand not to be had, I believe, at any price; nevertheless, an excellent mortar is here prepared, at a moderate expense. Invention is seldom more successful, than when necessity prompts it.

The scrapings of the public roads; namely, levitated lime stone, impregnated more or less with the dung and urine of the animals travelling upon them, are found to be an excellent basis for cement. For ordinary walls, the scrapings alone are frequently used. And, from what I can learn, the proportion, for the best building, is not more than one part lime to three of scrapings. Nevertheless, I found mortar, which had not lain in the walls more than ten years, of a stone-like tenacity: much firmer than the ordinary stone of this country: probably much harder, than either of the stones, from which the basis of the lime was made. Similar scrapings might be collected, in any district where limestone is used as a material of roads.

The method of PREPARING this CEMENT is, simply, that of collecting the road-scrapings, slaking the lime, mixing them intimately together, and, as the mass is worked over, carefully picking out the stones or other foulness, which may have been collected. This, for stonework, is found sufficient: for brickwork, however, it might be necessary, that the materials should pass through a skreen or sieve; previously to their being made up.

Rondelet (1803) Theoretical and Practical Treatise on the Art of Building.

Most authors who have written on the art of building since Vitruvius have copied what he said on sand. Most of them confirm what he said, such as Leon-Baptiste, Alberti, Palladio, Daniel Barbaro, Philibert Delorme, Scamozzi, Savot, the great Blondel. They think the sand found when digging - pit-sand - is usually the best to make mortar with, especially when it is used freshly extracted, because it loses its quality after long exposure to the air. There are others, however, such as Bullet and Belidor, who think river sand is better and according to the second Blondel and Patte, they think the most arid sand is the most preferable. Belidor even says, against everyone else's opinion, that the colour of the sand has nothing to do with its good or bad quality and that white sand can be used the more safely because it is naturally the one with the least earth.

Wishing to possess more certain notions on this important topic, I tried with the same lime, several different types of sand, cements, stone dusts, and pozzolans. The results were : 1°the sands purely vitreous or quartz form with three lime, a mortar less hard than the mixed sands, and this mortar takes longer to dry out. 2° the dug sand produces a better mortar than the one made from a river sand of about the same grain. Some of the dug sand can make a mortar as hard as cement. I also experimented and found out that arid (dried) sand does not make the best mortar and we must prefer, of that type, the sand of the darkest colour, except for the yellows. The best ones are the ones between the sands too fat and the ones too dry.

[...]. Mortar made with a too fine a sand does not acquire the consistency of the one made with a moderately coarse sand.

Of all what has been said about sands, we cannot, however, conclude that the pit sands are (always) the best because, as Alberti correctly observed, it is not the location from which the sand acquires its goodness, but from the quality of the elements of which it is composed. [...].

Thus, the most reasonable conclusion would be to examine the sands independent of their locations but if they appear to be of the same quality, the ones from digging are preferred for masonry to the ones from rivers, but the latter has always to be used for renders, according to Vitruvius.

Malcolm J (1805), Land Surveyor to their Royal Highnesses the Prince of Wales, and the Dukes of York and Clarence.
A Compendium if Modern Husbandry, Principally Written During a Survey of Surrey. London.

Mortar is made simply by working sand or other bodies insoluble in water, together with slaked lime, and is used for the purpose of joining bricks or stone together. The sorts of sand generally used are pit sand, river sand, and road sand. The former is almost always altered by admixtures of vegetables and calcareous earth, which weaken its efficacy; the second is purer and better suited for the purpose; and the last being generally the fragments of pulverized flints, or the gravel of flints, is by much the best. The angles which these fragments present, and the roughness of their surface, contribute to give a consistence to the mortar. The hardening of mortar appears to be merely the progressive regeneration of limestone.

Rees A (1819) The Cyclopedia or Universal Dictionary of Arts Sciences and Literature. Vol 29.

It is remarked, that the powder of lime, when reduced by means of water into a thin or fluid sort of paste-like form, and then suffered to become dry, concretes into a coherent mass, which fixes to stones and other rough bodies in a very firm manner, and in this way becomes a proper cement for building any sort of walls. And that, after this pasty material has once become firmly dry, it is quite indissoluble in water, and incapable of ever being softened again by the moisture of the atmosphere or other similar causes.

Hence it excels many other sorts of cements. When composed for the purpose of building walls, &c. it is usually denominated mortar; but when formed as an application in the way of a smooth coating upon any plain surface without intermixture with stony matters, it is commonly here termed plaster. _

When made from the lime of the purer sort of lime-stone, it is found to be more soft and crumbly, and to acquire a less degree of hardness, and to be broken with much less force, than where the lime-stone from which it is made contains a large proportion of sand, in which case it becomes much more hard, firm, and durable.

It has, however, been discovered that the purest lime may be rendered a firm cement by adding a proper proportion of clean hard sand to it; **hence the**

practice of blending sand with lime, when intended for mortar, has become so universal *(Which is to say that lime was previously used extensively without sand).*

Martin M E (1829) The Art of the Mason L'encyclopédie populaire ou les sciences, les arts et les métiers, Paris, Audot éditeur.

Qualities and use of sand

When we use the term 'common sand', we mean siliceous sand, with the grains more or less big, but completely cleaned of earthy elements, and which could be washed with a great amount of water without really changing the colour of this water. (P43) We frequently see this type of sand in rivers or in the ground. We choose sand with rough and angular grains, as it binds better with the lime and we sieve it when it contains larger gravel. Sand of this type is excellent for most constructions. **However, when the limes are very fat, we prefer a sand containing clay….**

Ordinary mortar is of better quality when we replace one part of the sand with fragments of tile or powdered pottery. This is only if it is a fat lime; if it was hydraulic lime, any such addition would seem pointless.

In Africa, we sometimes use a cement made of one part of sand, 2 parts of ashes and 3 parts of quicklime, sieved together, mixed and kneaded with water 3 consecutive times and wetted alternatively with linseed oil and water. This cement acquires a particular hardness.

Hydraulic mortars, or concretes, are made from fat limes and pulverised pozzolan or, in the absence of it, sandstones, slates or burnt, pulverised clays, or simply from coal ashes.
Hydraulic limes do not need to be mixed with common sand to produce good concretes. [...].

We prepare a cheap cement mortar by kneading 2 parts of lime, 1 part of coal *(houille),* well sieved and half a part of clay. This mortar is damped slowly and well stirred. Then it is left in a heap for several days after which it is beaten and stretched; it is then left to rest once more until it is flexible and pliable. This mortar can be used to create floors in attics. We apply it by layer, and when it is almost dry, we cover it in a light coat of good quicklime mixed in butter milk.

Vicat L J (1837) Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural. Translated by Capt JT Smith, Madras Engineers. London. John Weale. Donhead Reprint 1997.

...One thing which we know to be quite certain, and which we ought never to lose sight of, is this – **that there is no sand whatever, be it red or yellow, grey or white, with round grains or angular ones, etc, which can, if it be inert, form a good mortar with rich lime.** Whilst, on the other hand, **all possible kinds of sand,** provided they be pure, that their grains be hard, and do not exceed a certain size, **give excellent mortars with the hydraulic and eminently hydraulic limes. (86) (***Vicat lays his cards on the table here)*.

Influence of the size of sand

P87
211. (best sands) for the eminently hydraulic, and simply hydraulic: 1st. fine sand; 2nd. Irregular-grained sand, resulting from the mixture of coarse and fine; 3rd. coarse sand.

P88
212. For the slightly hydraulic limes: 1st. irregular-grained sand, mixed as above; 2nd. Fine sand; 3rd. coarse sand.
For rich limes, 1st. coarse sand; 2nd mixed sand; 3rd. fine sand.

213. (depending on the sand, the hardness of the mortars differs by 1/5 for the rich limes; but by more than 1/3 for hydraulic and eminently hydraulic.

Davy C (1839) The Architect, Engineer and Operative Builder's Manual. London. John Williams.

Opal, pumice, obsidian and pitch-stone, simply pulverised, form a good cement with hydrate of lime, while quartz and sand only produce an hydrated silicate upon the surface of each grain. Although the mass is thus connected, it does not readily become solid. If the quartz has been reduced to a fine powder, the more solid will the mass become. (158)

The greater the number of specifications prepared by surveyors for the erection of buildings, direct that the mortar shall be composed of stone-lime and sharp river sand, to be mixed in the proportions of one part of lime (quicklime) to three parts of sand. These proportions will make excellent mortar if properly compounded; but, as the quality of the lime varies considerably, so will it take more or less sand. (158)

Nicholson P (1841) Practical Masonry, Bricklaying and Plastering. London. Thomas Kelly.

57. Sand.—To employ lime alone in the composition of mortar would render it expensive, besides, it would be of inferior quality. The material commonly used to mix with lime is sand, and this sand should be of a hard nature, not very fine, but angular, and having a consider- able degree of affinity for lime, also the more irregular it is in size the better. It should be free from any mixture of soft or earthy matter, if it can be procured without. The reason is obvious; for mortar, composed of soft sand, cannot be harder than that sand. Sea-sand makes good mortar, particularly water-mortar. Very hard-burnt brick, or tile, reduced to a coarse powder, also makes an excellent substance to mix with lime, for many purposes.
The best proportion of sand, for common mortar, is easily ascertained by trial ; enough should be added to render the mortar rather short than tough under the trowel. The proportion varies from 4 parts of sand to 1 of lime (quicklime), to 1 1/4 parts of sand to 1 of lime, by measure, the proportion differing according to the coarseness of the sand, the nature of the limestone, and the precautions used in burning it…In many situations, it is impossible to procure good sand, except at an enormous expense. (22)

Making Mortar.The instructions given by Dr. Higgins for making stucco-mortar, apply only when a very superior kind is wanted ; but the same general principles ought to be followed even with the commonest kinds of mortar. We will, therefore, insert them in this place.

Of Sand, the following kinds are to be preferred; first, drift-sand, or pit-sand, which consists chiefly of hard quartose flat-faced grains, with sharp angles; ; secondly, that which is the freest, or may be most easily freed by washing, from clay, salts, and calcareous, gypseous, or other grains less hard and durable than quartz; ; thirdly, that which contains the smallest quantity of pyrites, or heavy metallic-matter, inseparable by washing; and fourthly, that which suffers the smallest diminution of its bulk in washing. Where a coarse and fine sand of this kind, and corresponding in the size of their grains with the coarse and fine sands hereafter described, cannot be easily procured, let such sand of the foregoing quality be chosen as may be sorted and cleansed in the following manner:

Let the sand be sifted in streaming clear water, through a sieve which shall give passage to all such grains as do not exceed one-sixteenth of an inch in diameter

; and let the stream of water, and the sifting, be regulated so that all the sand which is much finer than the Lynn-sand, commonly used in the London glass-houses, together with clay, and every other matter sneci- fically lighter than sand, may be washed away with the stream ; whilst the purer and coarser sand, which passes through the sieve, subsides in a convenient receptacle, and the coarse rubbish and rubble remain on the sieve to be rejected. (22)

Let the sand, which thus subsides in the receptacle, be washed in clean streaming water through a finer sieve, so as to be further cleansed, and sorted into two parcels ; a coarser, which will remain in the sieve, which is to give passage to such grains of sand only as are less than one-thirtieth of an inch in diameter, and which is to be saved apart under the name of coarse sand; and a finer, which will pass through the sieve and subside in the water, and which is to be saved apart under the name oi fine sand. Let the coarse and the fine sand be dried separately, either in the sun, or on a clean iron plate, set on a convenient surface, in the manner of a sand heap. (23)

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. (23)

Wright W H (1845) Brief Practical Treatise on Mortars, with an Account of the Processes Employed at the Public Works in Boston Harbor. Boston. Ticknor & Company.

Fat or common lime, in consequence of its great consumption for building purposes, is now an article of commerce in all the cities of the country…It is prepared on the largest scale in the State of Maine, and the kilns of Thomaston and the neighbouring villages furnish it in great abundance, at very cheap rates and of most excellent quality. (14) At the public works in Boston Harbor, the Thomaston lime has been generally preferred, as it combines lowness of price with a considerable degree of richness. It slakes promptly, and yields, in stiff paste (a good volume increase)….

Hydraulic limestones (as distinguished from cement stones) exist in great abundance in this country, though, I believe, **they are nowhere calcined with a view to sale in the large way.** The limes which they yield form the intermediate class between the common limes and the hydraulic cements….(15)….

SAND.

Sands may be classified with relation to their constituent parts, as the argillaceous, the siliceous, the calcareous, etc, worthy may be arranged, by reference to the size of the grains, into fine, middling and coarse sands. Constructors usually distinguish them into river sand, sea sand and pit sand….

The respective merits of the several varieties are still involved in question. Sand is, (24) however, an inert substance, and any variation in its quality must depend wholly upon the size, form, and hardness of the grains. Accordingly, pit sand, of a siliceous or quartzes nature, and entirely free from earthy impurities, may always be regarded as the best; its grain is more angular and sharp than that of river or sea sand, the particles of which are usually rounded from constant attrition, and therefore less adapted for forming a compact body with the cementing ingredient. It has not been universally preferred by constructors, because they have probably employed it without freeing it from earthy matters often mixed with it. Very excellent sands, however, are frequently obtained on the banks of rivers, as well as on the sea-shore. Of the two kinds, river sands are to be preferred to sea sands, by reason of the salts always existing in the latter, and somewhat objectionable, on account of their deliquescing properties; though exposure to the weather soon deprives sea sand, in a great measure, of its saline matters and leaves but little to choose between it and river sand.

With regard to the size of the grains, experiments show that there is an advantage to be gained from the employment of fine sand with the hydraulic limes, though they *establish* nothing with regard to its superiority over coarse sand, in combinations with *fat lime*.

All the sands should be carefully examined before they are used; for river sand and even sea sand are not always exempt from earthy powders, which experience proves conclusively, are often very injurious to mortars. Pure sands (25), rubbed between the fingers, should leave no stain, and, immersed in limpid water, should at once fall to the bottom, without altering the transparency of the liquid in a sensible degree. Should the water become muddy, it is an indication of the presence of some foreign matter, the nature and proportions of which it is important to ascertain, as it may possibly possess hydraulic properties. (Test by making cakes with fat lime of a) the extracted powder and b) the unwashed sand. Assess hydraulicity, or otherwise by setting times thereafter). (26)…

Sand performs no chemical part in mortars, but is entirely passive in its influence; **it appears rather to diminish the adhesiveness or tenacity of the limes,** and though it may often add to their resistance, is employed chiefly for reasons of economy. It is useful, however…in some other respects: it moderates the shrinkage of the cementing matter, making it uniform, and preventing cracks; probably facilitates desiccation and makes the induration more rapid. Sand diminishes the strength of *hydraulic cement* in every respect, whether we regard tenacity, resistance, or the property of setting under water….(28)

POUZZOLANAS.

(Strictly speaking, volcanic ash from Vesuvius)…but the word pouzzolanas is here used as a general term….for those products which, without containing lime as a principal constituent, form with it combinations, which possess the property of setting under water.

These substances offer very important advantages in the improvement of mortars….because hydraulic cement is not always to be had, and (natural) hydraulic limes often give mediocre results, <u>unless they are mingled with a certain proportion of pouzzolana;</u> 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.

The essential constituents of pouzzolanas are silica and alumina….

Pouzxolanas may be divided into two classes; the natural and artificial. The first, in their *natural* state, possess the property of forming hydraulic mixtures with fat lime. The second are obtained by the calcination of certain natural products, which, without being burned, would have no action upon fat lime…

Under the head of natural pouzzolanas may be comprised pouzzolana properly so called, tras or terras, and the arenes…..

Pouzzolana must always be reduced to the state of an impalpable powder before it is employed as an ingredient of mortar, as it acts, only when thus pulverised, with its full energy upon lime. It does not add much to the tenacity of fat lime, but augments its resistance in a remarkable degree. The weaker hydraulic limes are always improved by the addition of pouzzolana; the eminently hydraulic limes and hydraulic cement are always injured by its use (*although Portland cement can be improved by it)*….

A species of fossil sands….in France…(with the name of) arenes, to distinguish them from other sands. They may be made into a paste with water, and are often used alone, as a pise, in building the walls of houses, as they shrink less than clay, and resist better the inclemencies of the weather…. When mingled with common fat lime, they form mortars, which set underwater and acquire great hardness….(many colours)…The sand is sometimes fine, sometimes coarse, occasionally calcareous, but more frequently, siliceous or mixed.

Properties resembling those of the arenes have also been recently discovered by M Avril in graywacke, and even granite, when in a state of decomposition. Their hydraulic quality is, however, feeble….

When the natural pouzolanas are not to be obtained (or only expensively), they may be replaced…with artificial products of equal quality. Clays properly calcined, brick and tile dust, forge scales…and slag from the iron foundries, are artificial pouzzolanas.

Forge scales, as well as the siftings of iron stone, after calcination in the iron furnaces, called minion, were used…by Smeaton (36) with excellent effect. Both should be sifted clean from dust and glassy slag, and reduced to fine powder, by grinding in a mill.

The vitrified substance, called slag at the iron foundries, is **often used alone as a cement, without any admixture of lime.** It is ground to a very fine powder on a cast-iron bed, and then made into a paste with water. (37) (or may be mixed) two parts of lime paste with one powdered slag…The masonry laid with it is kept dry for a couple of days, during which time it sets. It continues afterwards, however, to indurate slowly, and acquires at length a stony hardness. (37)….

Chapter 3.

The object which we propose to attain, in mingling sands with a cementing material, is to form, as cheaply as possible, compositions, which, exposed to all vicissitudes of weather, and even placed under water, may nevertheless become hard and solid, attach themselves strongly to building materials and attain, in the end, a resistance superior to all disturbing forces. Such combinations are called mortars. (38)

(Advocates the mixture of coarse and fine sands - like Gillmore - fine sand added so long as it does not increase the volume of the coarser sand, thereby reducing voids and therefore reducing lime demand, but also stresses that filling the voids only would deliver an inferior mortar - enough to fill voids and then half as much again). (46-47)

(fine sand should be mixed first with the lime paste, then the coarser sand).

Brees S C (1852) The Illustrated Glossary of Practical Architecture and Civil Engineering. London. Savill and Edwards.

CONCRETE, an artificial cement composed of lime and gravel, or sand, and in high repute at the present time for the foundations of structures. It was first used in the year 1815, by Mr. Ralph Walker, C.E., at the West India Docks, and subsequently at the Custom House of London, after piles had failed.

Concrete is prepared in various proportions; about one-seventh or one-eighth of ground lime is the most general, but it depends entirely on circumstances. Two-thirds of the ballast should consist of small stones, with none larger than a hen's egg, and one third of sand. This, in fact, constitutes Thames ballast, which makes excellent concrete when combined with Dorking lime. It should be mixed together, and slaked like mortar, a*nd always used hot*, and thrown from barrows wheeled along planks from a height of 10 or 12 feet to the site of the intended foundation. This will have the effect of driving the particles closer together, and giving greater stability to the whole mass; after which it ought not to be disturbed until properly concreted and set, when it may be levelled, the footings laid upon it, and the walls carried up. It is thus distributed, in layers from 7 to 10 inches thick, and each should be allowed to set before another is commenced. It is further advisable to perfect one layer before commencing a second, but if this is not convenient, the second layer should be cast short of the first, and the whole stepped down in succession.

SAND, a granular mineral substance, insoluble in water, and employed in the preparation of mortar. - The sand procured from pits is the best for building purposes, being fat and tough; river sand is also much employed, but it should be well washed and ridded of all earthy impurities previous to being used. Sea sand is often used, the salt being thoroughly washed out of it, when it is particularly good for water mortar. 24 heaped bushels, or 30 striked bushels, equal 1 load; 27 cubic feet (equal 1 cubic yard) weigh 1 ton.

Burnell G R (1857). Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering, etc. first edition.

The quantities of sand to be used vary…according to the nature of the limes, and also the sand itself…we find that, for the rich limes, the resistance is rather increased if the sand in the proportions varying from 50 to 240 % of the paste **measured in bulk in the state of a firm paste.** Beyond that point the resistance decreases. The resistance of hydraulic limes increases if the sand be mixed in the proportion of 50 to 180 % of the paste. from thence it decreases.The much greater proportion of sand the rich limes are able to support, may perhaps, **account for the partiality of the builders in their favour** *[A-ha!]*….

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

Sands….

The generally received opinion that the sand should be perfectly free from all earthy matters, is only true to a certain extent. (discussion of the use of 'arenes' for construction in France - between 25% and 75% clay mixed with chalk aggregate, and used with rich limes for waterworks…). Some of the decomposed grauwacke rocks also yield an argillaceous sand, composed of quartz, schist, feldspar and particles of mica agglutinated by a species of clay, which is very valuable, whether used in its natural state, or calcined to make artificial puzzolanos, like the arenes. The granitic rocks of Devonshire, some parts of Brittany and of the extreme NW of Spain, all of which are characterised by a remarkable excess of feldspar, yield a sand of great value for building purposes, especially when the mortars composed of it are not immediately exposed to the effects of running water. In all probability, the potassa present in the decomposed and decomposing feldspar may influence the setting of the limes mixed with the sands thus obtained.

2. The Clays

The clays are rarely used in their natural state in combination with lime, **unless it be to give a certain degree of consistence to mud walls or pise work [*and for earth mortars and plasters throughout the UK and elsewhere!].*** When burnt, they act somewhat in the manner of puzzolanos; and for all cases in which the mortars thus made are not exposed to the action of sea water, they appear to answer very well.

3 The puzzolanos

The puzzolano is a volcanic substance of a pulverulent character, and a violet red colour, which was fist employed in the fabrication of mortars by the Romans...

Its aspect varies, however, very much; sometimes it is in a state of powder, at others in coarse grains; often in the form of pumice, scoria, or of tuffa or in small rubble-stone. Its colour is often brown, or yellow, or grey, of black, even in the same locality.

The Tripoli, and the sandstones and limestones altered by contact with the rocks of eruption, also frequently take the character of puzzolanos and may be classed, therefore, as pseudo-volcanic products of a similar category....The puzzolanos are principally composed of silica and alumina, with a little lime in combination, mixed with potash, soda, magnesia, and oxide of iron. The iron appears to be in a peculiar state of magnetism; for although in very feeble proportions, it is capable of affecting the needle.

...it is evident that the effect produced by the mixture of the puzzolanos and trass is eminently useful in rendering the rich limes fit for every description of works executed in either sea or fresh water....Less (puzzolano) is required when hydraulic limes are used, than when they are mixed with the rich limes. **The latter will bear at the same time a large quantity of sand or gravel, the former only a very small quantity.**

4. The term 'slag' is usually applied to the vitrified earths which are left in furnaces, either for glass or iron, after the purer products are withdrawn. 'Scoriae' are the lighter, more porous, and less perfectly vitrified earths, which arise principally from the puddling and refining of iron; the term is also applied to the less compact portions of the slag. Cinders are the earthy residues from the combustion of woods, peat, coal, or other combustibles.

