Hot mixed Mortars for the 21st Century

SPAB Conference

Traditional mortars and their primary historic uses:

Earth-lime mortars, typically 10% lime to a clay (and silt) bearing sub-soil:

Masonry construction, especially of stone buildings across the UK until around 1800; base-coat plasters. Always pointed with lime rich mortar and finished internally with lime rich or pure lime, haired finish coat and limewash.

Hot mixed air or feebly hydraulic lime mortars:

general building with stone and brick; repointing; plastering (except top coat); external renders. Feebly hydraulic in water works local to their sources, with and without pozzolanic addition.

Putty lime, slaked with minimum volumes of water and sieved:

Used on its own as a mortar for gauged brickwork, very fine stone ashlar, fine plaster finish coats. Very rarely as a binder before 20thC, when it was gauged with cement or gypsum.

Hot mixed moderately or eminently hydraulic lime mortars, either artificial (air quicklime and pozzolans) or NHL (typically blue lias in England and Wales, locally and then more widely after railways)

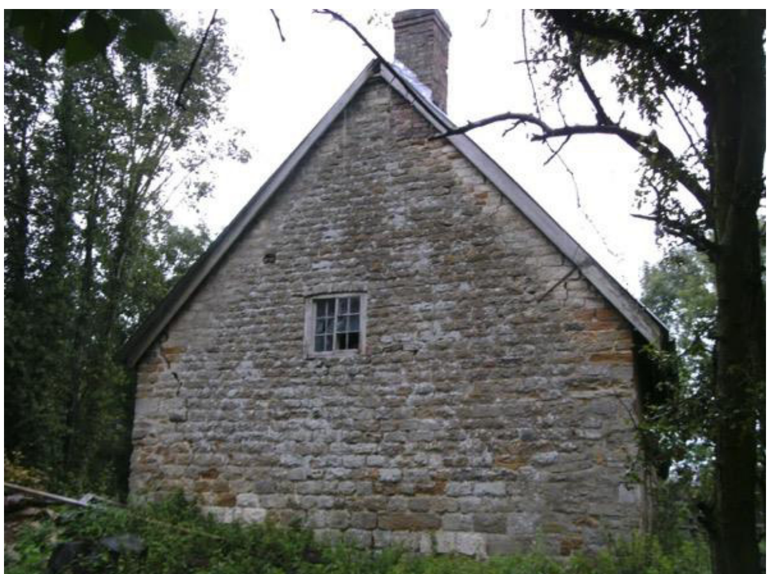
Underground or underwater works – docks, quays, sea-walls. Concrete footings.

Some above-ground construction late 19thC or where only locally available quicklime. Some gauging of hot mixed air lime mortars with NHL.

Natural Cement (after 1796). Waterworks, cast mouldings, fortifications (mostly as a gauge for hot mixed common mortars), external renders, some repointing over earlier mortars.