The slags and scoriae....principally consist of silica, with a feeble proportion of alumina, magnesia and very large proportions of the oxides of iron and manganese. (compared to pozzolano and trass...'a very remarkable difference in the proportions' in slags and scoriae, as also between scoriae and slag, with the latter having little iron, the scoriae a lot).

Coal cinders...when properly mixed appear to render the rich limes moderately hydraulic.

Wood cinders are often objectionable in consequence of (an) excess of alkali: if this be removed by washing, they may occasionally be useful in the absence of other materials capable of communicating hydraulic properties.

Vicat classes the different materials named and described above still further,

according to the energy of their action upon the limes with which they are mixed:

He calls '**very energetic**' any substance which, after being mingled with lime **slacked in the usual manner, and brought to the consistence of a thick paste,** produces a mortar capable of setting **from the first to the third day; of acquiring after the lapse of 12 months a degree of hardness equal to a good brick;** and of giving a dry powder if sawn with a tooth saw after that time.

'**Simply energetic',** any substance which will determine the setting **from the fourth to the eighth day;** and which is capable of acquiring **after twelve months the consistence of soft stone, and of giving a damp powder under the tooth saw.**

'Slightly energetic', when the setting only takes place between **the tenth and the twentieth day; the consistency of hard soap...after 12 months, and the mortar would then clog the tooth saw.**

'Inert' when the materials, if mixed with rich limes, exert no influence upon their action under water.

In all these cases the mortars are to be immersed immediately.

might this, without immersion, be a reasonable rule-of-thumb method?]

(Vicat maintains that no pozzolano added to rich limes can make them set under water...)

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.** *(Gillmore - see below - was also doubtful about the rigour of Vicat's research and of its proclaimed outcomes).*

Espinosa Pedro Celestino (1859) MANUAL DE CONSTRUCCIONES DE ALBAÑILERIA. Ingeniero Jefe de primera clase de Caminos. Canales y Puertos. Severiano Bas Madrid.

Sharp, angular sand binds better in mortars, and especially pit sand ('sand from the mine'). When one has to use sea or river sand, one prefers deposits that have been long on the shore, and have not been as much rolled around as those from the (river or sea) bed and will be less rounded. The sand can be quartz, granitic, calcareous, volcanic, etc. One gives this name to all mineral substances in the form of grains more or less coarse and insoluble in water. Sands may be made artificially by grinding bricks or stones. There are quartz sands of irregular grain, mixed with clay in variable proportions. One generally finds them on the higher slopes of some hills, in 'fijones' for limestones, in flood plains. These are pit sands. Also, one finds agglomerations of quartz, schist or feldspar, and particularly of mica, mechanically reunited with other material (greywacke to the Germans). To these belong the schist sands, soft to the touch, yellow, red or dark of fine grain which form a paste with water and which may be used in the confection of mortars - they belong in the schist lands and one finds them in banks and veins.

The sand used in plasters and mortars must be free of earth and passed through a sandbox to rid it of stones. When dealing with mortars the grading/size of the sand is significant according to the case and the end use. If you have to use sea sand, leave it sometime in the rain to wash out the salt it contains. If the sand used in mortars is not free of earthy or animal matter, it will form a soapy paste that will retard the setting. To ascertain if it is clean throw it into water, and if it muddies it, choose another source. Another way of assessing its goodness, is to squeeze a handful, whereupon it will be sharp to the touch and will crunch without leaving dust or mud. (Then gives Vicat's sand classification).

Scott Captain H(1862) Observations on Limes and Cements; their properties and employment. Papers on Subjects Connected with the Duties of the Corps of Royal Engineers Vol. XI. Woolwich. Jackson

It is necessary here to notice a very common error concerning **the effect of sand on mortars. Doubtless there are cases in which sand of a peculiar kind, within certain limits, improves mortars; but, as a general rule, the action of sand must be injurious to their strength, and the only valid reason that can be given for its employment is the advantage gained in the first cost of a structure by the saving effected in material.** In estimating the probable effect of sand upon mortar four points present themselves for consideration .. **the cohesion of the particles of the cementing material; their adhesion to the surfaces of the sand; the increase of strength that may arise, when the sand is stronger than the cementing material from the fracture having to take a longer path than it would, where no sand intervenes to break the direct passage in one plane; and the possibility of weak points occurring from several particles of sand**

remaining in contact without a sufficiency of cementing material to envelope them, and completely fill up their interstices. The latter consideration affects all descriptions of sand — whether granitic, calcareous, or argillaceous — pretty equally, and so far as this cause of weakness exists, the strength of mortar must suffer deterioration. So far as the particles of sand break joint, as it were, and

thus lengthen the path of the fracture, something doubtless is gained by its use, especially when the sand is intermixed with gravel, and its grains are of various sizes. In respect to the question of adhesion as compared with cohesion, wide differences may be supposed to exist, according to the nature of the surface of the sand, whether rough or smooth, and according as the lime is capable or not of exerting a chemical action upon it.

Now, as far as is known, the lime of mortar has no practically appreciable action upon quartz sand; and, therefore, as the greater part of our sand in this country is granitic, the adhesion of the lime to it must be independent of chemical effect, meaning by this term the formation of any new compound**. In France, however, a sand is found, termed an arene, which is a description of puzzuolana, and the employment of this sand has a decidedly beneficial action upon lime mortar.** A ferruginous sand, found in the gravel pit close to Prince Frederic's Bastion, on the Chatham Lines, possesses similar qualities, and it is probable that brick dust and burnt clay, as in some instances they form fair substitutes for puzzuolana, **would also, in a coarse state resembling sand, have also a beneficial effect both on pure and hydraulic limes,** though not, perhaps, on cements, because these naturally contain all, or nearly all, the clay which the lime can chemically combine with.

But with the majority of sands such chemical action is wanting, and the sand and lime particles hold together by the force of adhesion only. Experiments show that with most surfaces this force, as can readily be conceived, is less than that of the cohesion between the particles of lime. **The addition of sand, therefore, generally introduces an element of weakness into mortars in this way also. The loss of strength in respect of this will be greater in proportion as the sand is finer, and as the quantity is increased, for by enlarging the extent of surface over which adhesion takes the place of cohesion, not only is something absolutely abstracted from the resistance of the aggregate mortars, by a lesser force being substituted for a greater, but the chance of weak points, from a deficiency of cementing material between the particles of sand, is increased.** We introduce, then, into lime pastes three elements of future weakness when we add sand to them, arising from imperfection of mixture, and from the substitution of the weaker force of adhesion for that of the cohesion of their particles. We give them one element of strength by interposing, in the direct path which fractures might otherwise take, grains of a material stronger than themselves**. It seems probable, however, that the advantage thus gained does not counterbalance the sources of weakness introduced,** and it will be seen hereafter that experiment proves this to be the case. Experiment shows, too, that there is **little difference of resistance between mortars made of fine, coarse, and mixed sands, though as the sand approaches the size of gravel the diminution of strength from its addition becomes notably less.**

It was Smeaton who first pointed out the error, then upwards of 2000 years old, that the superiority of lime consisted in the hardness and whiteness of the stone from which it was prepared. The fallacy about whiteness is exploded, **but the** idea of the connection between the goodness of mortar and the density of the limestones yielding it, is still entertained by many practical men; and when the Dorking and Halling grey limes were first brought into the London market, it was considered necessary to call them " stone limes " to procure their introduction. In many of the builders' price books they are still so termed…..

When the means of two or more experiments are taken, **there is a loss of strength with each addition of sand,** excepting in one single instance, and then the difference in favour of the larger proportion of sand is quite insignificant. **According to experiments made by Colonel Nelson, in Bermuda, 1 part of lime powder barely filled up the interstices of 3 parts of sand.** Now with 2 1/2 parts sand, on the means of Nos. 7, 8, 9, and 10, there is the loss of nearly one half the strength of which the limes were capable when used without sand, and, when 3 parts of sand were used, of nearly two-thirds, the lime being measured always in paste. Again on the means of the three results given in Nos. 17, 18, and 19, an increase of sand from 2 parts to 3 parts occasioned a loss of considerably more than one half of the resistance which the prisms had when used with the lesser quantity. Bearing in mind that these experiments were made by one who entertained, to the last, the notion that sand had generally a beneficial action on the strength of mortars, we can hardly resist the conviction that the building world must be mistaken in its theories on this question....

Before leaving this subject it may be advisable briefly to recapitulate the contradictory evidence of writers and experimenters who hold to the beneficial effect of sand on mortars, and to contrast this with the simplicity of the view here advocated. **Pasley thought, with Belidor and Rondelet, that hydraulic limes would carry with advantage less sand than the fat limes, because they worked short with a smaller proportion of it.** Vicat decided by experiment that they would carry more. Writers, generally, have asserted that the fat limes are benefitted by a considerable quantity of quartz sand. Vicat and Raucourt de Charleville assert that they are injured by a small proportion of it, and consider they have proved the point by experiment. Raucourt explains why it is that " cements," in which term, as already explained, he includes all argillaceous limes, are peculiarly benefitted by making mortar of such proportions as will enable the "cement " to fill up the voids of the sand. General Pasley asserts that cement is injured by any proportion of it. At the same time, on examining the results of the only experiments which have been given in a satisfactory form and are free from objections, we find the views advocated in this paper fully borne out, for not only do **they show that the theoretic rule of just filling the voids of sand is founded in error, but that, as regards strength in heavy structures, where cracks from shrinkage or drying are not to be apprehended, all limes are weakened by even small proportions of it.** The limes tried by Treussart after one year, without sand, and with the theoretic quantity, lost (some) their strength in the latter case. The trials of Colonel Totten after 4 1/2 years, with 1/6 and 4/6 of the theoretic proportion, showed a resistance in the case of the larger proportion little greater than 1/2 of that which it showed with the less. The tendency of both their experiments **points unmistakeably to a loss of strength by each addition of sand in the case of limes, and Table XVIII shows the same rule to hold good with cements.** From the one view all is confusion and uncertainty, from the other, the view here taken, there are no unaccountable anomalies to be reconciled, and there is a **gradual decrease of strength with each addition of sand throughout the whole range of calcareous mortars** — in the fat limes, as asserted by Vicat and Raucourt de Charleville, and as shown by

849

the results obtained by Colonel Totten — in the cements, as established by Pasley — and in the intermediate sorts of hydraulic limes, as satisfactorily decided by the careful experiments of General Treussart....

Enough has now been brought forward to show how unsatisfactory and contradictory are the statements made and the rules followed, by the theorizers on the effect of sand on mortars used in brick and stone masonry, and it is hoped a consideration of all the evidence **will lead to the conviction that this is**

not a question to leave to be resolved by the convenience of the workman and the interests of the builder. Exception is taken, not so much to the proportion of sand specified for works, (for this is generally moderate, and would cheapen the mortar without materially detracting from the resistance of the masonry) as to the practice which permits a departure from the specification, and any quantity to be introduced that does not render the mortar " short," on the supposition that the plasticity which best satisfies the skilful workman is the surest criterion by which to judge of the proportion of sand and lime to secure the greatest resistance, and on a fanciful theory derived from the composition and hardness of granite.

(After discussion of others's thoughts on sands)... On considering all the evidence brought forward, and its very contradictory nature, it may be considered that our present knowledge and experience would not justify expense, in order to obtain for brickwork or masonry, quartz sand of any particular colour, size of grain, or from any particular source, **though it may be assumed that such as is rough and sharp will be preferable to smooth grained sands....**

On reviewing...opinions concerning the action of **salt**, and bearing in mind that some of the builders named were dealing with limes which set best when kept damp, and that others may have been dealing with fat limes, with which damp would occasion a retardation of the set; it seems reasonable to conclude that the observers were not mistaken in either instance, but that **for hydraulic limes, either sea sand or sea water may be used in brickwork and masonry, generally, without injury, if not with advantage.** *[Smeaton concluded the same].*

For plastering internally it is universally agreed that sea sand should be either rejected or washed, as the presence of salt will always keep the plastering damp and unfit to receive either paper or painting — of course to use sea water would be still more objectionable. For the internal parts of magazines and stores, also, sea water, and perhaps unwashed sea sand, may retard the drying and attract moisture sufficiently to render their use unadvisable.

In one point all writers excepting Rondelet, who may have been dealing with an arene, are agreed. **They all have decided that the sand must be clean.** ...Peter Nicholson complains that " to complete the hasty hash which was called mortar in his time, screened rubbish and the scrapings of roads, also, are used as the substitutes for pure sands; " and it may be truly asserted that at

Chatham, at least, clean sand is the exception and not the rule both in Government and Civil Buildings. For the Admiralty works, however, clean sand is procured. Here we find no disagreement sufficient to leave any doubts as to the validity of the common opinion against the common practice. **It is stated that one- seventh or one-eighth of clay in the sand used in making mortar causes the mortar to moulder in winter like marl, for clay absorbs water to a much larger extent than lime and sand.** There seems, then, the best ground for great stringency on that item of all specifications which prescribes that **the sand shall be clean as well as sharp, but which, at present, is a dead letter**. Few of us have ever seen a vat for washing sand, or indeed any sand washed at all, excepting for the finishing coat in plastering, and even in this case it is often dispensed with.

….It has been shewn, that so far as can be judged from the contradictory opinions of men eminent as builders and writers on constructions, and from the few experiments made on the point, it matters little whether the sand employed for mortar is course or fine, or obtained from pits, or the beds of rivers, or from the sea; but that it ought to be free from all dirt and clay; and that of two sands equal in other respects, the more angular will make the stronger work.

….The table not only shews the extent to which mortars will suffer from a rapid desiccation, but that the injury is greater in proportion as the lime used is more hydraulic....The purely lime mortars suffer less because in the internal parts they merely dry under any circumstances, and a rapid desiccation only interferes with the crystallization of the carbonate of lime where the air reaches them. It will be seen then that in hot weather, and especially in hot climates, the prevention of too rapid a desiccation becomes a point of great importance, especially where hydraulic limes are employed. Colonel Raucourt de Charleville recommends the use of straw mats for the purpose, which are to be suspended over the newly built masonry, and watered night and morning.

Austin J G 1862. Published in New York, summarizing Eastern US urban practice mid 19th C.

STRENGTH OF MORTARS.

...The only published experiments on this subject made in this country (USA) are those of Colonel Totten, appended to his translation of General Treussart's work.

From experiments, Colonel Totten deduces the following general results:-

1st That mortar of hydraulic cement and sand is the stronger and harder as the quantity of sand is less.

2nd That common mortar is the stronger and harder as the quantity of sand is less.

3rd That any addition of common lime to a mortar of hydraulic cement and sand weakens the mortar, but that a little lime may be added without any considerable diminution of the strength of the mortar, and with a saving of expense.

4th The strength of common mortars is considerably improved by the addition of an artificial puzzolana, but the more so by the addition of a hydraulic cement.

5th Fine sand generally gives a stronger mortar than coarse sand [this contradicts the observations of others].

6th Lime slaked by sprinkling gave better results than lime slaked by drowning. A few experiments made on air-slaked lime were unfavourable to that mode of slaking.

7th Both hydraulic and common mortar yielded better results when made with a small quantity of water than when made thin.

8th mortar made in the mortar mill was found to be superior to that mixed in the usual way with a hoe.

9th Fresh water gave better results than salt water.

CONCRETE – This term is applied by English architects and engineers, to a mortar of **finely pulverized quicklime, sand and gravel.**

BETON – The term beton is applied by French engineers to any mixture of hydraulic mortar with fragments of brick, stone or gravel, and it is now also used by English engineers to the same sense.

From experiments made by Colonel Totten on beton, the following conclusions are drawn:

That beton made of a mortar composed of hydraulic cement, common lime and sand, or of a mortar of hydraulic cement and sand, without lime, was **the stronger as the quantity of sand was the smaller...**

Beton made with just sufficient water to fill the void spaces between the fragments of stone was found to be **less strong than that made with double the bulk of mortar.**

... The strongest beton was obtained by using quite small fragments of brick, and the weakest from small, rounded, stone gravel.

A beton formed by pouring grout among fragments of stone or brick **was inferior in strength to that made in the usual way with mortar.**

Comparing the strength of the betons on which the experiments were made, which were eight months old when tried, with that of a smaple of sound red sandstone of good quality, it appears that the strongest prisms of beton were only half as strong as the sandstone *[BUT the hydraulic limes used still a long way from their initial strength at 2 years, which would likely be around twice that at 8 months]*.

Gillmore Q A (1864) Practical Treatise on Limes, Hydraulic Cements and Mortars.

CALCAREOUS MORTAR.

Being composed of one or more of the varieties of lime or cement, natural or artificial, mixed with sand, will vary in its properties with the quality of the lime or cement used, the nature and quantity of sand, and the method of manipulation. No fixed rules for its preparation, that shall be equally well adapted to all the varying circumstances of locality, temperature, and the seasons, can be prescribed *(although mortars were remarkably similar over, most of the time, 2000 years, in fact)*.

The objects to be attained by the use of a mortar are chiefly of two kinds:

First, **to bind together the solid materials used in masonry constructions; or, in other words, to produce in each particular case, artificial monoliths of the required form and dimensions.**

Second, to form coverings to the solid materials, under the general denomination of stucco work. Under this head may be included all exterior covering, and interior plaster work and ornamentation.

Sand exercises no sensible chemical action in the composition and induration of mortars of hydraulic lime. If the sand be siliceous, there is believed to ensue a slow formation of silicate of lime, which considerably augments their power of resistance, and in positions excluded from contact with the air, such as the interior of thick walls, becomes an important auxiliary in the hardening process (*Gillmore seems to be identifying on-going strength gain, but attributes this to the silica in the sand, not to the silica set of the hydraulic lime itself) (174)*.

The practical strength of aggregates, considered with regard to their tenacity, hardness, and power of resisting compression, depends upon four essentially distinct conditions:

1st The constant resistance of the parts enveloped by the matrix, whether composed of sand, gravel, pebbles, fragments of brick or stone, or a mixture of them all

2nd The resistance varying, and generally increasing with time, of the matrix or cementing matter

3d The force of adhesion between the matrix and the other parts, **resulting in part from the chemical affinities existing between them** *(such as between lime and limestone aggregate, most particularly when the limestone is the same as was burned to make the lime)*.

4th The strength due to the interlacement of the enveloped parts with each other, which produces leverage and friction among them, and enlarges the surface of least resistance.

It might be inferred theoretically, that the capacity of an aggregate possessing no voids, to resist any particular kind of strain, cannot surpass that of its matrix…; or rather cannot be equal to it, except when the inherent strength of the enveloped parts, as well as the adhesion between them and the matrix, equals or exceeds the resisting power of the latter (175).

In practice, when these conditions do approximately obtain in exceptional cases, mortars are weakened by the addition of sand or any of the substances above mentioned. **These latter, however, have the important effect, of preventing or diminishing shrinkage, of hastening the induration of rich limes, and of rendering all kinds of mortars less liable to crack in drying, which is often of very great advantage. They are, moreover, by far the least costly ingredient of mortars, and a due regard to economy compels their use in the largest possible proportions.**

It might also 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. This theory supposes that there is no shrinkage in the matrix while hardening, and that the manipulation 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 *(as they generally have been over recent decades),* 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% to the volume of the void space in the sand. (176).**

When sands of various sizes are at hand, a considerable saving of cementing material may be secured by mixing them together in suitable proportions… (suggests adding as much fine sand to a coarse sand as may be added without increasing the original volume of the latter. Also recommends use of stacks of sieves to identify range of particle size). (177)

METHODS OF SLAKING LIME.

Lime is usually sent to market in barrels, either in lumps, as it leaves the kiln, or, in the case of those varieties that are more or less meagre *(lean limes with high proportion of insoluble clay content)* and consequently difficult to reduce to a fine pulp, by any of the known methods of slaking, in the condition of coarse powder, to which it has been brought by grinding…

Three methods of slaking lime are usually described in works on mortars; on the continent of Europe, the third method, and **in the United States, the second and**

third are seldom resorted to in practice. *(so US craft practice almost exclusively wet-slaking by the ordinary method, in Gillmore's observation).*

The first or *ordinary* method termed *drowning* from the excessive quantity of water sometimes injudiciously employed, consists of pouring upon the lumps of lime, collected together in a layer of uniform depth not exceeding six to eight inches, either in a water-tight wooden box or a basin formed of the sand to be subsequently added in making mortar, and coated over on the inside with lime paste, to render it impervious to water, a sufficient measure of fresh water - previously ascertained approximately by trial - to reduce the whole to the consistency of thick pulp. It is important that all the water required for this purpose, which, **with the different limes, will vary from two and a half to three times the volume of the quicklime**, should be added at the outset, or, at least, before the temperature becomes sensibly elevated (179). In this condition the lime will remain entirely submerged, and comparatively quiescent, until after an interval of 5 to 10 minutes, the water becomes gradually heated to the boiling point *(Gillmore unfamiliar with modern quicklimes!),* when a sudden evolution of vapour, a rapid increase in volume, and a reduction of the lime to pulp ensues….*(this well-describes the slaking habits of oolitic limestone burned in a small-scale kiln, although 5 minutes about the upper limit).*

This process is liable to great abuse at the hands of workmen *(here we go again!),* who are apt to use either too much water, thus conferring upon the slaked lime a condition of semi-fluidity, and thereby injuring its binding qualities *(as per drowned and semi-fluid lime putty),* or, not having used enough in the first instance, they seek to remedy the error by adding more after the extinction has well progressed, and a portion of the lime is already reduced to powder, thus suddenly depressing the temperature, and chilling the lime, which renders it granular and lumpy *(the presence of residual lumps in a hot mixed lime mortar is not, generally, an indication of burning and chilling of the lime during preparation).*

As soon as all the water required has been poured upon the lime, it is recommended to cover up the vessel containing it with canvas or boards, in order to concentrate the heat and the escaping vapour *(the steam),* and direct their action upon the uppermost portions deprived of immediate contact with the water, by the swelling of the portions at the bottom. When it is not possible to apply this covering, a tolerable substitute is found in the sand to be subsequently added to the mortar. This can be spread over the lime in a layer of uniform thickness after the slaking has well progressed. Another precaution of equal and perhaps greater importance is, not to stir the lime whilst slaking; but to allow it gradually to absorb the water by capillary attraction and its natural avidity for it, taking care that all portions are supplied with it to that degree requisite to produce a paste of the slaked lime, and not a powder *(although dry-slaking with around 1 volume of water had been and was common throughout time - by mid-19thC, a growing consensus among engineers and others (Burnell, eg) that lime was best run to a thick paste from the get-go. This circumvented the necessity of ample beating of a dry-slaked mortar prior to use, although this was not the reason given)*. When the lime is to be used (180) for whitewashing or grouting, the water should be added at the outset in larger quantities *(within reason and not actually much more in first instance, most others would say)* than specified above, and the whole should be run off while hot into tight casks, and covered up to prevent the escape of water.

In slaking, the essential point is to secure, if possible, the reduction of all the lumps *(reduction, not complete elimination, which may be impossible)*. It will be found difficult to obtain this result with the hydraulic varieties, and the difficulty increases in direct ratio with the hydraulic energy, until we reach the intermediate limes, or the inferior limit of cement, when the reduction must be effected by mechanical means. Even with those hydraulic limes that do slake, it is often necessary to employ a mortar mill to reduce the lumps - a condition which should always be secured, as these lumps constitute not only a dangerous substitute for sand, if left intact, but furnish when pulverised, the most (hydraulically) energetic portion of the gang. *(we might disagree about this today - the lumps acting as porous and compatible aggregate, although much more likely to late slake in more eminently hydraulic limes)*.

Slaking by Immersion

The second method of slaking (by immersion) consists of suspending the quicklime, previously broken into the size of a walnut, and placed in a basket or other suitable contrivance, in water, for one or two minutes, taking care to withdraw it before the reduction commences. The lime should then be quickly heaped together, or emptied into casks or bins, and covered up, in order to concentrate the heat and **prevent the escape of vapour.** In this condition, it soon begins to swell and crack, and finally becomes reduced to a fine powder, which may be preserved several months without serious deterioration, if packed in casks and kept from direct contact with the atmosphere. The expense which would ordinarily attend the practical applications of this process, and the difficulty of securing with certainty, at the hands of workmen *(and again),* the period of immersion, have led to (181) a modification of it, which consists in sprinkling the broken fragments formed into heaps of suitable size, with one-fourth to one third of their volume of water *(Treussart advocated this method, calling it 'slaking by aspersion')*. This should be applied from the rose of a finely gauged water-pot, after which the lime **should be immediately covered with the**

sand to be used for 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 continental 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 *(a lime house)*….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 *(any slaking water above that necessary to slake the free lime content will initiate hydraulic set - when then knocked up, that hydraulic set that has developed will be broken and the hydraulic elements will perform as aggregate only)*.

Spontaneous Slaking.

Quicklime has great avidity for water, and when not secured from direct contact with the atmosphere, gradually absorbs moisture from it and falls into powder, exhibiting but very slightly, and sometimes not at all, the other phenomena *(such as heat)* usually developed in slaking. The lime is then said to be slaked spontaneously, or air-slaked. (Questions veracity of then current notions that this method somehow imparted slight hydraulicity to pure limes) (182)…A great and insurmountable objection…is the expense of storage room or sheds which it necessarily involves, to say nothing of the time required for its completion. Spread out in layers of from ten to twelve inches in depth, some varieties of fat lime might become thoroughly reduced in twenty or twenty-five days; others would require as many weeks; while, with a few, the process would continue for a whole year. Hydraulic limes are greatly injured by spontaneous slaking *(for same reason as above, although Davy (1839) says was the common method for slaking blue lias in its regions - although presumably to facilitate storage or transportation. It might also produce a less energetically hydraulic lime - perhaps deliberately, in this case?).* Fat limes slaked to powder by the second or third process, are converted into paste with less water, and undergo a lesser augmentation of their original volume, than when slaked by the first process….

Preservation of Lime.

The paste of fat lime, whatever may have been the mode of extinction, may be preserved intact for an indefinite length of time, if kept from contact with the air *(although most said its binding power may diminish the longer it was kept, eg Nicholson 1819)*. It is usually kept from contact with the air. It is usual to put it in tight casks, or in reservoirs or trenches covered with sand *(which would not necessarily be added to the lime before use, the lime being used on its own)* or, when shed room is available, to form it into rounded heaps similarly protected and undercover *(if slaked properly and mixed at around 1:2 with sand, this will make an excellent mortar, if somewhat different in character and behaviour to a promptly used hot mix)*….

Until quite recently, opinions among engineers were divided as to the effect of time upon the quality of paste of fat lime, preserved with suitable precautions for future consumption. General Treussart entertained the opinion that they should be made into mortar and used soon after their extinction. This idea finds few advocates at the present day, **although the practice in this country conforms to it with singular unanimity. (190).**

Fabrication of Mortars.

The relative qualities in which sand and the cementing substance, whether the latter be derived from common or hydraulic lime, or cement, should exist in a mortar, depend in a great measure on the character of the work in which it is to be used; its locality and position with regard to a state of moisture or dryness; and, if subjected to alternations in this respect, the character of the moisture, depending on its proximity to, or remoteness from (190), the sea, the nature and magnitude of the forces which it will be required to resist, the peculiarities of the climate, and the season of the year in which the work is to be performed (191)…

Gillmore Q A (1871) REPORT ON BETON AGGLOMERE; OR, COIGNET-BETON AND THE MATERIALS OF WHICH IT IS MADE. PROFESSIONAL PAPERS, CORPS OF ENGINEERS, U. S. ARMY. Government Printing Office, Washington

P7 BETON AGGLOMERE MORTAR.

Calcareous mortar is compounded of one or more of the varieties of common lime, hydraulic lime, or hydraulic cement — natural or artificial — mixed with sand and water into a plastic condition.

The degree of strength and hardness, and consequently the durability, attained by mortar in setting, is dependent on the quality of the lime or cement employed, the kind and quantity of sand, the method and degree of manipulation, and the position, with respect to moisture or dryness, in which it is subsequently placed.

A mortar, of which the matrix is common lime only, will never harden under water, or to any considerable extent if kept in damp places, excluded from the air. A condition of constant humidity, on the contrary, is favorable to the induration of all hydraulic mortars.

CONCRETE OR BETON.

These terms, by no means originally synonymous, have become almost strictly so by usage. As generally received and understood in modern practice, they apply to any mixture of mortar, generally hydraulic, with coarse materials, such as gravel, pebbles, shells, or fragments of tile, brick, or stone. Two or more of these coarse ingredients, or all of them, may be mixed together.

The matrix of beton was formerly understood to possess hydraulic energy, while that of concrete, being derived from common lime, did not. A concrete, destitute of hydraulic energy, is seldom used in works of importance at the present day.

As lime, or cement paste, or a combination of the two, is the cementing substance or matrix in mortar, so mortar itself occupies a similar relation to concrete or beton. The proportions of the ingredients, in either case, should be determined on the principle that ***the volume of matrix should (p8) always be somewhat in excess of the volume of voids in the materials to be united,*** the excess being added as a precaution against imperfect manipulation.

BETON AGGLOMERE. 3. This name is given to a beton of very superior quality, or, more properly speaking, an artificial stone, of great strength and hardness, which has resulted from the experiments and researches, extending through many years, of M. Francois Coignet, of Paris.

The essential conditions which must be carefully observed in making this beton are as follows :
First. Only materials of the first excellence of their kind, whether common or hydraulic lime, or hydraulic cement, can be used for the matrix.

Second. The quantity of water must not exceed what is barely sufficient to convert the matrix into a stiff, viscous paste.
Third. The matrix must be incorporated with the solid ingredients by a thorough and prolonged mixing or trituration, producing an artificial stone paste, decidedly incoherent in character until compacted by pressure, in which every grain of sand and gravel is completely coated with a thin film of the paste. There

must be no excess of paste when the matrix is common lime alone. With hydraulic lime this precaution is less important, and with good cement it is unnecessary.

Fourth. The beton or artificial stone is formed by thoroughly ramming the stone paste, in thin, successive layers, with iron- shod rammers.

MATERIALS SUITABLE FOR BETON AGGLOMERE.
The materials employed in making this beton are as follows:

Sand. — The sand should be as clean as that ordinarily required for mortar, for stone or brick masonry of good quality. Sand containing 5 or 6 per cent. of clay may be used without washing, for common work, by proportionally increasing the amount of matrix. Either fine or coarse sand will answer, or, preferably, a mixture of both, containing gravel as large as a small pea, and even a small proportion of pebbles as large as a hazel nut. There is an advantage in mixing several sizes together, in such proportion as shall reduce the volume of voids to a minimum. Coarse sand makes a harder and stronger beton than fine sand. The extremes to he avoided are a too (p9) minute subdivision and weakening of the matrix, by the use of fine sand only, on the one hand, and an undue enlargement of the volume of voids, by the exclusive use of coarse sand, on the other.

The silicious sands are considered the best, though all kinds are employed. When special results are desired in the way of strength, texture, or color, the sand should be selected accordingly.

Common or fat lime. — The lime should be air-slaked, or, better still, it may be slaked by aspersion **with the minimum quantity of water that will reduce it to an impalpable powder**. It should be passed through a fine wire screen to exclude all lumps, and **used within a day or two after slaking**, or else kept in boxes or barrels protected from the atmosphere. It is scarcely practicable, under ordinary circumstances, to employ fat lime alone as the matrix of beton agglom6re, particularly in monolithic constructions, in consequence of its tardy induration. Even when used in combination with hydraulic lime or cement it acts as a dilutent.

M. Coignet claims, with great confidence, if not with correct judgment, that good beton can be made with sand and fat lime alone, but it is not so employed in his artificial stone manufactory at St. Denis, and it is believed that all the works executed in beton by the company of which he is the head have contained hydraulic lime or cement. Attempts to make beton of even average quality, without good hydraulic ingredients, have failed in the United States; and it is extremely doubtful whether any characteristic excellence can be attained, after the lapse of weeks or even months, by a mixture of this character. When a matrix of fat lime alone must be employed for want of a better material, the manipulation should be conducted with watchful care. The quantity of water must be limited strictly to what is necessary to convert the lime powder into a stiff paste; and of this paste only enough must be used to cover each grain of sand and gravel with a thin, impalpable coating. The other conditions of prolonged trituration and thorough ramming, already referred to, are common to all varieties of this beton.

Hydraulic lime. — The most suitable limes are, like those of Theil, Seilley, and other localities in France, derived from the argillaceous limestones, in contradistinction to the magnesian or argillo-magnesian varieties. These limestones contain (p10) before burning from 15 to 25 per cent. — generally less than 20 per cent.— of clay. After burning, **the lime is slaked to powder by aspersion with water, and sifted to exclude unslaked lumps. Hydraulic lime cannot be considered an essential ingredient of beton agglomere, except in comparison with common lime. It may be altogether replaced by good hydraulic cement, or it may be used alone, or mixed with common lime, to the entire exclusion of cement.** A stiff paste of this lime should set in the air in from ten to fifteen hours, and sustain a wire point one-twenty-fourth of an inch in diameter, loaded with one pound, in eighteen to twenty-four hours. Its energy, and therefore its value, varies directly with the amount of clay which it contains, which generally will not exceed 20 per cent. before burning, although it may reach 25 per cent. Beyond this point the burnt stone can seldom be reduced by slaking and becomes a cement. No hydraulic lime of this variety has ever been manufactured in the United States. It is not known that stone suitable for it exists here.

(Portland cement is suitable). *(The Portland Cement discussed is early and more akin to an eminently hydraulic lime. Some is made directly from impure limestone; other by artificially blending the necessary ingredients)*.

P13 MATERIALS NOT SUITABLE FOR BETON AGGLOMERE. As a rule, all hydraulic cements **produced at a low heat**, whether derived from argillaceous or argillo-magnesian limestones, are light in weight and quick-setting, and never attain, when made into mortar or beton, more than 30 to 33 per cent. of the strength and hardness of Portland cement placed in similar circumstances. They are also greatly inferior to good hydraulic lime. This is true of all cements made at a low heat, including even those derived from limestones, **that might, with proper burning, have yielded Portland cement.** The celebrated Roman cement, the twice-kilned artificial cements, the quick- setting French cement, like that of Vassy, and all the hydraulic cements manufactured at the present day in the United States, belong to this category. They are **incapable**, under any known method or degree of manipulation, of producing a matrix suitable for beton agglomere of good quality.

P14 THE INDURATION OF MORTARS. 17. The setting or hardening of mortars, except so far as it is due in some degree to the absorption of carbonic acid from the atmosphere, is a species of crystallization induced when water is added to the compounds found in the kiln by the agency of heat. Mortars of common lime harden by the absorption of carbonic acid from the atmosphere, by which a sub-carbonate of lime is formed. The lime never takes up its full equivalent of carbonic acid. If the limestone be siliceous, the calcination produces silicate of lime. Si O3 3 Ca O, which **becomes hydrated by combining with six equivalents of water,** producing hydro silicate of lime, Si O3 3Ca O+6 H2O.

If the carbonate of lime be in excess in the stone, the burnt product will contain both silicate of lime, and quicklime, or protoxide of calcium. It will slake to powder by the suffusion of water, if the quick lime be present in sufficient quantity, producing a species of hydraulic lime, of which the hydraulic energy will depend on the amount of silicate produced during the calcination. If the limestone be argillaceous — that is, if it contain alumina as well as silica — a calcination **at a low heat** produces both silicate and aluminate of lime. The latter becomes hydrated by taking six equivalents of water, and is then represented by the formula Al O3 3 Ca O+6 H2O. If the silica and alumina be present in the form of homogeneous clay, and in suitable quantity, say less than 20 per cent, the burnt stone will slake, yielding hydraulic lime resembling more or less those of Seilley and Theil, France. If more than 20 per cent. of clay be present, the lime will be so little in excess that the burnt stone may not slake, but must be reduced to powder by grinding. The result, if burnt at a low heat, is light, quick-setting cement, like the Roman.

If this stone be burnt at a high heat, the reactions in the kiln are somewhat more complicated, particularly when the point of incipient vitrification is reached, a variable point, dependent in a great measure on the fluxes present in the stone. The compounds formed under these conditions, however, require but (p15) three equivalents of water for their hydration, their formulas being

Al O3 3 Ca O+3 H2O, Si O3 3 Ca O+3 H2O. **Herein lies the probable cause, in a great measure, of the superior strength and hardness attained by Portland cement over the quick-setting varieties burnt at a low heat**, in which the compounds take six equivalents of water to form hydrates.

TREATMENT OF THE MATRIX. 19. It is impossible to produce a cementing material, of suitable quality for beton agglomere, by the ordinary methods and machinery used for making mortars; for if we take the powder of hydraulic lime or Portland cement, and add the quantity of water necessary to convert it into a paste by the usual treatment, it will usually contain so much moisture, even after being incorporated with the sand, that it cannot be compacted by ramming, but will yield under the repeated blows of the rammer like jelly. If the quantity of water be reduced to that point which would render the mixture, with the usual treatment, susceptible of being thoroughly compacted by rammers, much of the cementing substance will remain more or less inert, and will perform but indifferently well the functions of a matrix.

To prepare the matrix, there is taken of the hydraulic lime or cement powder, say one hundred parts, by measure, and of water from thirty to thirty-five or forty parts, which should be the smallest amount that will accomplish the object in view. These are introduced together into a suitable mill, acting upon the materials by both compression and friction, and are subjected to a thorough and prolonged trituration, until the result is a plastic, viscous, and sticky paste, of a peculiar character, in both its physical appearance and the manner in which it comports itself under the subsequent treatment with rammers. There would appear to be no mystery in this part of the process, yet the excellence of the beton agglomere is greatly dependent on its proper execution. **If too much water be used, the mixture cannot be suitably rammed; if too little, it will be deficient in strength.**

TRITURATION. 21. The matrix in paste, and the sand, having been mixed together in the desired proportions, (given hereafter,) are then introduced into a powerful mill, and subjected to a thorough and energetic trituration until, without the addition of more water, the paste presents the desired degree of homogeneity and plasticity. When, for any special purpose, it is desired to introduce into the mixture a quantity of Portland cement, in order to increase the hardness or the rapidity of induration, it had better be added during the process of trituration, mixed with the requisite increment of water, so that after proper mixing the whole material will present the appearance of a short paste, or pasty powder, which is quite characteristic of this process of manipulation. **In ordinary practice, when sand and hydraulic lime only are employed, it will be found to answer very well to mix the two together dry, with shovels, and then spread them out on the floor and sprinkle them with the requisite minimum amount of water. The dampened mixture is then shovelled into the mill and triturated, as already described.** *(This is hot mixing, insofar as the hydraulic quicklime will exude heat)*. When a portion of Portland cement is used, it may also be incorporated with the other ingredients **before the water is added**, or introduced into the mixture in the mill, as may be preferred. When Portland alone is used for the matrix, the process is the same as when lime alone is used, except that the trituration should be more prolonged, especially if the cement be rather light and quick-setting.

The market value of Portland cement per ton is generally not far from double that of good hydraulic lime. Having both equally at command, the following proportions are employed for divers purposes, according to circumstances and the quality of the materials:

Sand by volume
Hydraulic lime in powder by vol Portland cement in powder by vol

6 5 4 5 6 1 1 1 1 1 0 0 0 1/4 1/2

4 4 1 1 1/2 1/2

5 5 5 1 1 1

1 1 1/2 1 1/2

It will rarely occur that the proportions given in the two columns on the right of the above table need be used. They are suitable for ornamented blocks, requiring removal and handling a day or two after being made.
23. It may sometimes happen that too much water has been introduced in the preparation of the paste. A proper corrective, in such case, is the introduction into the mill of a suitable quantity of each of the ingredients, mixed together dry in the required proportions. By employing none but white sand and the lighter-colored varieties of lime and cement, a stone closely imitating white marble

may be made, while, by the introduction of coloring matter into the paste, such as ochres, oxides, carbonates, &c, or fragments of natural stones, any variations in shade or texture may be produced, from the most delicate buff and drab, to the darkest grays and browns. In some cases it may be found more convenient to measure the ingredients directly into the mill, alternating with the different materials, in regular order, using for the purpose measures of various sizes, corresponding with the required proportions. When it is specially desirable to obtain stone of the maximum degree of strength and hardness, the paste may be returned a second or even a third time to the mill, but in all cases the mass must be brought to the characteristic state of incoherent pasty powder, or short paste....

47. All attempts to cheapen a matrix of Portland cement, by the substitution of common lime for a portion of the cement, result in a sacrifice of strength in proportion to the extent of the adulteration, and the ratio of loss is not materially changed by the increased induration due to age. This is specially true in thick walls or other large masses of masonry, of which the portion which hardens by desiccation, and the absorption of carbonic acid at the surface, forms but a small proportion of the entire mass. When, however, the matrix is cement alone, and the proportion of sand is so huge that the grains are not all coated, and the voids not all filled or nearly so, **increased strength of the mortar beton is secured by adding a small quantity of common lime. The result is that both the strength of the matrix and the porosity of the mixture are diminished**. The aggregate volume, however, remains the same, while the section of rupture upon the same area, and the rupturing force, are both augmented. In other words, with large doses of sand and a cement matrix — for example, when the volume of the sand exceeds five times that of the cement loosely measured — there is an advantage in increasing the volume of the matrix at the expense of its strength, by **adding common lime powder, within the limits generally of one- fourth of the weight, or eight-tenths of the volume, of the cement.**

P57 MANUFACTURE OP HYDRAULIC LIME. 98. **In France, the practice of using lime that has been slaked in large bulk to a state of paste, by a copious use of water, has been entirely discontinued within the last few years, for the reason that only the fat or feebly hydraulic limes can be so treated.**

The presence of a sufficient amount of clay to confer eminently hydraulic properties upon the lime, engenders the presence of lumps and portions not susceptible of thorough extinction by the ordinary means, which would not only render the mortar heterogeneous, but might endanger the stability and safety of the masonry, by subsequent slaking within the work. Hence, whenever the advantage of employing hydraulic lime, either alone or mixed with cement, in order to confer energy and strength upon mortar, has been recognized, the lime is invariably used **in a state of freshly slaked, impalpable powder**. The use of fat lime has been very generally discontinued upon important works.

99. The following method is the one commonly practiced for obtaining hydraulic lime from argillaceous limestones containing from 12 to 24 per cent. of clay, the latter being composed of about 2 of silica to 1 of alumina. **There is no advantage in a high heat**, like that necessary for burning Portland cement. **While still warm from the kiln, the stone is sprinkled with from 15 to 20 per cent. of its own weight of water, care being taken not to use enough to convert any portion of it into paste.** The slaking soon begins, and the stone falls to pieces, a portion of it in the condition of fine powder, while the rest remains in unslaked, or partially slaked, lumps of various sizes. The whole mass is then thrown together in large heaps, where it remains undisturbed for **six or eight days,** in order to complete the extinction as far as possible, and is then screened with a sieve of twenty -five to thirty fine wires to the lineal inch. **The portion which passes the screen is hydraulic lime of first quality,** if the stone be capable of yielding such, and, when used, requires only sufficient water to convert it into a stiff paste, in order to furnish an excellent matrix for mortar,

beton, or concrete**. The lumpy portions which do not pass the sieve either contain too much clay,** or have been burnt at too high or too low a heat to be susceptible of thorough extinction by exposure to the air, or aspersion with water. **The quantity of this lumpy residue will be great in proportion to the amount of clay in the stone, or the extent to which the heat in burning has been improperly regulated.** In some localities this residue is thrown away, as dangerous or worthless, **while in others it is the custom to grind it up separately, and mix it with the powder previously obtained by aspersion.**

When the burning has taken place at a heat suitable for making common lime, the residue owes its origin to the presence of clay, and may be a light, quick-setting cement, like the Roman. If so, its incorporation with the lime powder will augment the hydraulic activity of the latter, though perhaps not its ultimate strength and hardness. When the residue is too much under-burnt to slake readily, it may cause damage by a tardy extinction in the mortar, and should be rejected. **When burnt at a high heat, the residue may be Portland cement, if the stone contain from 20 to 22 per cent. of clay; or it may be inert clinker, partially or wholly vitrified, depending not only upon the amount, but also upon the form in which the silica and alumina exist in the clay.** The character of the residue, when ascertained, will determine whether it would be advantageous or otherwise to add it to the lime powder produced by slaking. (p59) and watchful care, in order that the introduction of ingredients that are worthless, or perhaps both dangerous and worthless, may be avoided....

...light, quick-setting cements are also produced by a moderate burning, from stone containing as high as 27 per cent., or even 30 per cent., of clay. Indeed, the amount of clay may reach, exceptionally, as high as 35 per cent. The cement made at Vassy, in France, the English and French Roman cements, and all of the American cements, (the Rossendale, Shepherdstown, Cumberland, Ooplay, and others,) belong to this class. In Austria the name of hydraulic lime is given to cements of this description. The Roman cement, made from the nodules of septaria derived from the Kimmeridge and London clay, is the best of the cements here referred to, though greatly inferior in strength and hardness to the Portland.