New Malton 1728, John Settrington. Vernacular and sustainable

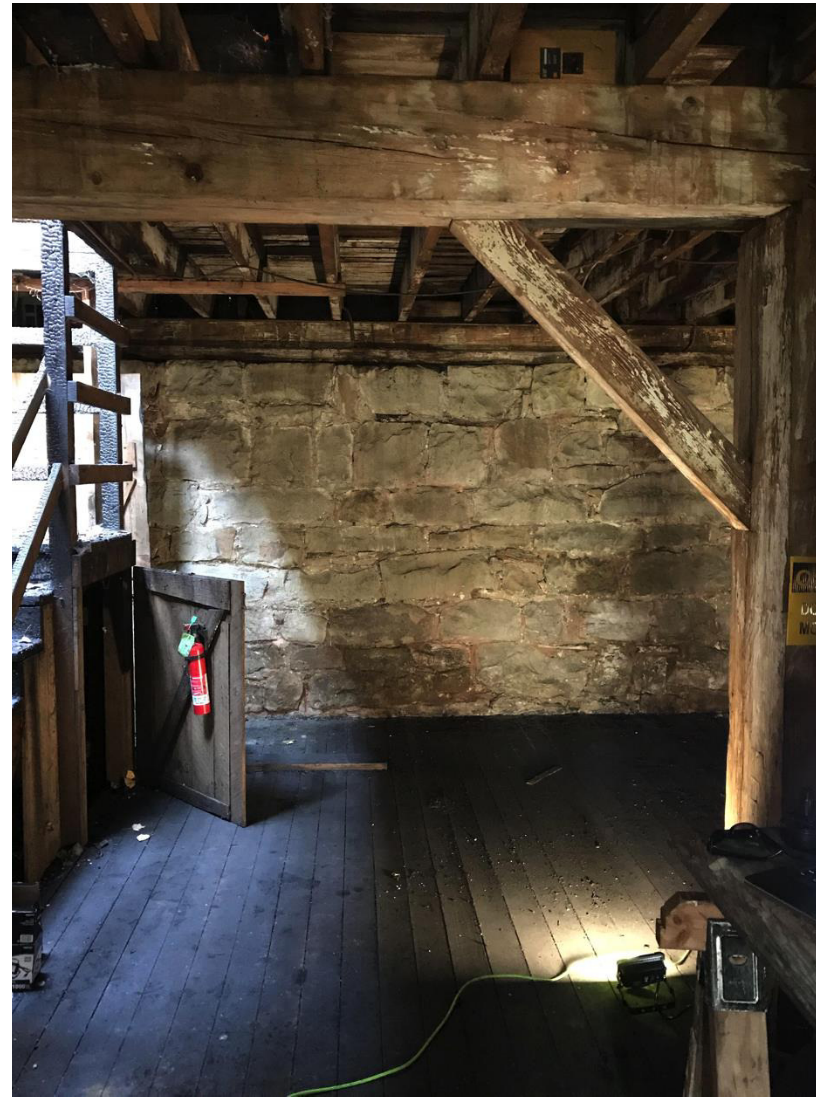





Romanesque Tower of St John the Baptist, Whitton, North Lincolnshire, reputedly built on the site of a Roman Temple. Earth-lime mortars. Lime pointing mainly lost. STILL THERE, STILL PLUMB.

Roman Lighthouse, Dover, England.