P61 Experience has fully proved that the heavy, slow-setting cements (the class upon which the name of Portland has been conferred, from the resemblance of the English variety to natural Portland limestone) **can only be obtained by burning, at a high heat, either limestones containing at least 20 and not more than 22 per cent. of clay, or an artificial mixture of the ingredients in similar proportions.**

Natural stone, suitable for this purpose, is found in Europe in the first range of the Jura formation, and on the lower slopes of the Alps in France and Austria, it generally occurs in numerous layers, which are very variable in the amount of clay which they severally contain, not exceeding from 10 to 15 per cent. in some, and reaching as high as 20, 25, and even 30 per cent. in others. The layers are generally thin, and there are but very few of them in which the desired proportion of 20 to 22 per cent. of clay exists, homogeneously distributed. By far the greater number contain either less or more than this amount. In whatever manner apparently homogeneous limestones may be exposed to burning, at a high temperature, it is impossible to avoid the complete vitrification of some layers containing too much clay, while others,

not containing enough, or less than 20 to 22 per cent, produce cements having lime in excess.

P62 107. It is to be borne in mind that Portland cement can only be made from a mixture, natural or artificial, of 20 to 22 per cent. of clay and 80 to 78 per cent. of carbonate of lime, and that the calcination must take place at a temperature sufficiently high to produce that peculiar softening which precedes incipient vitrification, it being at this stage alone that those silicates, upon the crystallization of which, in the presence of water, this cement depends for its peculiar merits, can be formed.

From an article entitled "Precautions in Building" in The Australian Town and Country Journal, 4 December 1875, discussing the poor quality of some mortars at the time:

The lime should be fresh, the sand a sharp grit and quite clean, and the water pure and free from salt. The sand is made into the form of a basin, into which the lime is thrown in a quick state; water is then thrown upon it to slake it, and it is immediately covered up with sand; after remaining in this state until the whole of the lime is reduced to powder, it is worked up with the sand, and then passed through a wire screen, which separates the core. More water is then added, and it is well worked up or larryed for use.

From around this time - certainly in the UK, less so at this stage in north american texts - we begin to see ordinary lime, even feebly hydraulic lime - being condemned as useless, in favour of hydraulic limes - usually artificially so, still made with pure or nearly pure lime but with coal or wood ashes or other kiln ashes being used as aggregate; or brick dust. Inevitably, in this context, natural hydraulic limes were looked upon more favourably - although this view of the latter would change once NHL became more commonly used for building mortars, no longer primarily for concretes. On all fronts, much of what we think we know about lime, aggregates and craft practice emanates mainly from this era - the late 19thC and on into the 20thC. Much of the thinking at the time, however, was at odds with the previous 2,000 years of thinking and practice. Searle (1935) stands out for looking more favourably on ordinary lime and mortars and arguing that these are better materials than cement for most purposes.

Heath A H (1893) A Manual on Lime and Cement, their Treatment and Use in Construction. London. Spon.

Sand is mixed with lime for three reasons:1) to lessen the quantity of lime used to make a given bulk of mortar; sand is generally cheaper than lime, and the cost of the mortar per cubic yard is thus reduced; 2) To confer on the mortar somewhat greater resistance to crushing, and also to prevent *excessive* shrinkage during the setting and hardening of the mortar in use. Mortar made from lime alone contracts when hardening. 3) To separate the particles of lime and render the mortar more porous (?), thus with the purer limes facilitating the penetration of carbonic acid, and accelerating the setting of the mortar….

QUALITY OF SAND. Sand should be in all cases clean, free from clayey matter or vegetable earth; when rubbed between the hands should not soil them, and when dropped into water should notcause muddiness (118); should consist of sharp, angular siliceous fragments *not less than 1/24th of an inch in diameter, and not exceeding 1/8 of an inch,* and should have a rough texture of surface. Calcareous or argillaceous sands are unsuitable, as the former will dissolve, and the latter partly dissolve *in acids*.

Fine sand may be defined as composed of fragments whose diameters range between 1/24 and 1/16 if an inch, coarse between 1/16 and 1/8 of an inch.

For making baton Coignet, or sand concrete, a sand having grains 1/3 of an inch diameter, about the size of a small bean or pea, may be used.

The strength of a mortar is found to depend largely upon the size of the grains of sand, and upon the coarseness of texture the grains. In sands of equal size of grain, the coarsest texture is the best; and in sands of equal coarseness oftexture, the larger grained are the best.

Coarseness of texture is, however, of greater importance than size of grains, and sand grains ofuniform size throughout do not necessarily make the best mortar.

Sands which are much waterworn, and consist mainly of rounded grains, are not so suitable for making either mortar or concrete; they are, however, often used in default of a better material….(119_

…There are two descriptions of sand in general use, ‘river’ or ‘pit’ sand. River sands are dredged up from the beds of rivers, either directly from sand-banks, or mixed with large coarse gravel, from which the sand is separated by washing and sifting. They are liable to be waterworn, and also mixed with mud and organic matter, thorough washing in clean water is essential.

Pit sands are found in layers or pockets among the rocks and soils of the earth's crust. These sands have all been deposited in place by the action of water at some period more of less remote. The grains are generally waterworn and rounde, and sometimes too small to rank mong the best class if sands; and may be loamy, that is, coated and mixed with clayey matter.

'Blown' sand is the fine-grained sand found forming hillocks and ridges at many places on the sea-coast. This sand is generally so fine grained that it is swept up and borne along by a high wind; the grains are much rounded and have a comparatively smooth surface. To make mortar or concrete with such sand, a large proportion of cementing material must be used to furnish the coating film, and the adhesion of the film to the smooth surface is comparatively weak. This sand should therefore only be used in default of a better material.

Sea sand may be used for mortar making with either hydraulic lime or Portland cement, but the mortar should not be used the erection of dwelling-houses, warehouses, etc, where the absorbent nature of the salt would tend to maintain a dampness in the walls. It is largely used in building dock walls and similar massive structures (120). Sea sand is often deficient in the essential qualities of sharpness of angularity, and roughness of texture of surface of the grains, and sometimes is not entirely composed of grains of silica (*alot of sea-shell/calcium carbonate - probably a benefit)*. If of suitable quality, and thoroughly washed in a stream of fresh water, sea sand can be used in mortar making for all purposes.

Loamy and clayey sands are injurious in cement mortar, *and to a less degree in lime mortar*.

Crushed sandstone, vitreous lava, quartzite, or quartz rock itself, will furnish a good sand for mortar making. For a dense impervious mortar, it is best to use the finer particles as well as the coarse, but with an additional quantity of lime or cement, above that which would be mixed with coarse sand only.

Finely granulated blast furnace slag, and crushed vitreous slag is sometimes used as sand: and puddling and reheating furnace cinders crushed small (121) and used for mixing within concrete for lacework. Scoriae from furnace hearthsandfirebars are also used, and if of well vitrified durable quality, make a good sand (122).

PROPORTION OF SAND USED

Gray chalk quicklime can be mixed with nearly three times its bulk of sand, an ordinary proportion is from 2 to 2 1/2 times the bulk of the lime before it is slaked.

Blue Lias lime should not be mixed with more than twice its bulk of sand for a strong mortar, and the best mortar is made with equal proportions.

For rubble stonework at Liverpool Docks, using Halkin hydraulic lime, the proportions were 1 of slaked lime to 2 of sand and 1/3 of crushed smithy ashes. For brickwork and for lacework of thick walls, 1 of slaked lime to 1sand and 1 of smithy ashes (122).

…..Cement mortar made with an excess of coarse sand may be peremeable to water. By adding lias or stone lime to the cement, the permeability may be greatly diminished. **A mixture of 1 cement to 2 slaked lime (133) to 6 of sand, was found to be an impermeable slab. Another proportion is given as 1 cement to 2 1/2 sand and a 1/4 of slaked lime for a stronger mortar than the foregoing.** *(this is in 1893, when portland cement remained relatively primitive and little stronger perhaps than the harder of modern NHLs - I wonder how these may equate with modern hybrid quicklime: NHL mortars, typically 1 quicklime: 1 NHL 5.0 or 3.5: 6 sand?).*

*A method (of working with lime in very cold weather) said to be adopted at Christiania (Norway) for building during severe frost, down to 14 degrees F, consists in the use of unslaked lime. The mortar is made in small quantities only, from unslaked lime, and used at once, and **the greater the cold, the larger the proportion of lime in the mortar**. The bricks used must be dry, and the mortar is probably used in a very moist condition and in thin joints. The new work is always protected as soon as built, especially against rain, snow and cold winds. (135) Heath (1893).*

Redgrave G R (1895) Calcareous Cements, Their Nature and Uses. London. Charles Griffin & Co.

Chapter X. The Composition of Mortar and Concrete.

Definition of a Mortar.

Mortar, as the term is commonly understood in this country, is applied to the mixture of lime or cement with water to form a plastic matrix for embedding or uniting together bricks or masonry. Such mortar invariably contains a certain proportion of sand. It was an opinion very widely entertained by the earlier writers on building construction that this sand had a beneficial effect on the mortar to which it was added, though we now know that there is no foundation for this belief.

Action of Sand in Mortar.

There are perhaps certain cases in which sand of a peculiar description and used in small quantities may tend to improve a sample of lime or cement, but such cases are quite the exception, for sand can only be regarded in the light of recent experiments as a dlutent or as tending to diminish the strength of any given specimen of lime or cement, and the only valid reason…is the advantage gained in point of economy by the employment of a cheaper material. *(Typical pointing mortars in North Yorkshire, from 16th and 17th Centuries were 2 parts lime to 1 part fine limestone dust, hot mixed. Such mortars have lasted 400 years)*. It has been, however, pointed out that, when exposed to compression in mortar joints, the influence of the hard particles of sand, if duly compacted, may be beneficial, owing to the increased power of resisting a crushing strain of hard particles of quartz, as compared with the friable or putty-like mass of a pure lime mortar or even a cement.

Properties of Mortar.

Mortar suitable for ordinary buildings must have the consistency of a creamy paste, in order to work well under the trowel into the joints and interstices of the materials. It should have considerable power of adhesion, so as to retain the substance with which it is being used in position, and it should possess the power of rapidly indurating and of becoming in course of time as hard as the remainder of the structure (?), which it should bind together into a species of monolith. Moreover, it should be capable of resisting the attacks of the atmosphere, moisture, and the other destructive influences to which buildings are ordinarily exposed. (112)

Influence of Sand…

Sand may act in four different ways…First, as respects the cohesion of the particles of the cementing material. Second, the adhesion of the lime or cement to the surfaces of the sand grains. Third, the possibility of causing the weak places, due to the occurrence of several particles of sand in contact without a sufficient supply of cementing material to envelop them and to fill up all the interstices, and lastly, the increase of strength the sand may develop, in such cases in which the sand grains are stronger than the cementing material, in consequence of the line of fracture being longer than it would be if no sand particles were present to interrupt the direct passage of the fracture in one plane.

Sand Tends to Weaken Cohesion of Mortar.

…we know from numerous tests, conducted by skilled observers, with every description of lime and cement, that the cohesion of the particles of mortar made from neat lime or cement is nearly always greater than….between the particles of the same cementing material when used with sand. If we regard the matter simply as one of cohesion and adhesion, though wide differences doubtless exist between the behaviour of various qualities of sand, whether the surface of the grains be rough or smooth, or whether the lime or cement be capable or incapable of exerting a chemical action upon them, the general effect of sand, which retains its position in the mass by the force of adhesion only, is to lessen the force of cohesion. The diminution of strength will be greater in the case of fine sand than it will when coarse or large-grained sand is employed, and it will invariably be larger in direct proportion to the amount of sand we use….**We substitute, in fact, a lesser force - that of adhesion - for a greater force - that of cohesion, the more sand we add.** To the same extent, also, that we increase the amount of sand, we incur the risk of weak points from a deficiency of cementing material. The only benefit we can trace then to the employment of sand is the interposition of the sand grains into the direct path of fracture…and insofar as these grains are stronger than the lime or cement we are using they may improve the mortar. (113)

(In general) Mortar is merely rendered cheaper by the employment of sand, but not in any sense improved by its use.

Opinions of Early Writers on Sand in Mortar.

From the time of Vitruvius onwards, all writers on the subject appear to have taken it for granted that a due admixture of sand must tend to improve the mortar. The earliest builders no doubt found that lime used alone, especially in the form of stucco, had a tendency to shrink and crack in drying, and that this failing could be corrected by the addition of a certain proportion of sand *(however, across UK, haired lime only plasters were very* common, especially over loam or loam-lime built fabric)….

Invariable Rule Established to Add Sand.

It gradually (114) became recognised as an established fact among builders that lime was capable of taking up a prescribed dose of sand…and it was not until Vicat and the careful experimenters of the French school, and out own countrymen, Smeaton and Pasley, began to conduct independent tests that the old faith in the efficacy of sand began to be shaken.

Proper Proportion of Sand to be Used.

….The views of Smeaton on the employment of sand are sound and good. He states that: “The use of sand in mortar, so far as I have been able to observe, is two-fold - 1st, to render the composition harder; and 2nd, to increase it in quantity by a material that in most situations is of far less expense, bulk for bulk, than lime. As there is no apparent change in the sand by the admixture of the lime, the sand seems only to render the composition harder, by itself being a harder body; for the best sand being small fragments of flint, crystal, quartz etc, is much harder than any body we know of that can be formed of lime only, which in paste is considered as a cement to the harder material, and therefore composes a harder body; for the same reason that if we had nothing naturally but lime as cement, and should build a wall with flints, crystals or rough stones cemented therewith, this wall would be harder than if built with lime alone."

(Vicat) asserts that the "intervention of pure sand does not tend or was before believed to augment the cohesion of which every kind of lime indifferently is susceptible, but it is injurious to rich limes, very serviceable to the hydraulic and eminently hydraulic limes, and is neither beneficial nor injurious to the intermediate kinds." (115)

Pasley's Rules for Use of Sand.

Pasley, whose (115) protracted investigations into the nature of cement mixtures and the influence of sand are so well known, did not fully recognise the facts of the case, for he seems to have thought that the strength *(perhaps more properly, the performance and fitness for purpose)* of mortar was in some way or other related to its plasticity or pleasantness in working (*He was right)*. He tells us that he found Calling lime would not stand so large an addition of sand as the common chalk lime, and he proceeds to state, "every one will acknowledge that the proportion of sand which will make good mortar with chalk lime, would entirely ruin (Natural) cement, which is scarcely capable of bearing one-third of that quantity". Of course he had in view the Roman cement of those days which will take but little sand; **but he spoke from the workman's point of view, and regarded a mortar as ruined when it was 'too short for use'.** (*Again, he was right)*. We now know that Portland cement will make a strong mortar with six volumes of sand, **although few workmen care to use it when mixed in these proportions.**

Totten's Theory as to Sand Addition.

We do not find any writer on this question who is entirely to be trusted until we come to the experiments of General Totten, who employed pure fat lime, and who clearly shows that each increase in the proportion of sand involves a

Nature of Lime.	Composition of Mortar. The Lime Measured in Paste.						
	0 Sand. 1 Lime.	¼ Sand. 1 Lime.	½ Sand. 1 Lime.	1 Sand. 1 Lime.	2 Sand. 1 Lime.	3 Sand. 1 Lime.	4 Sand. 1 Lime.
Smithfield fat lime,	262·5	245·6	222·5	214·7	170·3	154·6	135·1

falling off in the strength of the mortar, **the lime alone furnishing the strongest mortar (tested tensile, snapping strength of different mixes at 50 days).(116)**

Importance of the Size of Sand Grains

…The general experience is that coarse grained angular sand produces a tougher and stronger mortar than a very fine grained sand, **though the latter works more sweetly under the trowel.** This is probably due to the larger air spaces caused by the cavities and voids of relatively larger area….No mortar can be regarded as wholly satisfactory in composition in which the voids in the sand are not filled up by the cementing material, because otherwise certain of the grains might be in contact and have nothing to hold them together.

Scott on Proportion of Sand to be Used.

General Scott, as the result of the careful consideration of numerous specifications, comes to the conclusion that if we are using the feebly hydraulic gray chalk lime, such as is generally employed in the London district *(by this time, not so much before 19thC and not always even then),* **we may add 1 1/2 parts or even 2 parts of sand to 1 part of slaked lime by volume *(or 1 part of quicklime at least to 3 parts of sand at most, unless quicklime in powder form)*.** With a more hydraulic lime, such as that obtained from the lias formation, he would use 2 parts of sand to 1 part of slaked lime; and **with the pure chalk lime or the fat lime resulting from the calcination of a hard limestone** *(note the equivalence of chalk and (lime-) stone lime, albeit derogatory)* , since the mortar so obtained is at all times very inferior (*bullshit, lest hardness is the only criteria),* he states 'if we are compelled to use such miserable stuff we shall not be losing much in resistance if we increase the quantity to 3 parts of sand to 1 part of lime."

The Preparation of the Mortar

All the earlier writers on mortar laid great stress upon the thorough incorporation of the lime and sand, and it would seem by the price-books of the last century that in the country it took quite <u>a day for a labourer to beat together the ingredients necessary to make 1 cubic yard of mortar.</u> At the present time (1895) in all important works the (117) mortar is mill-made, and in this way, no doubt, a far better mixture of the sand and lime is obtained than by the old-fashioned system of beating or larrying. *(There is no empirical evidence to support this assertion, although 'mill-made' mortar is eminently workable, and perhaps the most pleasing to use).*

….Concrete in France and England.

In consequence of the inventions of M Coignet in France and of Mr F Ransome in this country, increasing attention has in recent times been paid to the production of monolithic structures formed of gravel or ballast, aggregated together into masses by means of lime (NHL, doubtless) or cement. Concrete is really a mortar matrix, serving to bind together a suitable proportion of pebbles, flints, or broken stones. The amount of lime or cement to be used in making concrete must thus be to a certain extent determined by the nature of the materials to be employed as aggregates. It ought theoretically to consist of a perfectly made mortar, sufficient in quantity to fill the voids of the larger materials, for which it is to be used as the incorporating medium. The proportion of lime or cement may vary from one-seventh to one twelfth of the aggregates, but no concrete can be really sound and good where the materials - the sand and gravel - are not properly adjusted. We mean by this that the lime or cement should be sufficient to amply fill the interstices of the sand, and the lime and sand mortar should properly fill the voids in the larger masses of stone. It has been found….that while the voids in pebble-gravel will average about 34% of the volume it occupies when dry, the voids on broken stone may average from 40 to 50% of the volume. Taking a mortar composed of 1 part of (119) cement to 3 parts of sand, we might safely add, for the purposes of concrete making, 3 parts of gravel to 1 of mortar, or 2 parts of broken stone. … When concrete is merely used as a material for foundations in trenches, this is not a matter of very great importance, but where the concrete is to be used moulded into blocks, or in order to form monolithic structures, it is very necessary to study these matters with care. (120)

Richardson C (1897) Lime, Hydraulic Cement, Mortar and Concrete. Part III. The Brickbuilder Vol 7 May. Rogers and Manson Boston.

Part III May 1897

LIME MORTAR.

Mortar is a mixture of some cementing material with sand.
Lime mortar is composed of lime paste and sand, with the addition, for certain parts of plastering, of hair and similar bonding material.

Necessity of Sand in Mortar. —

Good cream of lime might be used alone as cement, as it hardens on exposure to the air by drying, were it not that, under these conditions, it shrinks and cracks very badly. It is, therefore, customary, both on this account and for economy, to temper it with sand. This should be clean, sharp, and rather coarse for masonry, finer for plastering. When discussing hydraulic mortars and concretes there will be occasion for a further consideration of sand and its qualities and proper use.

Proportion of Sand to Lime.

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

In ordinary sands the voids are from 30 to 40 per cent, of the volume of the sand. With sand, having 40 per cent, such as that which is used for the best lime mortar, 1 volume of paste would fill the voids in 2.5 volumes of sand with no excess. **As a matter of fact, practice leads to the addition of only from 1.25 to 2 volumes of sand to 1 of paste which, when the caustic lime yields 2.5 volumes of paste, means 3 to 5 volumes of sand to 1 measured volume of caustic *(quick)* lime.** In this way a plastic mortar and one that will not crack in drying is made. **With fat lime and sharp sand 3 volumes of sand to 1 of lime forms a rich mortar and these proportions are often required in the best specifications. The greater part of the mortar used in ordinary brickwork is, however, made with 5 volumes of sand, or more, and is probably satisfactory.**

…Volume of Sand for Mortar. —

If but twice the volume of the lime is added to the paste in the form of sand, the resulting mortar is too rich. It contracts and cracks on drying. Three volumes of sand make a very rich and satisfactory mortar such as should be used for laying up fronts and pointing.

Five volumes form a mortar good enough for ordinary brick masonry where not exposed to moisture, while greater amounts of sand furnish mortars which are very porous, but serve for cheap work in absolutely dry situations.

Powell George T (1889) Foundations and Foundation Walls For All Classes of Buildings. New York. William T Comstock.

The purest limes require the largest proportion of sand and water, and harden in less time than the common limes...

Various substances are **sometimes** added to mortar to increase its **tenacity** (*good word*), and they impart thereto the principles of hydraulic cement **to a greater or lesser degree.** They chiefly consist of burnt clay, ashes, scoriae, iron scales and filings, broken pottery, bricks, tiles etc. They are useful in mixing with lime or mortar to increase their hardness, but they must be pure and reduced to a fine powder...

…Common mortar of ashes is prepared by mixing two parts of fresh slacked lime with three parts of wood ashes and when cold to be well beaten, **in which state it is usually kept for some time... by some it is considered equal to some of the water cements.**

Sutcliffe G L (ed) THE PRINCIPLES AND PRACTICE of MODERN HOUSE-CONSTRUCTION. VOL 1 1899 Blackie, London, Glasgow & Dublin

p119 The wisdom of allowing no more than four volumes of sand to be used with cement is manifest, and it is certainly better that even a smaller proportion of sand should be used, or that a certain amount of thoroughly slaked lime should be added in order that the mortar may be more dense. The writer usually specifies cement-mortar to be a 1 to 2 mixture, and never goes beyond 1 to 3. Excellent mortar can be made from hydraulic lime, such as the well-known Lias limes, mixed with sand in the proportion of 1 to 2. The lump or shell lime may be used, but the ground lime is much to be preferred, especially where a mortar-mill is not available. The ground lime can be distinguished from Portland cement by its yellow colour.
As sand (or some substitute for sand) forms the greater part of nearly all mortars, its importance cannot be denied. Certainly pure sand is inert, but much " sand " used in buildings is mixed with clay, iron and other salts, and organic impurities, and is detrimental to the lime or cement with which it is used. In one case about a thousand concrete blocks, in which sand containing iron-pyrites had been used, were quite worthless, as the pyrites destroyed the setting

TABLE II.

TENSILE STRENGTH OF GRAY LIME AND PORTLAND CEMENT MORTARS, &c., AT THE AGE OF SIX MONTHS.

No.	Composition by Volume.					No. of Tests.	Average strength in lbs. per sq. inch.		Ratios of strength.	Cost per cub. yd. of mortar.	Relative cost per unit of strength.
	Portland Cement.	Gray Lime.	Loam.	Sand.	Water.						
1	—	1	—	2	1·33	17	27·13			s.	
2	—	1	—	2	1·33	27	47·09	36·88	1	11·83	100
3	—	1	—	2	1·33	27	36·44				
4	1	—	—	6	1·25	15	103·79		2·81	11·56	35
5	1	—	—	8	1·66	20	68·8		1·86	9·93	45
6	1	—	—	10	2	35	50·16		1·36	8·88	55
7	1	·5	—	6	1·5	70	73·47		2	12·2	52
8	1	·66	—	8	2	74	58·94		1·6	10·72	57
9	1	·83	—	10	2·5	85	42·34		1·14	9·75	72
10	1	—	·5	6	1	21	60·8		1·64	11·44	59
11	1	—	·66	8	1·33	25	38·43		1·04	9·82	80
12	1	—	·83	10	2	19	28·66		0·77	8·76	96

It will be noticed that a mortar composed of *one* part of Portland cement, *one-half* part of gray lime, and *six* parts of sand,—a mortar, be it said, which is sufficiently plastic for the bricklayer's purpose,—is, at the age of six months, exactly twice as strong as a mortar composed of *one* part of gray lime and *two* parts of sand, while the cost per cubic yard is practically identical. As far, therefore, as convenience in working, strength, cost, and, I may add, durability, are concerned, the advantage is on the whole greatly in favour of the cement-mortar, but it must not be forgotten that a mortar containing such a large proportion of sand is far from impervious. In any volume of sand, the inter-

951

properties of the cement. The salt in sea-sand, when this is made into mortar or plaster, attracts moisture, causing dampness and often leading to efflorescence. The clay in loamy pit-sand may lessen the strength of cement- mortar as much as 50 per cent. Soot in mortar or plaster will cause stains in paint and wall-paper. Organic matter, such as dung in road-scrapings, may lead to the colonization of the house-walls with innumerable micro-organisms, which may be quite harmless or quite otherwise.

Sand from quarries, quickly-flowing streams, and little-frequented roads macadamized with coarse-grained stone, is usually suitable for mortar. Pit-sand is good, if reasonably free from clay and other impurities.

" Sand " from sluggish streams and ditches, from roads macadamized with hard, fine-grained limestone and "granite", and from foundries, had better be rejected; so also must street-sweepings.**The principal substitutes for sand are ashes or "breeze", brick-dust, and burnt clay-ballast.** Ashes yield mortars of a somewhat weak and porous character, and may interfere with the proper setting of cement if they contain coal-dust or other impurities. Brick-dust and clay- ballast make good mortar, if they are properly burnt, hard and clean.
P120 When a mortar-mill is not used, all grit and lumps should be carefully screened from the sand and lime before these are mixed, as they would tend to crack the bricks and stones if used in the mortar.
In making mortar, a little sand more or less does not matter very much when ordinary lime is the matrix, but even in this case the measurement of the lime and sand should be carried out with some approximation to accuracy. When, however, hydraulic lime and cement are used, the careful measurement of these and the sand, in suitable boxes or frames, must be insisted on.
Water used in mortar should be fresh and clean.

Kidder F.E. (1920) Building Construction and Superintendence. Revised and enlarged by Thomas Nolan. Part 1 Masons' Work.

149 SAND. The reason sand is used in mortar is because it prevents excessive shrinkage and reduces the cost of the lime or the cement; and while its addition to cement mortar always weakens it, its addition to lime mortar in the proportion of 1 to 2 for example, adds to the latter's strength...

the usual specifications for sand used in making mortar require that it shall be angular in form, of various sizes, and absolutely free from all dust, loam, clay, earthy or vegetable matter, and also from large stones.

Recent tests and experiments, however, seem to lead engineers to the following conclusions:

1. it is not necessary to have the grains sharp;

2. the coarseness of the grains governs largely the quality. In mortars loam or clay is sometimes injurious, and sometimes beneficial, at least in cement mortars

3. **the pouring of water into sand does not accurately determine the voids**, which can be found by weighing the sand and finding its moisture

4. because of the effect of varying degrees of moisture, a study of voids does not result in a method of comparing sands

5. dry sand measured loose is heavier than moist sand

6. when mixed with cement coarse sand makes a denser mortar and requires less water than fine sand

7. fine sand with grains of uniform size and screened coarse sand when dry have nearly the same weigh, but with ordinary moisture fine sand is lighter and more porous than coarse sand

8. the weight of mixed sand is usually greater and the volume of voids smaller that that of coarse or fine sand...

For rough stonework a combination of coarse and fine sand makes the strongest mortar. For pressed brickwork it is necessary to use a very fine sand. ...

Some masons attempt the use of fine sandy loam in their mortar, as it takes the place of lime in making their mortar work easily; but it generally tends to weaken the mortar, and it is better not to permit its use.

Pulver H E (1922) Materials of Construction. Engineering Education Series. McGraw-Hill New York.

PROPORTIONING AND MIXING OF LIME MORTAR

Sand should be added to the lime paste for four reasons:
1. to prevent excessive cracking and shrinking of the lime mortar when the

water evaporates
2. to give greater strength to the mortar
3. to divide the lime paste into thin films and to make the mortar more porous, thus aiding tin the absorption of carbon dioxide...which causes the lime to set or harden
4. to reduce the cost.

The usual proportions vary from 2 to 4 parts of sand to 1 part of lime paste. With most sands and limes, the correct proportion will be from 2 1/2 to 3 parts of sand to 1 part of lime paste by volume. ...The volume of the lime paste should be just a little more than enough to coat completely all of the sand grains and fill the voids.

In mixing the mortar, the lime paste is first spread out in a thin layer a few inches thick and the sand spread uniformly over the top. The lime paste and sand are then mixed by hoe or shovel until the mass is of uniform color. A little water should be added, if necessary, to make the mortar of the proper consistency. Thorough mixing is required to make a good mortar....

If too much sand has been used the mortar will be ‘short’ and ‘stiff’ and will not work properly; while if too much lime paste is used, the mortar will be too sticky to work properly. A mason can tell very quickly whether the mortar is correctly proportioned or not when he starts to use the mortar in his work. The proportions which give the best working mortar are also the best proportions in regard to strength, hardening and other properties (except when clay or loam is used instead of sand).

Frost W (1925) The Modern Bricklayer, a Practical Work on Bricklaying in all its Branches Volume I. London. Caxton Publishing Company.

Aggregates.—Aggregates for mortars usually consist of sand, although crushed bricks and other materials are sometimes used. They should be clean, free from dust, soil, and organic matters, and must not contain salt. Salt causes effervescence and dampness in the mortar, and prevents the cement and lime used in the mortars from adhering to the particles of sand.

Sand should always be clean. Loam can be detected sometimes by the naked eye and also by taking a handful of sand and rubbing it together; the loam will be detected by the touch, the sand being sharp and the loam rather of a soft sticky nature. Sand is sometimes examined under a microscope to see whether the grains are of a sharp angular shape or rounded.shape Sand is sometimes washed through a sieve to eliminate the loam and other matters found in it.

In sea sand and river sand the grains are of a round shape on accounts of the continual movement of one grain against another while a good pit sand possesses grains which are of a sharp, angular shape. Being very often found mixed with stones or gravel, it is sifted or screened. The wires in the sieves or screens are spaced according to the fineness of the sand required. The frame is usually fixed at an inclined angle with a prop placed at the back of it to keep it in a firm position. The mortar man has a large pile of sand deposited to be sifted, in front of this he places his screen, and fixes it in position, he then shovels up the unsifted sand and throws it against the screen. This being in an inclined position, the surplus stones from the sand roll down the face of it slowly and form a heap, the fine sand passes through the screen and forms another heap and is removed from time to time when ready for use.

Quicksand is sand which is easily distinguished by the particles, which are very small and round, in some cases the sand is as fine as a powder. These small particles are worn round by the action of water. **This sand should not be used for mortar**. The quicksand, if made into mortar in combination with another material, has the tendency to settle to the bottom, leaving the matrix in the topmost position. The mortar man has to be continually mixing it, in order to combine the two together.

Crushed bricks form an excellent aggregate. Mr. L. E. Walker cites the case of a speculative builder who put up a large block of flats on a plot partly occupied by small houses, which he pulled down. The bricks were crushed on the job, and were mixed with the lime (no sand being used) in the mortar mill. The proportion of lime was below the average, yet the mortar proved quite satisfactory.

Indeed, when part of the brickwork had to be cut away, it was found that the mortar had developed amazing strength within a month or two.A useful mixture is 1 part lime, 2 parts crushed brick, 1 part fine sand; next dry and gauge as in usual way.
Water.—Water used in mixing mortar must be clean, free from clay, soil, salt, or organic matter.

Searle A B (1935) *Limestone and its Products, Their Nature, Production and Uses.* London. Ernest Benn Ltd.

3. THE USE OF LIME IN BUILDING CONSTRUCTION

Lime has been used since prehistoric times as the chief constituent of *mortar, lime cement,* and *lime concrete,* in the production of *plaster, stucco,* and other facing materials in later times, and, still more recently, as a binding agent in the manufacture of *lime sand bricks* and to facilitate the placing of *concrete*.

Other minor, yet important uses of lime in building construction are its employment as a *lime wash* or distemper, and as a constituent of some *paints*.

For most building purposes, a somewhat impure lime is often preferable, because the argillaceous material present, or the siliceous material introduced by burning the stone in contact with the fuel, produces **feeble** hydraulic properties which make a stronger joint or surfacing material.

A rough distinction exists in the building trade between " fat " or " rich," and " poor " or " lean " limes. The former slake rapidly with high rise in temperature ; the latter slake slowly and without much rise in temperature. Fat limes set only by absorption of carbon dioxide, but lean limes are hydraulic and set like diluted cements.

LIME FOR USE IN MORTAR

Mortar is a mixture of sand and water with some binding material, such as lime or cement or both. A fibrous material, such as hair, is often added to increase the strength. In lime mortar the lime forms a colloidal gel with some of the water and this gel coats the sand grains. As the mortar dries, the colloidal gel dries and shrinks and so holds the particles together. A small proportion of crystalline calcium carbonate is also formed and the interlacing of the crystals increases the strength of the mass. The mixing of the various ingredients must be thorough; all fat lime mortars are improved by prolonged mixing, but in those containing hydraulic-lime cement the mixing must not be continued after the cementitious portion has begun to set. The mixing may be by hand or machinery; the use of the latter is generally known as *grinding,* but no actual grinding should occur with properly prepared materials. Mortar made with fat lime should not be used for 24 hours or more as storage greatly improves its workability.

For the production of ordinary mortar for general use by builders either a fat lime, a lean lime, or a hydraulic lime (Lias lime) may be used. Fat limes are preferred, but lean limes can be employed if they do not slake too slowly ; they are regarded less favourably by some builders, because they have a much smaller sand carrying capacity, and the resulting mortar does not “work” very smoothly. **Hydraulic limes are stronger in cementing .power, and behave like a mixture of fat lime and Portland cement.**

Magnesian limes are generally suitable for mortar and sometimes excel calcium limes in smoothness, working, sand carrying power, and resistance to weather. There is also evidence that magnesian limes give mortars that eventually give greater strength than those made of high calcium limes. They slake more slowly than calcium limes, and, unless care is taken, the mortar may prove to be unsound by a steam pat test. The slow slaking is often due to partial overburning of the lime.

Greystone limes are highly appreciated for the strength of the mortar which they produce as a result of being feebly hydraulic, though this reason is seldom realized. **Ground greystone lime requires about one month after being mixed with water before it develops appreciable hydraulic strength. It loses this property if the lime is stored in the form of putty or if it is soaked and kept for a long time before use.**

Mortar made with a *fat lime* or a *lean lime* with a low silica-content does not “set " in the same manner as hydraulic lime or concrete. Such lime merely dries, and by gradual absorption of carbon dioxide on its surface it becomes moderately hard externally, but the interior of the mass may remain soft for several hundred years *(although rarely)*. The purer the lime and sand used in the preparation of the mortar, the softer will be the mortar, no matter how long it has been in use. The carbon dioxide absorbed from the air combines with the lime at the surface of the joints, and, by closing the pores, prevents a further penetration, so that most joints in old masonry are only hard for a very short distance below the surface *(this, too, is rarely so and - for myself - I have never worked on an old building wherein the lime mortars had not fully set up at depth)*.

Hydraulic lime, on the contrary, undergoes a complex chemical change when in contact with water and " sets " to a hard mass. It does this equally well in air or under water, provided the mortar is supplied with sufficient water to ensure its adequate setting and subsequent hardening. **If the supply of water is insufficient, the hardening will be incomplete.**

Fat limes can be caused to harden like hydraulic lime and cement, by adding a suitable proportion of a material which will combine with the lime, forming a compound somewhat resembling those in hardened cement concrete. Such material is known as *pozzuolana ;* the commonest variety is *trass,* which is extensively used on the Continent, but an equally good substitute is made by grinding underburned bricks or tiles to a fine powder, provided they are sufficiently rich in clay.

Pure limes to which no pozzuolana has been added should not be used for work in contact with water, but only for structures above ground level.

Lump limes for ordinary mortar may be composed chiefly of calcium oxide, or of a mixture of calcium oxide and magnesia, according to the nature of the stone from which the lime has been made.

***High calcium limes* are generally regarded as preferable, because they slake readily and completely in a short time whereas magnesian limes slake more slowly and uncertainly and may, therefore, cause trouble (see p. 485).**

The precise composition of such limes is not of great importance provided the lime is properly burned. To guard against the inclusion of unburned stone or *core* and of overburned lime, it is desirable to specify that the sample shall not contain more than 10 per cent, of carbon dioxide and that when the sample is washed through a No. 20 sieve, it should not leave a residue of more than 5 per cent, (when dried).

Opinions differ greatly as regards composition, but for a high-class lime, the sum of the lime and magnesia present should not be less than 95 per cent, on the ignited sample, and a high-class magnesian lime should not contain less than 20 per cent, of magnesia.

For many structures, a lime containing only 85-90 per cent, of lime and magnesia is quite satisfactory.

In comparing two or more limes, it is important to compare the amount of sand which can be mixed with each lime without the mixture being too " lean to " work " satisfactorily. Alternatively, the plasticity of the samples can be determined before and after mixing with various proportions of sand.
In limes used for building construction, the physical characteristics, such as plasticity, time of set, colour, hardness, and strength, are of great importance, whereas chemical composition is immaterial except indirectly, inasmuch that limes made from limestone of different purity and composition usually have different physical characteristics. Thus, magnesian limes in general are more plastic than high calcium limes and are preferred for " finishing " purposes (but see p. 578).

The lime which can carry the largest quantity of sand should be the best for mortar. A useful indication of the quality of a lime is to measure its volume before and after slaking. All good limes will increase in volume, but a fat one should increase to three times its original size. Limes which produce less than twice their volume of slaked lime are described as *lean* or *poor*.

Before mixing it with sand or any other solid material, a quicklime should be slaked and made into *lime putty*;- the hydrated lime merely requires to be mixed with water, and the hydraulic lime should be slaked by sprinkling it with water, avoiding an excess, and finally passing it through a No. 5 or finer sieve.

The chief disadvantages of lump lime for use in mortar are : -

(i) It requires slaking, which is troublesome and tedious.
(ii) It frequently contains much *core* and useless material.
(iii) The quality varies greatly and cannot easily be checked by the builder; consequently, the quality of the mortar also varies.
(iv) It soon spoils if kept before being used.
(v) It is inconvenient to keep on account of its caustic properties.
In short, it has all the disadvantages of a crude material. **In the United States, it has been replaced almost completely by hydrated lime, which is free from all these objections.**

In some localities, the quality of lime, as compared with that made fifty years ago, has deteriorated seriously. This is due to the skilled burners having left or died and other men with less care and skill having taken their places. To a smaller extent, the change is also due to the use of inferior coal, which does not burn the stone so effectively, and introduces a larger percentage of ash into the lime. It is, therefore, more than ever necessary that builders should ascertain the quality of the lime they are buying.

As lime in mortar fills the voids or interstices between the grains of sand, the dry mortar has only about three-quarters of the volumes of the sand and lime measured separately.

Hydrated lime **serves precisely the same purposes in building as lump lime, but it does not require slaking (merely mixing with water) and it is free from several other disadvantages of lump lime. It does not " set " or " harden " like cement, but behaves in mortar like a skilfully slaked lime.**

Hydrated lime may be a high calcium or a magnesian lime. In either case, the total lime and magnesia should not be less than 95 per cent, of the weight of the ignited sample in a high class hydrated lime, but may be 85-90 per cent. in an " ordinary " hydrated lime. The carbon dioxide present should not exceed 5 per cent.

As a check on proper preparation, a hydrated lime should pass completely through a No. 20 sieve and the high-class hydrated lime should not leave more than 1 per cent, of residue on a No. 50 sieve or 10 per cent, on a No. 200 sieve. The " ordinary " hydrate may be rather coarser, but should not leave more than 15 per cent, of residue on a No. 200 sieve. Water should be used during the sifting.

Hydrated lime should not " blow " or " pimple " when mixed with sand and water and allowed to harden.

The advantages of hydrated lime in making mortar are :

(i) It can be stored indefinitely and easily.
(ii) It requires no slaking.

(iii) It is more uniform in quahty.
(iv) It contains less " core " or useless material and so can be used without waste.
(v) It avoids the production of bad putty through carelessness or ignorance of the man in charge of the mortar.

(vi) It avoids the loss otherwise caused through having to make more putty than is needed to allow for useless material in the lime.

(vii) It is particularly easy to measure and use.

(viii) E. W. Lazell has shown that mortar made with hydrated lime is stronger than that made with hand slaked lime and used immediately. The reason is that mechanical slaking under proper control ensures complete hydration, whereas, with hand slaking, the paste must be left for some weeks before the hydration is complete. Moreover, in hydrated lime, the coarser, unaltered particles are separated, so that the risk of caustic lime in hydrated lime from a good firm is negligible. Much of the hydrated lime on the market is not as good as a hand slaked lime putty about a year old, because the plasticity of lime can only be developed in the presence of more water than is permissible in hydrated lime. **For most building purposes, however, hydrated lime is as good as need be desired.**

Various notes on hydrated lime and mortar are given in the section on

" Hydrated Lime " (p. 517).

The *advantages* of fat lime—either lump or hydrated—are :

(i) It enables bricks to be laid more rapidly and more easily than when cement is used, as lime is more plastic than cement. 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.**
(ii) Fat lime produces the only mortar that can be prepared in large quantities in advance, *i.e.* that made from either quicklime or hydrated lime. All the lime mortar needed for a structure can be mixed before the walls are started. It may be stored, either in a stack or pit, until required, and, in fact, is actually better and more easily worked because of the ageing. This feature of lime mortar affords a good chance for economy, as machine mixing is particularly suitable and satisfactory. As the mortar is required, it may be fe-tempered to the desired consistency and used with full confidence.

(iii) Fat lime makes the most economical mortar. The cost of the materials is low, because of the high sand carrying capacity of the lime. The strength of the mortar is ample, thus permitting it to be used under practically all conditions. The natural plasticity of the lime decreases the cost of mixing the mortar, of spreading the mortar bed, and of placing the bricks. No mortar is wasted. If the mortar is mixed as needed, any left over at the end of a day, or not used, because of a sudden shut down on the job, can be stacked and used when work begins again. If cement mortar works short, the droppings are excessive, 10 per cent, being sometimes wasted. This is not the case with lime mortar, for the only droppings are due to trimming the joints, and these are negligible.

(iv) Fat lime mortar avoids delaying the bricklayers, who, when .cement mortar is used, have to wait for mortar to be mixed. Lime mortar is always ready for use and so increases the efficiency of the entire force and makes maintenance of construction schedules easy.

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.

In order to secure the best results, the lime must be properly treated. The best method is to prepare a lime putty by slaking the lump lime or by mixing the hydrated lime with water (p. 525). The modern desire for speed makes most builders unable to keep the putty for a long time, and, consequently, the full plasticity of the lime is seldom developed in modern mortar. This is wasteful of lime as old lime putty will carry more sand, than newly made putty.

Specification for lime for Mortar. A tentative specification for quicklime and hydrated lime for use in mortar has been prepared by the Building Research Station which suggests :

Quicklime : Class A.—Not less than 95 per cent, of calcium oxide and magnesia in the ignited sample.

Class B.—Not less than 85 per cent, of calcium oxide and magnesia in the ignited sample.

.In both classes: not more than 5 per cent, of residue when washed on a No. 20 sieve. •'

No fineness or soundness tests are imposed.

Hydrated Lime : Class A.—Not less than 95 per cent, of calcium oxide and magnesia in the ignited sample and not more than 5 per cent, of carbon dioxide. No residue to be left on a No. 20 sieve, not more than 1- per cent, on a No. 50 sieve, and not more than 10 per cent, on a No. 200 sieve.

Soundness : A pat, 4 in. diam. and 1 in. thick, of the lime with five times its weight of sand and enough water to make a paste, is allowed to set in air for 24 hours ; it is then covered with a thin coat of lime paste, allowed to set a further 24 hours and is then exposed to steam for five hours. It must not crack.

Class B.—Not less than 85 per cent, of calcium oxide and magnesia in the ignited sample, and not more than 5 per cent, of carbon dioxide. No residue on a No. 20 sieve and not more than 15 per cent, on a No. 200 sieve. No soundness test is imposed.

Hydraulic limes can be purchased-in the lump or ground form, the latter being far more convenient. They are characterized by their power of setting and hardening in water and behave in many respects like a mixture of Portland cement and lime. **They differ greatly in composition and properties,** and are conveniently divided into three classes : (i) feebly hydraulic ; (ii) moderately-hydraulic ; and (iii) eminently hydraulic.

Moderately hydraulic limes set in water in about 6 or 8 days and harden for a further period of several months. Eminently hydraulic limes may set in 3 or 4 days and become quite hard in one month….

Hydraulic limes are chiefly used where a mortar is required to have a' greater strength than can be produced with a fat lime. At one time they were widely used, but since the use of Portland cement has become so popular the latter is

usually preferred, as it is stronger and more regular in composition an'd properties.

Hydraulic limes are also used in foundations and in locations where the.- brickwork or masonry may be in occasional or constant contact with water.

When slaking hydraulic lime, the use of too much water must be avoided: too little will do no harm. It is usually better to buy the hydraulic lime ready-slaked.

LIME FOR WINTER MORTAR

When brick laying must be carried out in very cold weather, the most satisfactory mixture consists of one measure of Portland cement, two of fat lime, and nine of sand. This is much cheaper than a cement sand mortar, is less sensitive to frost, and is easier to work. Mortar must not be used during actual frost, and bricks laid just prior to a frost must be covered, or otherwise protected until the mortar has hardened.

LIME IN CEMENT MORTAR

The addition of a little lime putty or hydrated lime to cement mortar makes the latter spread more easily and work more smoothly. It also increases the adhesive properties of the mortar.