Hot mixed mortars with pozzolan



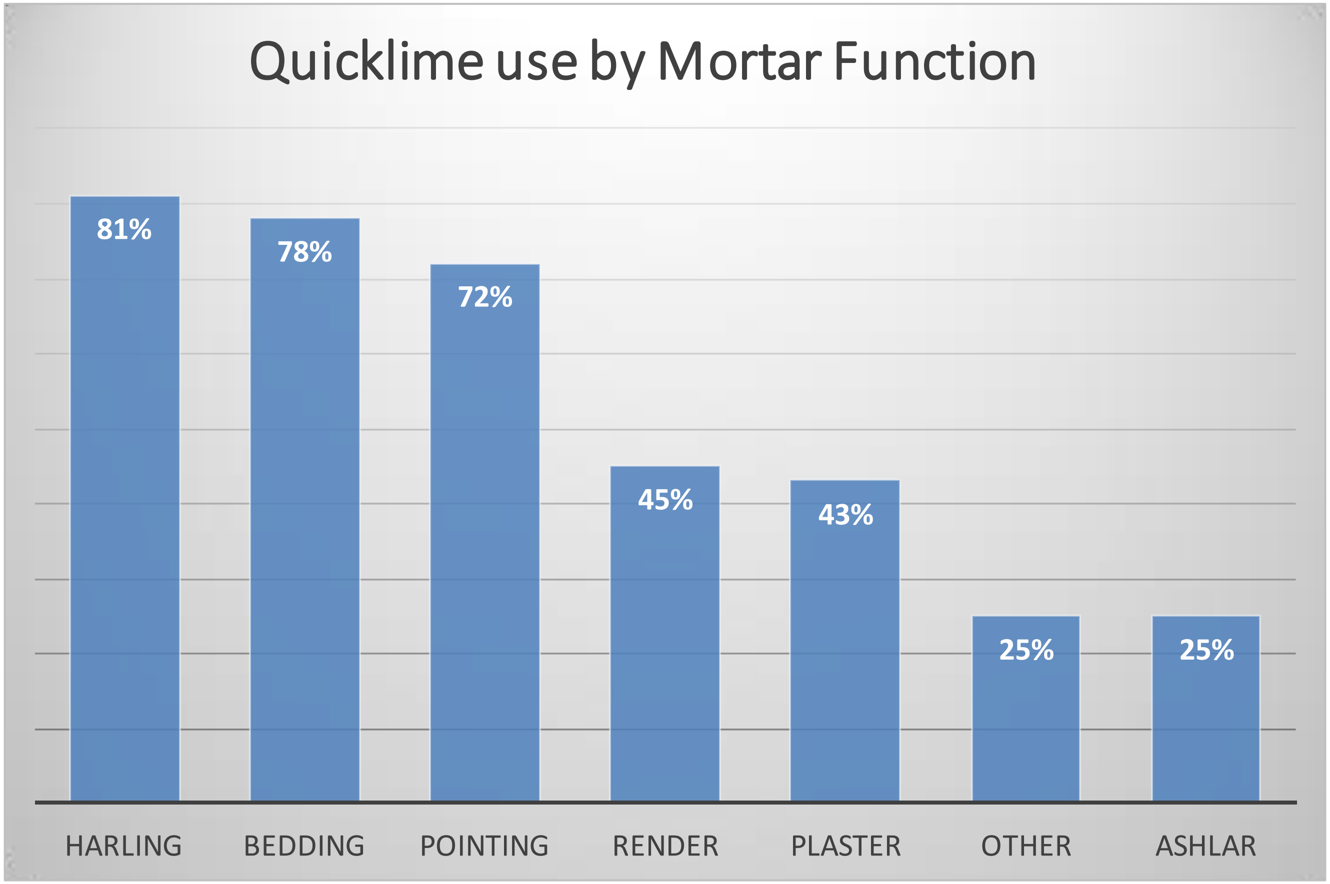
Butte Creek Corn Mill, Oregon, 1873

Boynton Hall, East Yorkshire.
16th, 17th and 18th Centuries

Archbishop's Palace, Trondheim, Norway. 13thC

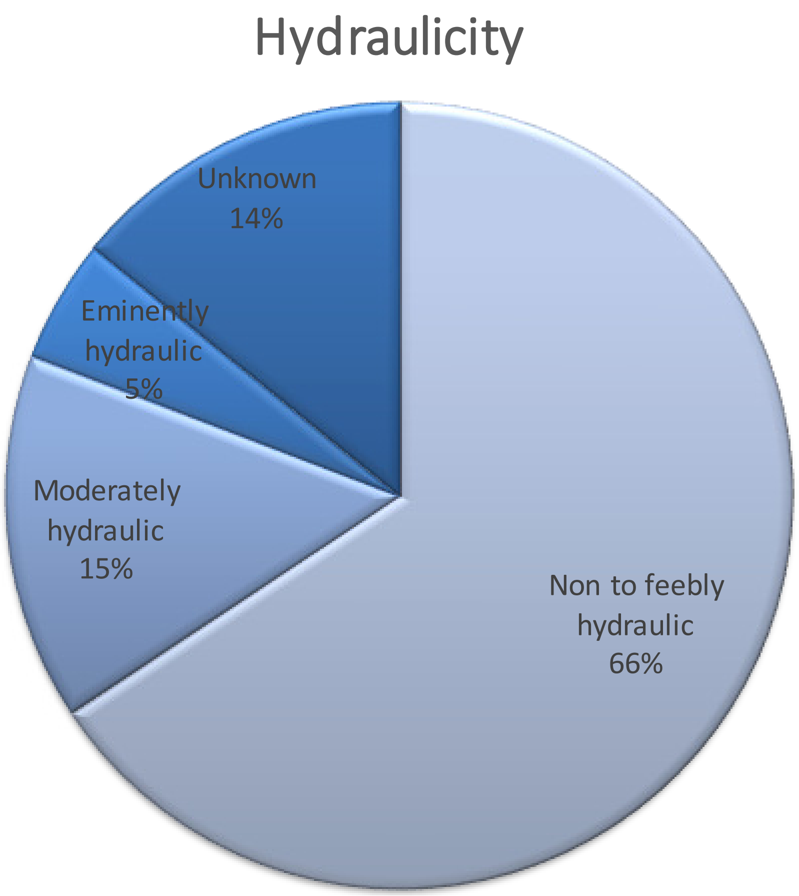
Decorated plaster 17thC

The Scottish Experience



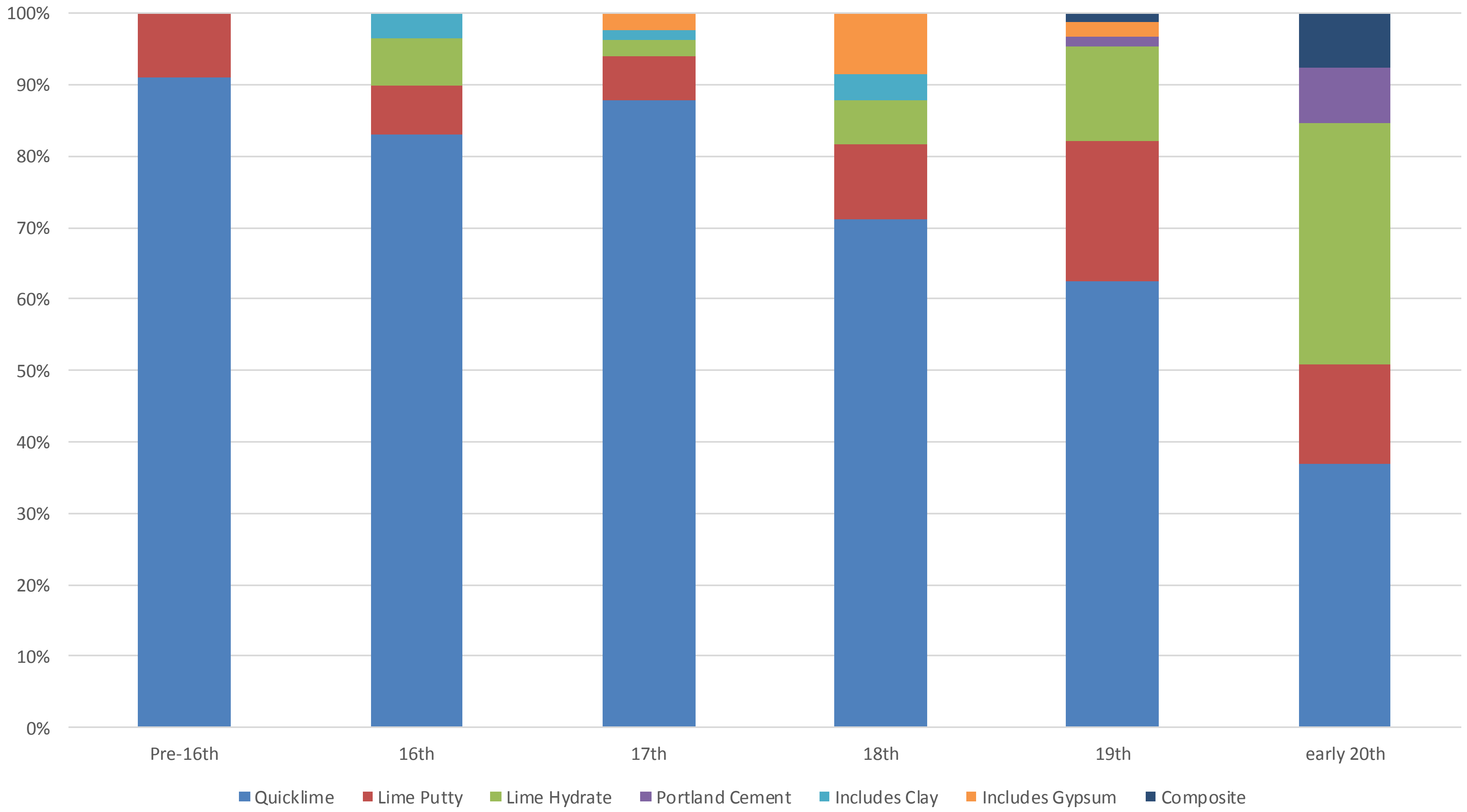
Information from 3,407 mortar samples from the Scottish Lime Centre's Historic Mortars Database
Adapted by Craig Frew from a presentation by Anne Schmidt, HES Hot-Mixed Mortars Seminar, February 2017, Edinburgh.

The Scottish Experience



Information from 962 Scottish mortar samples from the Scottish Lime Centre's Historic Mortars Database
Adapted by Craig Frew from a presentation by Anne Schmidt, HES Hot-Mixed Mortars Seminar, February 2017, Edinburgh.

Binder type use per century



Research Anne Schmidt courtesy Jessica Snow, Historic Environment Scotland

The several kinds of Mortar used in Buildings are Eight, viz

*Inside and Outside mortar made of Lime and Sand

*Terrace Mortar, made of Lime and Terrace

*Brick-Dust Mortar, made of red Stock Brick dust and Lime

*Bastard Terrace, made of a Smith's Forge Ashes and Lime

*Pargetting Mortar, made of Lime and Horse-dung

*Furnace Mortar, for Furnaces, Ovens, Kilns, etc made of Woolwich Loam or Windsor Loam only

*Plaister Mortar, made of calcined Alabaster

*Fine Mortar, called PUTTY, **for rubbed and gaged Works,** made of Lime only.

Langley 1750