The lime putty, or a paste made by mixing hydrated lime with water, should be added to the dry mixture of cement and sand, any additional water required being then added and the whole mixed thoroughly.

On work frequently exposed to water, the addition of lime is undesirable as it tends to be washed out and leaves a porous mortar.

The best lime is a fat, high calcium lime, such as is used for *fine stuff* in plastering. Hydrated lime is more convenient than lump lime…..

LIME CONCRETE

Long before the invention of Portland cement, lime concrete was extensively used, especially in the East. The lime is mixed with twice its volume of coarse aggregate. If half the sand is replaced by trass, or, still better, by an artificial pozzuolana made by lightly calcining clay and grinding the mass to powder, a better concrete will be produced. The concrete is excel- lent in quality, but requires longer to harden sufficiently than do cement mortars.

The lime used should be a fat lime, such as is employed for mortar, but hydraulic lime is also used for the same purpose.

When rapid hardening is not essential, lime concrete will serve many pur- poses for which cement concrete is generally used, and will be much cheaper. It is not, however, suitable for reinforced concrete.

LIME IN PLASTER

Lime plaster consists of a mixture of slaked lime and sand (with or without hair) which is largely used for coating the walls, ceilings, or roofs of buildings. A finer quality lime and sand is used for interior work, and hair is usually added to increase the tensile strength of the mixture ; other fibrous materials,

including asbestos and wool waste, may be used for the same purpose. Instead: of hair, other fibrous material may be used, but the fibres must be long and thin or the plaster will not adhere to them.

A coarser lime and sand—often with some gravel—is used for exterior work and, instead of hair, cow dung is sometimes added to make the mixture work

more smoothly and dry to a harder mass. The short pieces of straw and other undecomposed vegetable fibre present in the dung also acts as a strengthening agent, like hair.

Hence, the use of lime in plaster includes its employment for (i) interior plaster on walls and ceilings ; (ii) exterior plaster, such as rough cast and stucco ; (iii) fresco, and (iv) floor plaster.

For *interior Plaster,* either quicklime or hydrated lime may be used.

For the first coat or *Coarse Stuff,* a lime of inferior quality may be used if •desired, provided the sum of the lime and magnesia (on the ignited sample) is not less than 85 per cent, and that not more than 10 per cent, of carbon dioxide is present. Where lime of better quality is desired, the sum of the lime and magnesia (on the ignited sample) should not be less than 95 per cent, and the carbon dioxide should not exceed 10 per cent. With either quality of lime there should not be more than 5 per cent, of residue left on a No. 20 sieve after the sample has been slaked and washed on the sieve.

Magnesian limes slake very slowly and are, therefore, less suitable for plasters than wholly calcium limes, unless ample time is allowed for complete slaking before use.

Any hydrated lime of good commercial quality may be used and has the same advantages as are described under " Mortar." Greystorie lime is largely used for the first coat on account of its slight hydraulic properties.

For *Fine Stuff,* only first-class fat lime should be used. It should contain not less than 95 per cent, of lime and magnesia (on the ignited sample) and less than 10 per cent, of carbon dioxide. It should slake readily, and when the slaked material is washed through a No. 20 sieve, there, should be less than 5 per cent, of residue left. Magnesian limes may be used, but are open to the objection mentioned above.

Hydrated lime of good quality is excellent and preferable to lump lime.

Plasterers are always afraid of using slow slaking limes, as these often " blister " when on the walls or ceilings and are then very objectionable.

Fat lime is particularly suitable for interior plaster, because :

(i) It is more plastic than any other, can be spread, with less effort, and covers a large surface.

(ii) It is cheaper than cement or plaster of Paris, both in first cost and in sand carrying power.

(iii) It does not spoil (like cement) if used slowly.
(iv) The plaster can be prepared some time before and used when required. (v) There is less waste than with other materials>
(vi) It is an ideal base for colours and decoration.

Lime for use in plastering must not crack when in use. The shrinkage

of fat lime is overcome by the use of a suitable proportion of sand.
It is a common mistake for plasterers to use too little sand; the result is that the plaster shrinks, cracks, and may fall away. For ceilings, the addition of a little plaster of Paris is an advantage which is well worth the extra cost.
For *Exterior Plaster,* including *rough cast* and *stucco,* lime is the most suitable binding agent. It has a greater covering power than Portland cement. It is a mistake to use too little sand with the lime, as both " rough cast " and " stucco " should be as lean as possible.

The most suitable lime is a fat lime, such as that specified for interior plaster (" fine stuff") and, whilst an inferior lime may be used, it is not recommended.

The advantages of lime for exterior work are :
(i) It is cheaper and " goes further " than Portland cement.

(ii) **It is equally durable.**
(iii) It has a greater sand carrying power.
(iv) It is more plastic and so is easier to use.
(v) *The slow hardening enables the material to adjust itself to the back- ground better than cement plaster can do.

(vi) The waste is much less.

Fresco is made by mixing a fine, fat mortar with fine sand and water, applying over the ordinary " coarse stuff " on a wall, and painting on it with coloured distempers whilst the surface is still damp.

The quality of lime which should be used is the same as for the " fine stuff " in interior plaster.

Floor Plaster is now seldom made with lime, as a harder surface is obtained more rapidly when cement is used. When the wear is not likely to be severe, lime plaster makes an excellent floor ; it is also useful as a base on which a thin coat of cement sand plaster can be laid.

The lime used for floor plaster should be the same as that used for *coarse stuff in* interior plaster, but, for the surface, the lime used for *fine stuff* is preferable.

Hydraulic lime is sometimes used for floor plaster and is satisfactory where wear is not excessive. It produces a sHghtly harder floor than fat lime, but not so hard as when Portland cement is used….

LIME IN CEMENTS

Lime is an important constituent of *Portland cement, Roman cement,* and similar materials, but as it is not used in the form of lime (but as stone), it is outside the scope of the present chapter.

Portland cement can be made slower setting and more plastic by the addition of a small proportion of hydrated lime. This is not usually done by the cement manufacturer, but by the concrete mixer (see " Use of Lime in Concrete ").

Slag cement is made by grinding granulated slag to a fine powder and then adding a little lime or gypsum to retard the setting to a suitable extent.

Lime-glue cement.—Lime is occasionally mixed with *glue* to form a strong adhesive for wood and similar materials. One method of preparing such a mixture consists in mixing ^ oz. of finely ground slaked or hydrated lime with 2 oz. of sugar and 6 fl. oz. of water, heating the mixture for several hours at 65° C, filtering and adding to the liquid one-fifth of its weight of glue. The product, which solidifies on cooling, is easily melted.

Lime-albumen cement is usually made by mixing finely-ground lime or hydrated lime with sufficient white of egg to produce a paste. It should be used at once. Other lime-albumen cements are known as casein-cements.

Casein-cements.—Lime is largely used in the manufacture of casein-cements, which are somewhat indefinite compounds of cheese and lime. For this purpose, the lime should contain at least 95 per cent, of free calcium oxide and it should, after slaking, be free from all gritty matter. To ensure this, the slaked lime must usually be sieved. Hydrated lime, if properly made, can be used without any preliminary treatment other than mixing with water. The most suitable form is *milk-of-lime,* which has been passed through a sieve with 80-holes pec linear inch. It is important that the lime should be fully slaked before it is miLd with the casein, and, for this reason (unless hydrated lime is used), the " milk " should be made some time before it is required, particularly if a slow slaking lime is used.

Casein-cement is largely used by joiners and other wood workers, as well as for a variety of minor purposes by plumbers and other workmen engaged in the building trades.

Ministry of Works Advisory Leaflet No.6 (1950) Limes for Mortar. London HMSO.

How to Use Lime When Mixing Mortar.

The Kinds of Lime.

All limes start as lump lime, or quicklime, which is obtained by burning chalk or limestone in a kiln.

1075

Blue Lias, and similar limes, which come from limestone containing clay, have the property of setting under water soon after slaking; they are therefore known as hydraulic limes, and are used mainly for mortar.

Greystone Limes come from chalk containing only a little scattered clay minerals – not enough to make them fully hydraulic – but they will harden under water or when moist in two to three weeks after slaking. These limes are classed as semi-hydraulic; they can be used for both mortar and plastering.

White Limes (mountain limes, chalk lime etc) come from rocks which are practically pure limestone or chalk. They do not set hard under water, and are therefore classed as non-hydraulic limes. They are used for plastering and making cement-lime mortar.

Magnesian Limes are made from dolomitic limestone. They are in a class by themselves and are used mainly for mortar, but they must not be used with bricks containing sulphates. They are mostly non-hydraulic.

Lime Putty.

Quicklime must be slaked before it can be used. In the old days all builders used to slake their own lime, running it to a paste known as lime putty *(this is true only of the 20th C, for the most part].*

Lime putty run from quicklime is still used in some parts of the country and for special jobs, since one of its chief characteristics is good workability.

Slaked non-hydraulic limes improve with keeping, so they should stand for **at least two weeks** to fatten up before use. They should be kept moist and undisturbed until they are needed. **Semi-hydraulic quicklimes are usually slaked as non-hydraulic limes, but the wet putty must not be stored.**

Slaked hydraulic limes do not keep – the quicklime is usually slaked on the building site by spraying it with water on a clean wooden platform until thoroughly moist: it is then heaped together, covered with sandand left for about 36 hours. The material is then put through a sieve before use, to remove any unslaked particles which might slake later in the hardened mortar and cause unsoundness or even cracking. **Magnesian limes are also slaked in a heap.**

Dry Hydrated Lime

Nowadays most lime used in building is dry hydrated lime – a ready-made form of slaked lime, which is a white or greyish powder supplied in paper bags like cement. It is usually manufactured from white lime **or from greystone lime,** and is therefore non-hydraulic or semi-hydraulic. Hydraulic limes are also available in dry hydrated form – they set in the same way as cement, but not quite so quickly.

Lime Putty from Dry Hydrated Lime.

Dry hydrated lime is often mixed and used at once as a mortar or plaster. If it is not of the quick hardening or hydraulic type, it is better to soak it in water for 24 hours before adding the sand. **This will give a much more workable mix**. Stir the hydrated lime into the water until a putty-like mixture is obtained. **Don't add the water to the lime or you will get a lumpy putty.**

Lime Mortars.

Lime mortars are usually of a 1:3 lime: sand composition. **For external brickwork it is usually best to use hydraulic lime mortars because other lime mortars do not stand up well to frost. Semi-hydraulic and non-hydraulic lime mortars, however, are used for bedding limestone and sandstone.**

Mixing Lime Mortars.

To make mortar from non-hydraulic lime putty or soaked hydrated lime, mix the sand and lime putty on a clean platform until an even consistency is reached. Round off this 'coarse stuff' into a heap, smooth the sides and leave undisturbed until required for use, but don't let it dry out if you keep it for any length of time. The coarse stuff will stiffen up on standing, but with vigorous beating and stirring it can be knocked up to its original plastic state. **If possible, don't add any water when knocking up – working the mortar vigorously will give a better material than the addition of water.**

Semi-hydraulic putties are mixed in the same way – but when using them, don't make up any more mortar than is sufficient for one day.

To make mortar from hydraulic quicklime which has been slaked on site, mix the sand and the lime thoroughly, adding more sand and/or water if necessary to get the right proportions and consistency. Magnesian lime mortar is also prepared in this way. Hydrated hydraulic lime must not be soaked overnight. Mix it dry with the sand, then add water, and use within four hours.

Cement-Lime Mortars

Lime gives a mortar good working properties. **The more lime in the mix, the better the workability. A fat lime slaked to a putty gives the best working properties, and an unsoaked hydrated lime the poorest.**

Cement gives a mortar strength and durability. Not only is the hardened mortar strong, but it hardens quite quickly. **Without lime, a high proportion of cement to sand is needed to make a workable mix**, but this is wasteful and may easily

1077

cause cracking due to too much shrinkage. Unlike a lime mortar, a cement mortar will readily lose water to a thirsty brick and thus give loss of adhesion.

A mortar containing both lime and cement will normally possess a desirable combination of both properties. It will be workable, will set reasonably quickly, and is adequately strong for all purposes in small housebuilding. Hydraulic limes should be used with sand alone and not with cement...

For normal types of brickwork under normal conditions use a 1:2: 8-9 cement: lime: sand mortar. If, however, brickwork has to withstand severe weather, or for bricklaying during winter where earlier strength may be demanded, use a 1:1: 5-6 mix; a 1:3:10-12 mix is only suitable for internal work when there is no danger of frost affecting it.

Cement-lime-sand mixes are also very good for external renderings; a 1:2:8-9 mix is suitable for normal use, but where a wall has to stand up to severe weather conditions, a 1:1:5-6 mix is better.

Mixing Cement-Lime Mortar

These are usually prepared by first making up a wet mix of lime and sand usually known as a coarse stuff. If the lime is added as putty the coarse stuff may be used immediately, but if you use dry hydrated lime, mix up enough coarse stuff for the day's work and let it stand overnight to improve its properties. Immediately before use, mix the cement thoroughly into the coarse stuff, adding more water if necessary. Don't mix up all the mortar at once. Do it in batches so that each batch can be used up within tow hours of adding the cement; throw away any left after this.

Cement-lime mortar may also be prepared by mixing dry hydrated lime, cement, sand, then adding the water, and using straight away. **This often speedy and convenient, but remember that such a mortar does not have good working properties.**

Type of lime; other names; source; type of slaking; expansion of slaking; method of slaking; maturing time; mixing mortar; when to use mortar; knocking up: use of hydrated lime.

Non-hydraulic limes; (fat lime, high calcium lime, Mountain lime, chalk lime; limestone lime; white lime; white chalk-lime); chalk, mountain limestone; and other almost pure limestones. Slake rapidly with much heat; considerable expansion; gradually stir quicklime into excess of water; mature for at least 2 weeks, but as long as possible; mix putty thoroughly with sand; must be kept moist if not used at once; can be knocked up if it stiffens; as hydrate, stir into water and leave for 24 hours, then use as lime putty.

Magnesian limes; dolomitic lime; dolomitic limestone; slakes very slowly; variable expansion; slake as hydraulic lime or add (hot) water to the lime, sieve; mature 36 hours; mix putty thoroughly with sand; use within 24 hours; can be knocked up if it stiffens.

Semi-hydraulic limes; grey lime, greystone lime; source: grey chalk; slow slaking; moderate expansion; to slake for putty, stir into excess water; for mortar, soak with water and cover with sand; mature 36 hours. Mix putty thoroughly with sand; use within 24 hours; can be knocked up within 24 hours; as hydrated lime, stir into water and leave for 24 hours, then use as lime putty.

Hydraulic limes; Blue Lias lime; blue lias limestone; slakes very slowly, requires fine grinding; small expansion; spray with water and cover with sand, sieve; mature 36 hours; mix covering sand with the slaked lime, adding more if required; use within 4 hours; should not be knocked up after it stiffens; If hydrated: mix dry with sand, add water and continue mixing, use within 4 hours.

British Standard Code of Practice 121.201 (1951)

Cement. Cement should be stored on a wooden floor, well above ground level, in a perfectly dry structure. Consignments should be placed in a manner that permits inspection and use in rotation of delivery. Cement affected by dampness should not be used. Cement delivered hot need not be aerated to cool before use.

Quicklime. Quicklime should be delivered to the site as soon after manufacture as possible.
Semi-hydraulic (calcium) quicklime and non-hydraulic (calcium) quicklime deteriorate rapidly on exposure to the atmosphere and are liable to cause fire if stored in an unslaked condition adjacent to combustible materials. Quicklime should, therefore, be slaked immediately.

Hydrated lime. Hydrated lime, hydrated or pre-treated hydraulic lime and quick-hardening lime (Roman cement) should be stored in the same manner as cement.

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

A) Preparation from quicklime. The slaking vessel or pit should first be partly filled with water to a depth of about 1 foot and enough quicklime should then be added to cover the bottom and come about half-way to the surface of the water. Stirring and hoeing should begin immediately, and the quicklime should not be allowed to become exposed above the surface of the water.
Should the escape of steam become too violent or the quicklime become exposed, more water should be added immediately. The mix should boil gently and, as it thickens, more water should be added. Water and then quicklime should be added alternately until the requisite quantity of milk of lime is obtained.

The stirring and hoeing should continue for at least five minutes after all reaction has ceased. The resulting milk of lime should then be run through a sieve of 1/8-inch mesh into a maturing-bin. It should be protected from drying out and remain undisturbed for a period of at least two weeks to permit it to fatten up to lime-putty.

B) *Preparation from dry hydrate.* The hydrated lime should be mixed thoroughly with water until a mixture of the consistence of thick cream is obtained; this should then remain undisturbed for not less than 16 hours.

505 Mortar Mixing (a) General. Mortar may be mixed on the site, either mechanically or by hand. Mechanical mixing may be carried out by any suitable mixing machine. Hand mixing should be done on a clean watertight wooden platform or other clean surface. If coarse-stuff is to be used, the lime-aggregate mix (coarse stuff) may be delivered ready-mixed....

c) Portland cement/lime mortars

- i) CEMENT/DRY HYDRATED LIME/FINE-AGGREGATE MORTAR. Cement, hydrated lime and fine-aggregate should be thoroughly mixed, in the required proportions, first dry and then with the addition of water until the required consistence is obtained. The mortar should be used within two hours of the addition of the water, and mortar not then used should be discarded. Under no circumstances should retempering of dried or partly set mortar be carried out.

- ii) COARSE STUFF GAUGED WITH CEMENT. Cement should be thoroughly mixed with the coarse-stuff in the correct proportions immediately before the mortar is required. Water should then be added to bring the mix to a workable consistence. The mortar should be used within two hours of the addition of water and mortar not then used should be discarded and not retempered.

d) ***Lime mortar***

i) HYDRAULIC LIME MORTAR 1) *preparation from quicklime*

A) Slaking. Hydraulic quicklime should be fresh and should be slaked as soon as possible after delivery. The quicklime should be slaked upon a clean platform or in a suitable container.

Lump quicklime should be piled into a heap, any lumps larger than 6 inches being broken down. Water should be thrown on or sprayed on as the heap is formed.
Ground quicklime should be piled into a heap. Water should be sprayed on, and the heap turned over three times to mix the lime and water thoroughly.

P34.

Care should be taken not to use too much water; approxiamately 70 gallons is required per ton of quicklime.
The heap of lump quicklime or ground quicklime should be covered with fine-

aggregate, banked down to retain the heat and left undisturbed for at least 36 hours or longer, until required. The heap at all times should be protected from the rain.

Mixing. The requisite quantities of slaked lime and fine-aggregate should be mixed with sufficient water to give a mortar of workable consistence. When prepared from lump lime, the slaked lime should be passed through a sieve of 1/4 inch mesh before use, in order to remove any unslaked lumps. The mortar should be used within four hours of mixing....

Preparation from hydrated or pre-treated hydraulic lime. Hydrated or pre-treated hydraulic lime and fine-aggregate in the required proportions should be thoroughly mixed, first dry and then with water until the necessary consistence is obtained. The mortar should be used within four hours.

MAGNESIAN LIME MORTAR

Slaking. Magnesian quicklime should be slaked in a manner similar to...hydraulic quicklime in lump form, but the heap should remain undisturbed for at least two days. Approximately 90 gallons of water is required per tin of quicklime....

NON-HYDRAULIC (CALCIUM) LIME MORTAR AND SEMI- HYDRAULIC (CALCIUM) LIME MORTAR.

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

preparation from quicklime. The slaking vessel or pit should first be partly filled with water to a depth of about 1 foot and enough quicklime should *then* be added to cover the bottom and come about half way to the surface of the water. Stirring and hoeing should begin immediately, and the quicklime should not be allowed to become exposed above the surface of the water. (This indicates twice the volume of water as the volume of the quicklime in the first instance – the proportion approximately necessary to slake the quicklime to a powder – subsequently added to with more water and more quicklime. This would pre-empt the drowning of the quicklime and other prescriptions would avoid burning of the quicklime).

Should the escape of steam become too violent or the quicklime become exposed, more water should be added immediately. The mix should boil gently and, as it thickens, more water should be added. Water and quicklime should be added alternately until the requisite quantity of milk of lime is obtained. The stirring and hoeing should continue for at least five minutes after all reaction has ceased. The resulting milk of lime should then be run through a sieve of 1/8 inch mesh into a maturing-bin. It should be protected from drying out and remain undisturbed for a period of at least two weeks to permit it to fatten up to a lime putty.

C) Preparation from dry hydrate. The hydrated lime should be mixed thoroughly with water until a mixture of the consistence of thick cream is obtained; this should then remain undisturbed for not less than 16 hours. If left longer, it should be protected from drying out.

2) *Coarse-stuff.* Coarse stuff may be prepared in two ways:

A) *Preparation from lime putty.* The lime putty should be mixed thoroughly with the required proportion of fine-aggregate.

B) *Preparation from dry hydrate.* The dry hydrated lime should be mixed thoroughly with the fine-aggregate, first in the dry state and then with water. The coarse-stuff should be kept for at least 16 hours before use.

If the coarse stuff is to be kept for any length of time, it should be protected against drying out....

507. Jointing and pointing. It is recommended that mortar in the joints be allowed to protrude slightly and be left for cleaning-off flush at completion...

Lucas E (1964) *Modern Practical Building Vol 2.* London, Caxton.

This summarises general thinking in the 1960s, a (slight) confusion of cement, cement-lime and lime mortars all seemingly allowable as suitable for similar purposes and with an emphasis on stronger mortars offering greater durability. The recommended mixes for ashlar, however, were generally weak and lime rich, as well as using limestone aggregates, and the first site of a cement-lime mortar less strong even than 1:3:12 – 1:4:16. This is the orthodoxy in the years before the onset of the 'Lime Revival'.

Brickwork, Materials and Bonds. Lime Mortars.

Lime mortars are usually prepared in the proportions 1 part lime to 3 parts sand by volume.

For hand-mixing the sand is placed in the shape of a ring on a clean, watertight platform. The lime is placed in the centre, water is added, and the heap left to slake for about twelve hours. Thorough slaking is essential, otherwise the lime will expand and 'blow' in the mortar joints.

After mixing, the heap should be smoothed over the exterior with a spade, so that air cannot readily penetrate the interior. Non-hydraulic lime mortar so treated will keep in good condition for a period of up to seven days. It should be knocked up as necessary to bring it to a suitable plastic condition. Non-hydraulic lime mortar is not recommended for permanent walls, as it has little strength.

Moderately *(feebly)* hydraulic lime mortar should be used if possible on the day of mixing, or within twenty-four hours at the outside. If allowed to stand longer, the setting and hardening action will take place in the heap, and much of it will be lost when the mortar is used.

Strongly hydraulic lime mortar, such as a mortar made with blue lias lime, has a strong setting and hardening property. It makes a durable mortar if properly prepared, but must be used within a few hours of mixing. If allowed to stand for long, the setting action takes place before the mortar is used...Ground hydraulic limes should be slaked by mixing with damp sand to make a stiff mix. The finished mix is then prepared by adding further sand and water. The mortar should then be used within four hours. Any mortar left after standing for half a day should be rejected.

...Cement Mortars.

...The following is of adequate strength for all ordinary purposes: 1 part Portland cement to 3 parts sand by volume....There are disadvantages in a stronger mix....

Lime-cement mortar.

This is sometimes called *compo* or *gauged mortar.* It combines the advantages of lime and cement mortars, and for all ordinary work it is preferable to either.

Setting and hardening of compo is superior to lime mortar and, though strength is not so great as cement mortar, it is adequate for walls and piers bearing normal loads. A great merit of lime-cement mortar is that it is not likely to develop shrinkage cracks (1:3 cement mixes will). It works easily off the trowel, and sound work can be done at a higher speed than with cement mortar...

The following proportions make a moderately strong mortar: 1 part Portland cement, 1 part non-hydraulic lime, 6 parts sand. ...

Retempering by adding water after the mortar has stood for some hours has a weakening effect, though re-tempering within twelve hours, using the minimum amount of water, is permissible where maximum strength is not important...

Sand.

Any clean sand is suitable for making mortar. It is desirable to use *graded sand,* by which is meant a mixture of sand particles from small to large....if very fine sand is used, more water is necessary, resulting in excessive shrinkage and some loss of strength.

MASONRY.

For *rubble walling* where, as has been said, the mortar supplies the chief bond, a good mortar is required. This should be composed of 1 part Portland cement to 4 parts sand.

Mason's putty is composed of 3 parts stone dust and 1 part lime putty. This is used for setting stones in wrought facing where the joints are required to be fine. The joints themselves are often grouted with neat Portland cement or with 3 parts stone dust mixed with 1 part Portland cement. For polished granite 2 parts sand to 1 part Portland cement is used...

Lime mortar consists of 3 parts clean sharp sand to 1 part slaked lime, which may be blue lias lime, grey chalk, or stone lime, pure or white chalk lime. Slaked lime is lime which has powdered owing to exposure to the air or from the addition of water. Grey chalk lime is used in the proportion of 1 part lime to 3 parts sand. Pure lime is used in the proportion of 1 lime to 3 1/2 sand.

Lime putty consists of a mixture of fat lime and 3 parts by weight of water. *Fat lime* is derived from white chalk and forms a paste when mixed with water. It is pure white; rapid-slaking, slow-setting and non-hydraulic.

It is a mistake to use a strong cement mortar, except where an exceptionally strong, dense stone is used. For ordinary load-bearing masonry mix No.3 specified below is quite strong enough and is generally used for Portland stone and stones of similar density. The two weaker mixes are of adequate strength for ashlar and facing work.

The three mason's mortars following have been favourably mentioned by the Building Research Station:

- 1) 16 parts fine crushed stone (by volume), 4 parts lime putty or hydrated lime, 1 part Portland cement.

- 2) 12 parts fine crushed stone (by volume), 3 parts lime putty or hydrated lime, 1 part Portland cement.

- 3) 7 parts fine crushed stone (by volume), 5 parts lime putty, 2 parts Portland cement.

... PLASTERING.
...The materials available are:

- 1) Portland cement, which has a strong setting action

- 2) Non-hydraulic or feebly hydraulic limes, which have no setting action or
  very little

- 3) Hydraulic limes with a strong setting action, but not so strong or so quickly developed as Portland cement

- 4) Sand, which provides the aggregate in many mixes

- 5) Gypsum plasters...which have a strong setting action. Some types can be used with admixtures of lime and/or sand, and some are used neat.

Portland cement. Normal Portland cement is used in lime-cement-sand undercoats for interior plastering and in all coats for exterior rendering. Portland cement gives strength, good adhesion and resistance to damp, but it shrinks on setting and for this reason mixes strong in cement should be avoided except under very damp or exposed conditions...

Limes. Traditional lime plastering is now obsolete owing to the length of time taken to slake the lime and the need to allow undercoats to set before applying the next coat – the setting takes several weeks. Gypsum and anhydrite plasters have largely replaced lime plasters.

Lime is chiefly used in the form of lime putty and hydrated lime powder, complying with BS 890. These limes have little or no strength. Their value is in making the mix easier to work, giving it a 'fatty' property, less liable to develop shrinkage cracks, more porous and so a better thermal and sound insulator, and in reducing the cost of the mix.

Hydrated powder lime, sold in 1 cwt paper sacks, is now widely used in plastering and rendering mixes. There are two methods of using it, as follows:

- 1) *Soaking to putty:* this is done by partly filling a suitable tank or container with clean water and then adding the lime powder to the water, stirring it to produce a thick, creamy mix. This should be allowed to stand for at least sixteen hours. Excess water will rise to the top and can be poured or siphoned away, leaving a putty which can be used in the same way as putty run from quicklime in a pit.

- 2) *Preparing coarse stuff:* this is done by mixing the dry hydrate lime powder with dry sand and then adding sufficient clean water to make a stiff mix, which should be left to stand for at least sixteen hours before use. The wet mix is called 'coarse stuff' and can be used with Portland cement or suitable plasters at any time within a few days, but it should be covered to prevent drying.

The two methods just described develop the maximum workability or 'fattiness' in the mix. It is possible, however, to use hydrated lime with other ingredients, first mixing dry and then adding water, and to use the mix at once. But it will not be so easy to work as those made by methods 1 and 2.

ANALYSES OF REAL MORTARS. ANALYSIS BY BILL REVIE, CMC LTD.

In most cases, aggregate size is finer than modern practice, often very fine indeed. Inmost cases,thelargest aggregate grains were residual quicklime inclusions. Lime proportion is universally high and, once more, significantly higher than standard modern lime: aggregate proportions. In limestone districts, limestone aggregate dominates, with some very fine sand and silt on occasion, usually sourced from nearby rivers or other watercourses. For many many building mortars, the aggregate was sub-soil or loam - clay, silt and sand. Earth aggregated mortars, however, were rare for pointing, which mortars were normally of lime and hair, or lime and sand or limestone aggregate.

Old Sun Inn, Spout House Farm, Bilsdale.

The mortars were sampled from behind later, cementitious pointing mortars from a part of the building considered to date from the later 16thC. Photos taken circa 1980 show that much of this mortar survived in situ. The lime was a high calcium lime. The binder: aggregate proportion was 2:1 and the mortar hot mixed.

Aggregate

The aggregates in this mortar sample are dominated by limestone fragments with a low proportion of other lithic particles. The latter are dominated by quartz grains, along with minor quartzite, fine grained sandstone and siltstone and rare altered indeterminate lithic fragments. There are also trace proportions of opaque minerals, ash clinker and pieces of wood. It is not possible to clearly identify all of the opaque minerals by optical microscopy alone, although ironstone and coal fragments are both indicated to be present.

The limestone fragments are typically angular to sub-angular, with the quartz and other lithic fragments typically sub angular to irregular in shape. The latter displaying rounded, water worn, margins.

The limestone fragments have the appearance of having been crushed with most of the larger angular fragments containing Ooliths and bioclasts, and it is considered that they were added to the mortar in the form of crushed Oolithic limestone fines. However, a very small proportion of limestone fragments displayed dolomitic textures, though their low abundance would suggest that they may have originated as a contaminant rather than infer that the source was a dolomitic limestone, though it may contain a thin seam of dolomitic material.

The quartz and lithic sand grains range from 0.06mm to 0.8mm in size, whereas the limestone fragments range in size from 0.05mm to 1.5mm in size, and most show sharp fractured margins.

Old St Margarets Church, Harwood Dale, North Yorkshire

The church was built new in 1634. It has been roofless for around 80-100 years. The mortars have proved durable in this situation. The binder: aggregate proportion was 1: 1.58, hot mixed, indicating a probable mix of 1 part high calcium quicklime: 3 aggregate.

Aggregate

The aggregates in this mortar sample are dominated by quartz grains with limestone, sandstone, and a low proportion of altered lithic fragments present, mostly of quartzite, chert and ferruginous sandstone, along with opaque minerals and a trace proportion of ash clinker and pieces of wood. It is not possible to clearly identify all of the opaque minerals by optical microscopy alone, although ironstone, coal and charcoal are all considered to be present. The coal and the charcoal possibly carried over with the lime from the kiln, as many show altered, burnt, margins.

The aggregate grains, are typically sub-angular to sub-round in shape, and locally flaky, with many displaying water worn margins, with the shape and the texture of the aggregates suggesting a glaciofluvial source for the sand.

The sand grains range from 0.04mm to 4.6mm and are dominated by quartz grains, limestone fragments, sandstone/siltstone particles, along with minor quartzite, and chert, with rare altered igneous rock types, ironstone, coal, wood and ash clinker. The aggregate would be classed as a medium to fine grained sand, with a proportion of silt and clay sized material (<0.63μm) diffused throughout, which may infer that the aggregate was used as an as-dug material rather than as a processed (washed) sand.

Although some aggregate grains were up to 1.5mm, 93% of the aggregate passed through a 1mm sieve; 81.2% through a 0.5mm sieve.

Stonehouse, Brook Lane, Thornton-le-Dale.

Pointing mortars were sampled, still in situ, from the lower building, built of oolitic limestone circa 1656. Bedding mortars were of earth. The mortar was hot mixed with a high calcium lime and were 1 lime: 0.75 limestone dust, with some added animal hair, interpreted as horse body hair and some small volumes of ash - either from the kiln or deliberately added.

Aggregate

The aggregates in the mortar sample are dominated by calcareous limestone fragments, with Dolomite and minor quartz grains with other heavily altered lithic fragments also present.

The limestone aggregate grains are predominantly sub-angular to sub-rounded, and with a majority of the grains displaying partially abraded and rounded margins. This may infer that the aggregates were from a crushed and ground limestone, i.e. limestone dust. The aggregate grains range in size from 0.012mm to 1.9mm (medium silt to coarse sand grains in size). (no overall size proportions given in this analysis, but generally very fine sand and ground limestone aggregate).

Limestone is present as fresh angular fragments of both Oolitic and micritic limestone, along with a low proportion of Dolomitic limestone fragments, with no evidence of having been calcined. However, there is also an abundance of other Limestone fragments present, which consist of overburnt or partially burnt fragments. This, along with partially slaked limestone fragments suggesting that the mortar appeared to have been mixed from quicklime or an unscreened slaked lime putty, which included both under burnt and overburnt limestone fragments, and limestone dust as an aggregate.

A low proportion of ash material, presumably from the kiln is also present, but there is only very miner indications that any of this had acted as a pozzolan, and not sufficiently, with regard to quantity, or reactively, to have impacted on the properties of the mortar.

Minor opaque minerals were also present, and these include residue from the kiln fuel, which are irregular in shape, some are granular in texture, though none are typical of coal or coal ash residue. Others opaque grains may be iron rich minerals present in the feedstock or aggregate.

A proportion of animal hair was observed within the mortar, with the hair being typical of that obtained from horse body hair, though this would require further analysis to confirm. The hair is in sufficient proportion to infer that it was purposely added as a reinforcement.

Component Sample and Proportion (%by mass) of mortar sample:

Calcite 96.0 Quartz 2.1 Friedel's Salt 1.0 Gypsum 0.9 Total 100.00

Kitchen Garden Wall, Thornton Hall, Thornton-le-Dale.

The kitchen garden wall is a brick and oolitic limestone wall, brick to its inner leaf and stone to its outer. Original pointing mortars displaced some 20 years ago by portland cement: sand mortars, promoting extensive saturation and frost damage. The mortar in which bricks and stone were laid is was the same. The effective binder: aggregate ratio was 1: 2.6. With lime inclusions added the actual lime: aggregate proportion was 1:1. 99.6% of the aggregate passed a 1mm sieve. Notably, 9% clay had been deliberately added to the otherwise high calcium lime and fine river sand and silt. The sample itself was initially interpreted as an earth-lime mortar. The mortar was hot mixed.

Aggregate

The aggregates in this mortar sample are dominated by quartz grains with a low proportion of lithic fragments present, mostly of quartzite, chert and ferruginous sandstone, along with opaque minerals and a trace proportion of ash clinker fragments. It is not possible to clearly identify all of the opaque minerals by optical microscopy alone, although ironstone, coal and charcoal are all considered to be present. The coal and the charcoal possibly from the kiln, with these carried over with the lime.

The aggregate grains, are typically sub-angular to sub-round in shape, and locally elongated and flaky, with many displaying water worn margins, with the shape and the texture of the aggregates suggesting a glaciofluvial source for the sand.

The sand grains range from 0.02mm to 0.55mm and are dominated by quartz grains, with minor quartzite, and chert, with rare igneous rock types and sandstone fragments, along with coal and ash clinker. The aggregate would be classed as a medium to very fine sand, with a proportion of silt and clay sized material (<0.63μm) also present. As the clay appears as discrete inclusions within the mortar, with only a low proportion distributed throughout the paste, it is likely that they were either added separately to the sand, and poorly mixed, or the sand was used as-dug, with it containing clay lenses or inclusions rather than the clay being present as finely disseminated material throughout the sand deposit. The clay inclusions, measure up to 3.2mm in size, but typically <0.3mm, and they contain a significant proportion of fine silt sized quartz grains, with the appearance suggesting that the clay was from a sandy silty clay that was included in the mortar.

Rare straw fragments were also observed, but at low concentration, a probable contaminant.

Sample Reference	**SR2794 – S1 Wall Core Mortar**	
British Standard Sieve Size	**Percentage Retained**	**Percentage Passing**
8.00mm	0	100
4.00mm	0	100
2.00mm	0	100
1.00mm	0.4	99.6
0.500mm	0.7	98.9
0.250mm	8.2	90.7
0.125mm	39.1	51.6
0.063mm	32.2	19.4
Passing	19.4	

Circa 1850 bricklaying mortar, 60 Goodramgate, York.

This mortar had proved entirely durable and retained excellent tenacity. 99.1% of aggregate passed a 2mm sieve; 89.7% a 1mm sieve. The mortars were hot mixed, initially to a dry hydrate, with a magnesian lime (typically high calcium with less than 5% magnesia. A gauge of site-slaked natural hydraulic lime (most likely lias lime from Barrow-on-Soar) was added to an otherwise non-hydraulic mortar. Effective lime: binder ratio was 1.0 : 1.45. With lime inclusions added in, 1.0: 1.0, indicating mixing 1 part of quicklime with 2 parts of aggregate. The sand aggregate will be from the Rivers Foss or Ouse.

Aggregate

The aggregates are dominated by quartz grains along with a proportion of lithic fragments present. The latter are composed of quartzite, chert, sandstone, and limestone, along with trace proportions of opaque minerals. Although it is not possible to clearly identify all of the opaque minerals by optical microscopy alone, ironstone and coal are both considered to be present.

The aggregate grains, are typically sub-angular to sub-round in shape, and locally elongated, with many displaying water worn margins. The shape, apparent single size, and the texture of the aggregates suggesting a fluvial source for the sand, which may be from a local water course.

The sand grains range in size from 0.07mm to 2.85mm and are dominated by quartz grains, with minor quartzite, and chert, altered igneous rock types and weathered sandstone fragments present along with rare coal and ironstone particles. The aggregate would be classed as a medium grained sand, with very low fines content, i.e., <0.2mm> This would have resulted in a harsh mortar requiring a high binder content to be workable. This is confirmed in the thin section with the mortar appearing to be binder rich with all aggregate grains fully surrounded, and separated, by paste with grain-to-grain contacts being rare.

Mortar from footings of medieval town wall, Hull.

The footings and former walls were of brick. The lime was a high calcium lime. There was very low level ash inclusion, either from the kiln or as a result of conscious addition. The mortars were fully carbonated. The effective binder: aggregate proportion was 1: 1.34. With lime inclusions added, the proportion was 1: 0.79.

The aggregates in the mortar had the appearance of a natural quartz rich sand, containing flint fragments, fine sandstone and siltstone fragments along with indeterminate lithic fragments and a low abundance of shell. Brick fragments and ash clinker werte also noted to be present. The sub-rounded shape of the majority of the natural sand grains and the presence of shell would infer an estuary or beach source. The aggregate also contained a proportion of charcoal and ash, perhaps included with the binder or a contaminant of the aggregate, or perhaps added as a pozzolan.

The brick fragments to which the mortar adhered had the appearance of low fired, or sun- dried clay brick, they were highly porous, and although firm they could be broken and disrupted under firm finger pressure.

Aggregate

This aggregates in the mortar sample contains a mixed suite of rock types, including quartz, quartzite, flint, igneous rock fragments, sandstone, siltstone, along with brick fragments, shell fragments, opaque materials (coal/charcoal), with a small quantity of ash clinker.

The aggregates are rounded to sub-round in shape, with a low proportion of elongated aggregate particles also present. In addition there were small smooth rounded brick fragments, and coal, which along with shell fragments may infer that the aggregates were won from an estuary or beach source.

The aggregates range in size from 0.04mm to 3.7mm (coarse silt to very coarse sand and fine gravel) in the section examined With no clay or fine silt material observed, it is again inferred that a water transported material was used as the aggregate.

The aggregates are mostly well bound within the paste. Although peripheral microcracks and localised areas of high microporosity, with localised binder depletion by leaching were noted, they do not appear to have been detrimental to the performance of the mortar.

…From the examination of this sample it is indicated that the mortar was probably mixed with the aggregate, in the form of a quicklime, but it was well slaked prior to placing. However, in the absence of significant shrinkage crack development and the patchy microporosity observed, the mortar may have been made in the form of a "hot lime mortar" in which most of the quicklime had slaked, at the time of mixing, with the mortar placed after remixing, and likely to have been placed cold.

York Minster.

15thC mortar. Non-hydraulic lime. Effective binder: aggregate proportion 1: 1.4. With lime lumps included, 1: 0.62. The lime was dolomitic, 49% calcite: 38% dolomite. It was hot mixed.

Aggregate

The aggregate is composed of a mixed suite of minerals, dominated by quartz and limestone along with feldspar and altered lithic (rock) fragments. The grains are sub- angular to sub- round, and irregular in shape, although the grains display partial rounding at their margins, indicative of water transport. The grains are between 0.24mm and 1.4mm in size and quartz accounts for 59.6% of the aggregate grains present, with limestone (22.8%) and minor sandstone (5.3%), quartzite (3.7%), chert (3.1%), Dolomite (1.4%), feldspar (1.2%) and opaque minerals (2.9%).

The aggregates are well bound within the paste and although some peripheral cracking is apparent, these are mostly discontinuous and have the appearance of early plastic and drying shrinkage features and are considered unlikely to have an impact on the performance of the mortar.

A low proportion of the limestone fragments apparent in aggregate show dolomitic textures along with burnt margins, and this may infer that they had been included in the mortar, along with the quicklime, as unburnt feedstock from the kiln, rather than with the aggregate.

…The binder is of a non-hydraulic lime, with the mortar noted to contain an abundance of incompletely burnt and incompletely mixed, but fully slaked, quicklime inclusions, along with a low proportion of overburnt particles also present.

York Minster.

19thC core mortar. Non hydraulic lime with wood ash forming 8% of the mortar volume, making the mortar feebly hydraulic. Effective binder: aggregate proportion 1: 2; with lumps, 1: 1.7. Magnesian lime.

Aggregate

The aggregates in the mortar sample consist of a mixed suite of rock types, which is dominated by quartz (64.5%), along with quartzite (2.3%), sandstone (2.7%), limestone 24.6), chert (1.8%) and minor feldspar (1.2%) and opaque minerals (2.9%).

The presence of a proportion of coal ash and clinker, (15.1%) along with some wood ash was also observed, and its inclusion at a significant proportion would infer that the former had probably been added as a pozzolan, rather than as a contaminant of the aggregate, or the quicklime. The wood ash may have been added with the lime or be a contaminant in the aggregate. Although, it has been reported that proportions of wood ash were added to some lime mortars to improve wet weather performance and aid curing.

The aggregates are sub-angular to sub-round in shape, with a low proportion of elongated aggregate particles also present. The shape of the grains, along with the sharp margins and texture of the aggregates suggesting a pit deposit as the source for the sand.

The aggregates are mostly well bound within the paste and the aggregate grains range in size from 0.04mm to 1.7mm (coarse silt to coarse sand).

…The binder is typical of a lime mortar, with the presence of lime inclusions apparent within the section. The inclusions appear to have formed from non-hydraulic quicklime, which appear to have been well burnt and fully slaked. Most of the intact inclusions observed are fully slaked and have the appearance of uncarbonated hydrate, however, there is a low abundance of under burnt inclusions available, which retain a faint imprint of the original rock fabric, with these confirming that a proportion of the limestone was Dolomitic or Magnesian limestone, some of the fragments appear calcareous and are from an oolitic limestone, partially dolomitised.

Combs Wood Ironstone Mine and processing facility. North York Moors.

Pozzolanic mortar made with non-hydraulic lime and ironstone kiln waste. Effective binder: aggregate proportion: 1: 1.9. Most industrial structures and workers housing associated with the ironstone industry were built with similarly kiln waste aggregated mortars. These remain generally sound, but where roofs another weathering detail has been lost, the mortars have tended to suffer frost damage, the north york moors have high wind-driven rainfall and lower average temperatures than lower lying ground in the region. ***87% of the aggregate passed through a 1mm sieve; 75% through a 0.5mm sieve*** *see table below).*

Aggregate

The aggregates in the mortar sample are dominated by ironstone, with minor quartz, feldspar, coal, coal clinker, ash, limestone and brick fragments, along with a trace proportion of clay minerals as coatings on some coarser aggregate particles. The latter possibly derived from alteration (weathering) of the aggregate, and/or present as contamination from soiling. Several small pieces of charred wood are also present.

Ironstone fragments are the dominant component in the aggregate and form approximately 28% of the aggregate, and are present as a mixture of fresh stone and weathered stone fragments, with a low proportion that show indications of having been partially burnt, with these ranging in size from 0.02mm up to 3.6mm.

The coal fragments are a mixture of fresh unburnt particles and partially burnt coal, which along with coal ash clinker, would infer that coal was the fuel used in the iron processing works. The coal fragments range in size from 3.7mm down to 0.08mm. Brick fragments are rare and these have rounded margins along with evidence of weathering, and are typically <0.7mm in size. The brick fragments form a low proportion of the total aggregate and it is unlikely that the brick was added as a pozzolan in the mortar, but rather as a component of the waste material used as aggregate.

Ash is present as fine fragments randomly distributed throughout the paste and as small clusters of poorly bound grains. Ash clinker fragments are also present, up to 2mm in size, but these are rare in the sample examined. A low proportion of limestone fragments were observed, with these mostly angular to sub-angular in shape with both fresh and partially burnt fragments present, they measure up to 2.0mm in size and are rare in the sample.

The aggregates are generally angular to sub-angular, locally rounded to elongate in shape, with a proportion displaying sharp margins and contain cracks, and these may have been crushed. It is, therefore, likely that they had been sourced from the waste material from the processing plant.

Binder

The binder has the appearance of a non-hydraulic lime, with a low proportion of sub-round to irregular shaped lime inclusions observed. Most of the sub-rounded inclusions are fully hydrated, whereas a proportion of the denser fragments appear to be only partially slaked and some of these retained a granular texture. This would suggest that the mortar had been mixed with a binder in the form of a hydrate. Locally the hydrate had the appearance of a powdered hydrate that had ‘balled’ typical of those that form when a dry hydrate is mixed with damp sand.

Sample Reference	**SR2802– S1 Masonry Mortar**	
British Standard Sieve Size	**Percentage Retained**	**Percentage Passing**
8.00mm	0	100

4.00mm	0	100
2.00mm	5.3	94.7
1.00mm	7.3	87.4
0.500mm	12.3	75.1
0.250mm	19.5	55.6
0.125mm	28.2	27.4
0.063mm	10.9	16.5
Passing	16.5	

Table No. 1: Results of the grading on recovered aggregate.

Rosedale East Iron Kiln mortar, from stonework.

Although containing coarser aggregates, 64% of the aggregate nonetheless passed a 1mm sieve. Non-hydraulic lime and pozzolanic aggregates.

The mortar in this sample is different to that in sample S1A (RESK1A), in that it is more binder rich, and has the appearance of an HMM, although it contains similar aggregate components, but in less quantity.

Aggregate

The aggregates in the mortar sample are again dominated by opaque minerals, with minor limestone with a low proportion of weathered brick fragments and very fine quartz grains

The limestone aggregates consist of both bioclastic and micritic forms i.e. algal/colloidal limestones. No Dolomitic limestone was observed in this sample. Some of the limestone fragments are partially burnt and may have been included with the quicklime binder, rather than the aggregate.

The opaque minerals are dominated by coal and coal clinker with a proportion of ironstone. The particles range from fresh, to weathered, fragments, with a proportion of both the coal clinker and the ironstone fragments displaying alteration. This would infer that they had originated from the waste material from the iron processing operations ongoing in this area of the moors.

Some of the coal fragments are partially burnt and locally these were observed bonded to partially burnt limestone, and, therefore, these particles are considered to be components from the lime kiln and were included as contaminants along with the quicklime.

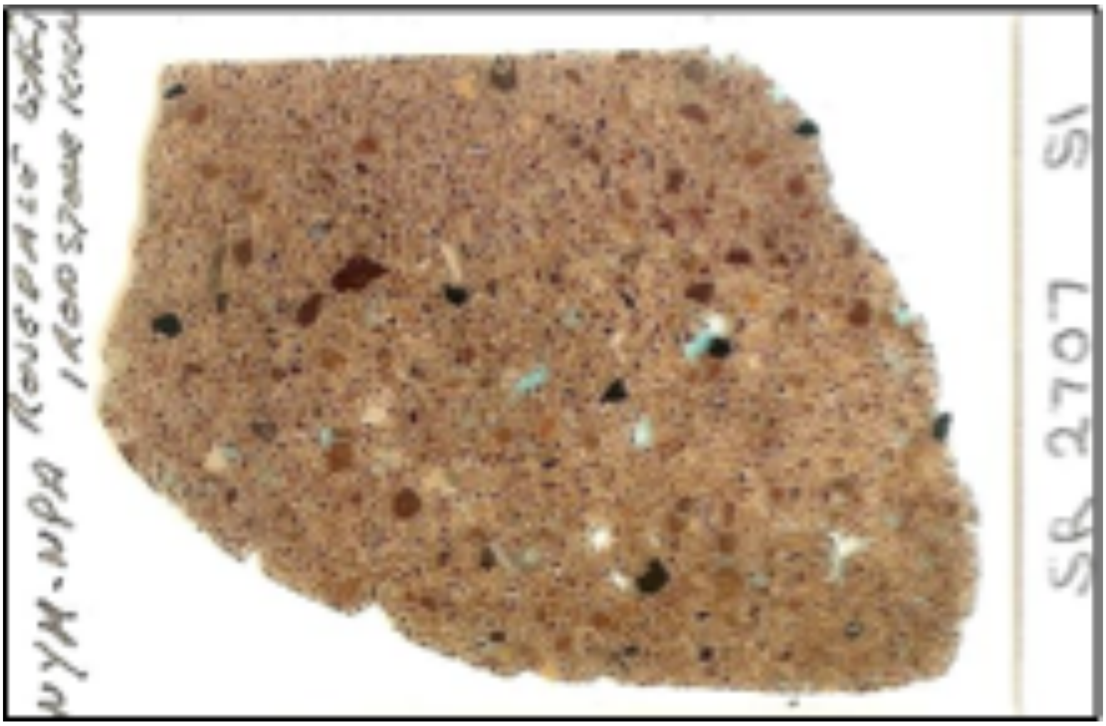
Aggregates range in size from <0.1mm to 5.4mm, with irregular coal clinker particles measuring up to 5.4mm, angular coal fragments up to 3.2mm, ironstone up to 1.8mm and limestone 2.4mm. Most particles display sharp margins, and these may have been sourced from the crushed waste from the iron processing kilns, with, perhaps, minor components from lime burning kilns.

Binder

The binder has the appearance of a lime mortar, with a high abundance of lime inclusions observed within the section. Although there was evidence of potentially hydraulic components in the paste, its concentration and appearance would suggest that, in this sample, its occurrence is associated with the aggregate. As all of the lime inclusions, and the paste, have the appearance of having been formed lime a high calcium lime (non-hydraulic lime).

A quantity of the incompletely slaked inclusions retain a faint imprint of the original rock fabric, with both a bioclastic and micritic texture common. The lime inclusions observed are mostly angular to sub-angular, along with a minor proportion of sub-rounded inclusions. A number of the angular inclusions show features consistent with the limestone being either over or under burnt.

From fire-brick kiln lining:



Aggregate

The aggregates in the mortar sample are dominated by coal, coal clinker, ash, ironstone with minor limestone fragments, and rare brick fragments, along with a trace proportion of very fine quartz grains. The latter possibly components in the ash and/or from soiling contamination.

The coal fragments are a mixture of fresh unburnt particles, and partially burnt coal along with coal clinker. The coal fragments range in size from 3.2mm down to 0.07mm. Brick fragments are rare, these have rounded margins and evidence of weathering, typically <0.4mm in size. Ironstone fragments are again a mixture of fresh stone fragments and partially burnt fragments, with a proportion showing the impact of weathering, these range in size from 0.02mm to 6.4mm.

The brick fragments are present in allow proportion and it is not considered that the brick was added as a pozzolan, but rather as a component of the waste material used as aggregate.

Ash is present as fine fragments diffused through the paste and as small clusters of poorly bound grains.

A low proportion of limestone fragments were observed, with these angular to sub-angular in shape and all show no evidence of having been burnt, they measure up to 2.0mm in size.

The aggregates are generally angular to sub-angular, locally rounded to elongate in shape, with a high proportion displaying sharp margins and these have the appearance of having been crushed. It is, therefore, likely that they had been sourced from the waste material from the Iron processing kilns, that had been crushed, and possibly screened.

Binder

The binder has the appearance of a non-hydraulic lime, with a proportion of sub-round to irregular lime inclusions observed. The lime inclusions are all well slaked, with most of the sub- rounded inclusions being fully hydrated, whereas a proportion of the denser fragments were only partially slaked and some of these retained a granular texture. This would suggest that the mortar had been mixed with a binder in the form of a hydrate. Locally the hydrated had formed concentrations which had 'balled' typical of those that form when a dry hydrate is mixed with damp sand.

Sample Reference	**SR2707– S1 (REIK1) Masonry Mortar**	
British Standard Sieve Size	**Percentage Retained**	**Percentage Passing**
8.00mm	0	100
4.00mm	16.1	83.9
2.00mm	17.9	66.0
1.00mm	1.3	64.7
0.500mm	6.9	57.8
0.250mm	15.4	42.7
0.125mm	16.6	25.8
0.063mm	11.4	14.4
Passing	14.4	

Table No. 1: Results of the grading on recovered aggregates

Shrewsbury Flax Mill. Kiln mortar, circa 1850 main elevation. Sample S13

Water droplet tests confirmed that the mortar contained a well-connected open pore structure, with the rapid absorption of droplets placed onto both bed faces and freshly fractured surfaces, with their diffusion throughout the full thickness of the pieces tested.

The mortar contains an abundance of irregular to sub-rounded lime inclusions with these extending up to 0.6mm in size, but mostly <0.3mm. These have the shape and texture similar to that formed from balled accumulations of hydrated lime. This commonly occurs when a dry powdered hydrate (or cement) is added to moist sand.

The colour of the mortar was found, on a freshly fractured surface to be 2.5Y 3/1"Very Dark Grey".

Aggregates differ from those in sample S2 in that they have a high coal clinker content along with a proportion of unburnt coal present along with a quartz rich sand. Fine coal ash and rare brick fragments are also present. The coal and clinker fragments measure up to 2.7mm in size, but mostly finer than 0.5mm, with the quartz grains mostly finer than 0.3mm. The coal, clinker and the aggregate particles are predominantly angular to sub-angular in shape.

Aggregate

The aggregates in the mortar sample are dominated by opaque particles which are a mixture of coal and coal clinker (Furnace bottom ash), with a low proportion being fresh unburnt coal, combined these form 42% of the total aggregate. The other components present in the aggregate are quartz (39.6%), along with sandstone and siltstone (2.1%), limestone (0.5%), igneous rock types (6.2%), brick fragments (0.2%) and fine coal ash (9.4%).

The abundance of coal clinker and coal appears to have been added as an aggregate, perhaps due to its readily availability and shortage of natural aggregate. This has coloured the mortar producing the Grey/black appearance common in "ash" mortars. It was noted during examination that there was a very localised occurrence of some coal fragments displaying unsoundness, with shrinkage and cracking observed within and around the particles. This is minor and generally the coal and clinker appears sound and well bonded within the paste.

The natural aggregates have a shape that ranges from angular to sub-angular to sub-round in shape, with a low proportion of elongated aggregate particles also present. The shape of the grains, along with the sharp margins and texture of the aggregates suggesting a screened sand from a glaciofluvial deposit, with possibly, due to the high incidence of sharp margins observed, a proportion of processed (crushed gravel) sand may be present.

The aggregates are mostly well bound within the paste and the natural aggregate grains range in size from 0.02mm to 0.5mm (fine silt to medium sand), whereas the coal and clinker fragments range from 0.04mm to 2.8mm in size, but most lie within the 0.1mm to 0.5mm fraction. The fine ash is mostly finer than 0.04mm in size, with small cenospheres in the region of 0.01 observed, with fine brick fragments up to 0.6mm also observed, but these are rare. The Furnace bottom ash forms approximately 50% of the total aggregate.

Binder

The binder is typical of a high calcium lime mortar, used in the form of a hydrate, where a number of balled inclusions had formed, with these measuring up to 0.4mm in size. The lime inclusions apparent are sub-round to irregular in shape, with a number displaying partial depletion, perhaps due to water percolation through the mortar.

A low proportion of small dense inclusions, having the appearance of putty inclusions (formed from fully slaked hydrate) are also apparent though these are sparse and randomly distributed, they are in the most intact, with no evidence of leaching.

There is an abundance of clinker and ash in the mix, some of which appears to have altered, with coarser particles displaying reaction rims, thereby inferring that a pozzolanic reaction had occurred. With this imparting a measure of hydraulicity to the mortar. The pozzolan components having been added, in the sample examined, at a dosage of 1 part binder to 1 part furnace bottom ash, with the fine ash content being equal to 1 part lime to 1/4 part ash.

Gypsum was observed finely distributed throughout the sample, and this is considered to be due to a reaction between sulphates, present in the coal and ash, and/or leached from the brick, or absorbed from the environment, with the lime in the binder, rather than the gypsum having been added as an set accelerator.

Shrewsbury Flax Mill. Kiln mortar from high level Sample number S14.

As with sample S13, the water droplet tests confirmed that the mortar contained a well- connected open pore structure. Droplets placed onto bed surfaces and freshly fractured surfaces were very quickly absorbed and diffused throughout the thickness of the piece tested.

This sample was noted to contain a higher void content than sample S13, with random patches of entrained and entrapped air noted.

The colour of the mortar, as assessed on a freshly fractured surface, and was found to be Gley 1 N6 “Grey”.

Aggregates appear to the same as in sample S13, both in respect to composition and size.

Aggregate

The aggregates in the mortar sample are essentially the same as for sample S13, with only minor differences in the proportions, and it is considered that the two mortars were made using the same materials.

The aggregates in the mortar sample are again dominated by coal clinker with a proportion of unburnt coal present with the total forming 35.5% of the aggregate present, with fine coal ash forming another 11.7%, which would infer that the total quantity of furnace bottom ash added was 47.2% of the aggregate, again similar to that in sample S13. The remainder of the aggregate being a natural sand composed of quartz 40.6%, sandstone/ siltstone 5.6%, Limestone 3.2% and other rock types 3.2%, with a trace of brick fragments (0.2%).

The natural aggregates are sub-angular to sub-round in shape, with a low proportion of elongated aggregate particles present, and these are considered to be from the same aggregate source as those in sample S13.

Although this sample has a higher void content than the mortar in sample S13, the aggregates are mostly well bound within the paste and the aggregate grains range in size from 0.02mm to 2.3mm.

Binder

The binder is again typical of a non-hydraulic Calcareous lime mortar. Although in this sample there are again a number of small lime inclusions apparent, as in sample S13, that have formed from balled hydrate, there is also a proportion of the inclusions that are from incompletely burnt limestone and incompletely slaked quicklime. It is, therefore, indicated that in this mortar the quicklime had been slaked with the sand and furnace bottom ash mixture, and was probably mixed as a hot mixed mortar, with the quicklime slaked to produce a mortar mix in a dry condition, which was most likely screened, banked and remixed prior to use, as a cold mix mortar.

An abundance of coal clinker and ash is again observed in this sample, and although this is likely that this has acted pozzolanic and impart strength to the mortar. The furnace bottom ash being added, in the sample examined, at a dosage in the region of 1 part binder to 1 part furnace bottom ash, or 1 part lime to 0.3 parts ash fines, which is at a similar concentration to that in sample S13.

Woral C Smith, Limeburner's house and kiln, Fairbury, Nebraska

The house is of limestone, as is the nearby kiln. 70% of the aggregate passed a 2mm sieve; 48% a 1mm sieve. Effective binder: aggregate proportion: 1: 2.2.

The sample is composed mainly of calcite (Carbonated lime), with minor quartz and feldspar from the fine aggregate. There are no hydraulic components or pozzolans present in the sample and it is concluded that the binder is a non-hydraulic air lime.

The sample is composed mainly of calcite (Carbonated lime), with minor quartz and feldspar from the fine aggregate. There are no hydraulic components or pozzolans present in the sample and it is concluded that the binder is a non-hydraulic air lime.

Sample Reference	**SR2738 – S1**	
British Standard Sieve Size	**Percentage Retained**	**Percentage Passing**
8.00mm	0	100
4.00mm	12.7	87.3
2.00mm	17.1	70.2
1.00mm	22.0	48.2
0.500mm	26.1	55.1
0.250mm	17.3	4.8
0.125mm	2.7	2.1
0.063mm	1.1	1.0
Passing	1.0	

Table No. 1: Grading analysis of recovered aggregate, following acid digestion

Aggregate

The aggregates in the mortar sample are dominated by quartz, with minor chert fragments also present. In addition, perthite, microcline and orthoclase feldspars were observed with a trace proportion hornblende (amphibole) and muscovite mica. The aggregates have the appearance of being granitic in origin.

The quartz and other lithic fragments range in size from 0.05mm to 3.2mm (very fine to very coarse sand to fine gravel) in the section examined, although there were rare coarser fragments, quartz particles, up to 6.2mm in the hand specimen.

The aggregates are round to sub-round and sub-angular in shape and are predominantly of quartz with chert with a high proportion of the lithic grains displaying a perthitic texture, although microcline and orthoclase feldspars are also present as individual fine grains.

Binder

The binder is typical of an air lime in appearance with no hydraulic components apparent within the section examined. The paste displays an abundance of fine discontinuous cracks, typical of that observed in putty lime mortars.

Lime inclusions are sparse in the section, albeit very localised small dense patches of paste display features consistent with poorly disseminated putty lime inclusions.

Wayne County Courthouse, Wayne, Nebraska

Sample of original bricklaying mortar - pointing had added hematite to give a red colour.. 1899. Elsewhere, bedding mortars were coloured as per pointing mortars. Effective binder: aggregate proportion: 1: 2.55.

Lime inclusions are abundant, with the majority being finer than 1.0mm in size but locally inclusions up to 5.9mm were observed. The inclusions are irregular to sub- angular in shape and appear to have formed from quicklime, rather than putty lime.

The aggregates are dominated by quartz and appear to have a **maximum grain size of 1.4mm but mostly finer than 0.4mm.**

Aggregate

The aggregate is composed of a mixed suite of minerals, dominated by quartz, with feldspar, including Plagioclase, Microcline and Orthoclase along with heavily altered volcanic igneous rock fragments, granite, and microcrystalline silica (chert). There is also a proportion of weathered sandstone (greywacke) and indeterminate weathered metamorphic grains. The grains are sub to rounded to rounded in shape, with smooth water worn surfaces.

Binder

The binder is of a non-hydraulic lime, with the binder containing an abundance of incompletely burnt limestone fragments. There is also a low abundance of incompletely slaked lime inclusions. The inclusions are sub-angular to sub-round in shape and their appearance and texture would suggest that the quicklime had been slaked with the sand, and not prepared as a hydrate or run to a putty before use. The mortar has not, however, been placed as a Hot Mixed Mortar (HMM), but mixed as such, with the lime slaked with the sand, banked to cool and fully hydrate the quicklime, as much as practical, using this technique. With the sand lime mixture probably rescreened, to remove oversize and unslaked lime, prior to being mixed and retempered, with the mortar placed cold.

Red Mortar.

The mortar was found on testing to be fully carbonated and porous, with the rapid absorption of water droplets placed onto fresh surfaces. The mortar also displayed a high entrained air content, which is not uncommon in lime-based mortars.

The lime inclusions ranged from sub-angular to sub-round in shape, and as in sample S1 had the appearance of having formed from a quicklime.

Similar aggregates and lime but with Haematite flour added.

Calgary, Alberta, Canada. Pointing mortar, Anglican Cathedral of the Redeemer.

High calcium lime with probable, low level addition of early Portland cement, rich in belite. Effective binder: aggregate proportion: 1: 1.8. With lime lumps, 1: 0.99.

Aggregate

The aggregates are composed mainly of limestone fragments, along with a proportion of quartz grains, chalcedony, indeterminate weathered metamorphic particles with minor feldspar and shale. The limestone is dominated by calcareous limestone/marble along with dolomitic limestone and siliceous limestone.

The aggregates are mostly sub angular to sub-round in shape with a low abundance of angular fractured grains, the latter displaying minor internal fracturing but these are in trace proportions and would infer a proportion of crushed aggregate in the sand. A proportion of the aggregate particles show alteration of weaker minerals, to varying degrees, with these having the appearance of pre-encapsulation features, however, there inclusion do not appear to be detrimental to the performance of the mortar.

The aggregates are well bound within the paste and although peripheral micro-cracks are observed, where present, these do not appear to inhibit the aggregate/paste bond. The aggregates range in size from **0.03mm to 1.8mm (coarse silt to fine sand) in the section examined.**

Roman masonry mortars a) 100 AD, bath-house; b) 213 AD Rampart backing mortar. Vindolanda, Northumbria.

Bath House Mortar. *This much coarser in its aggregates (including brick aggregates than examples above. Only 36% passed a 1mm sieve; 71% passing an 8mm sieve. 31%, however, passed a 0.5mm sieve, and 25% a 0.25 sieve. Particles larger than 4mm were noted to be of brick fragments. Vitruvius commended the use of brick aggregate in the plastering of inherently damp walls - such as those of a Bath House. 1 lime: 1.36 aggregate by volume. Hot mixed and placed hot.*

The aggregate particles greater than 4mm are predominately of sub-angular pieces of broken clay tile/brick, with between 4mm and 0.5mm the grains are comprised of crushed limestone fragments, and fine tile/brick fragments, whereas below 0.5mm the aggregates are dominated by sub-rounded quartz grains with fine clay tile/brick fragments and a trace proportion of indeterminate lithic fragments. The fines in the aggregate appear to be from a natural quartz rich sand, which display water worn surfaces and this may therefore have been obtained from a river or river terrace source.

From the mineralogical composition of the mortar in sample S1, and from the lime inclusion picked from the same sampled, it can be confirmed that the lime used was a high calcium air lime, which contained no hydraulic components. A further XRD analysis carried out on a piece of limestone present as an aggregate also confirmed that this was dominated by calcite with trace proportions of aragonite (probably from the shell within the limestone) along with dolomite, from alteration veins within the rock. It may, therefore, be suggested that the limestone aggregate encapsulated within the mortar was from the same source as the limestone used to produce the binder.

The presence of both AFm and c-s-h phases, albeit in trace proportions in the sample of concentrated fines from the matrix in sample S1, would infer that there has been a reaction between the ground clay tile and ash/clinker, in the fines, with the lime of the binder, with this producing the strength and durability apparent in this sample of mortar.

Rampart Mortar

1 lime: 1.41 aggregate. 80% of aggregate passed a 1mm sieve and 71% a 0,5mm sieve. 3.7% only passed a 4mm sieve. Hot mixed but placed cold.

The aggregates in this sample were dominated by quartz along with sandstone fragments, quartzite and indeterminate lithic fragments. The aggregates were sub- round to sub-angular in shape, with the finer particles displaying smooth water worn surfaces. This may infer that it was a mixture of partly crushed material and a natural river, or bank, sand.

The aggregates in sample S2 differ from those in sample S1, and they are predominantly of sub-round to sub-angular particles of quartz, limestone, sandstone, and quartzite, along with a minor proportion of shale and coal fragments. The aggregates contained a high proportion of material passing the 63 μm sieve which is mostly of silt and clay, which would infer that the aggregates were from an as-dug material from a clayey sand deposit, or that the aggregate was purposely mixed with a proportion of clay, to produce a clay-lime mortar.

The aggregates are dominated by sandstone fragments, along with quartz, with minor quartzite, limestone and igneous rock fragments, along with trace proportions of shale and coal. A noticeable proportion of clay minerals were also observed with these either coating aggregates or existing as balled clay inclusions.

The aggregates are mostly sub angular to sub-round in shape with a number of the sub-angular fragments displaying internal fracturing. The fracturing observed are pre-encapsulation features and would infer that the coarse aggregate particles contains a proportion of crushed material.

Where the aggregates are surrounded by paste they are well bound within the paste. The aggregates range in size from 22mm to <0.3mm.