Inside Mortar: 1 Load of Sand put 1 ½ Hundred of Lime, **which mix up together as the Lime is slacked in small Quantities.**

Out-Side Mortar: (sharpest, cleanest sand) The Proportion that the Lime should have to the Sand, is as 2 is to1, viz. **2 heaped Bushels of unslacked Lime to 1 ditto of Sand**

Terrace Mortar is **chiefly used in Walls exposed to Water, as to Rivers, Ponds, Cisterns, Bog-Houses, Cold Baths &c…**The best Terrace Mortar is made with two Bushels, &c**. of hot Lime**, and one Bushel &c. of Terrace **.**

Brick-dust mortar: 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.

Likewise**, sea coal/forge scale** mortars.

Smeaton later showed (1756) that 2 parts sharp sand: 1 part pozzolan: 1 part quicklime provided an underwater lime.

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

It is only proper for gauged brickwork, or for the ornamental outside work of brick walls…." (9). Pasley 1826)

Four modes of measuring lime have been employed…

The most ordinary mode is to measure it in lumps, as it comes from the kiln; a second method is to measure it in slaked lime powder; a third, in quick lime powder; and a fourth, in slaked lime putty or paste.

The first method is usually employed by builders, when their works are not on a large scale, and is always supposed to be adopted, if nothing be said to the contrary….

In ordinary practice, the cohesion of the mortar is greatly impaired by too large a proportion of sand, **which should not in general exceed two volumes, for every volume of lime paste**.

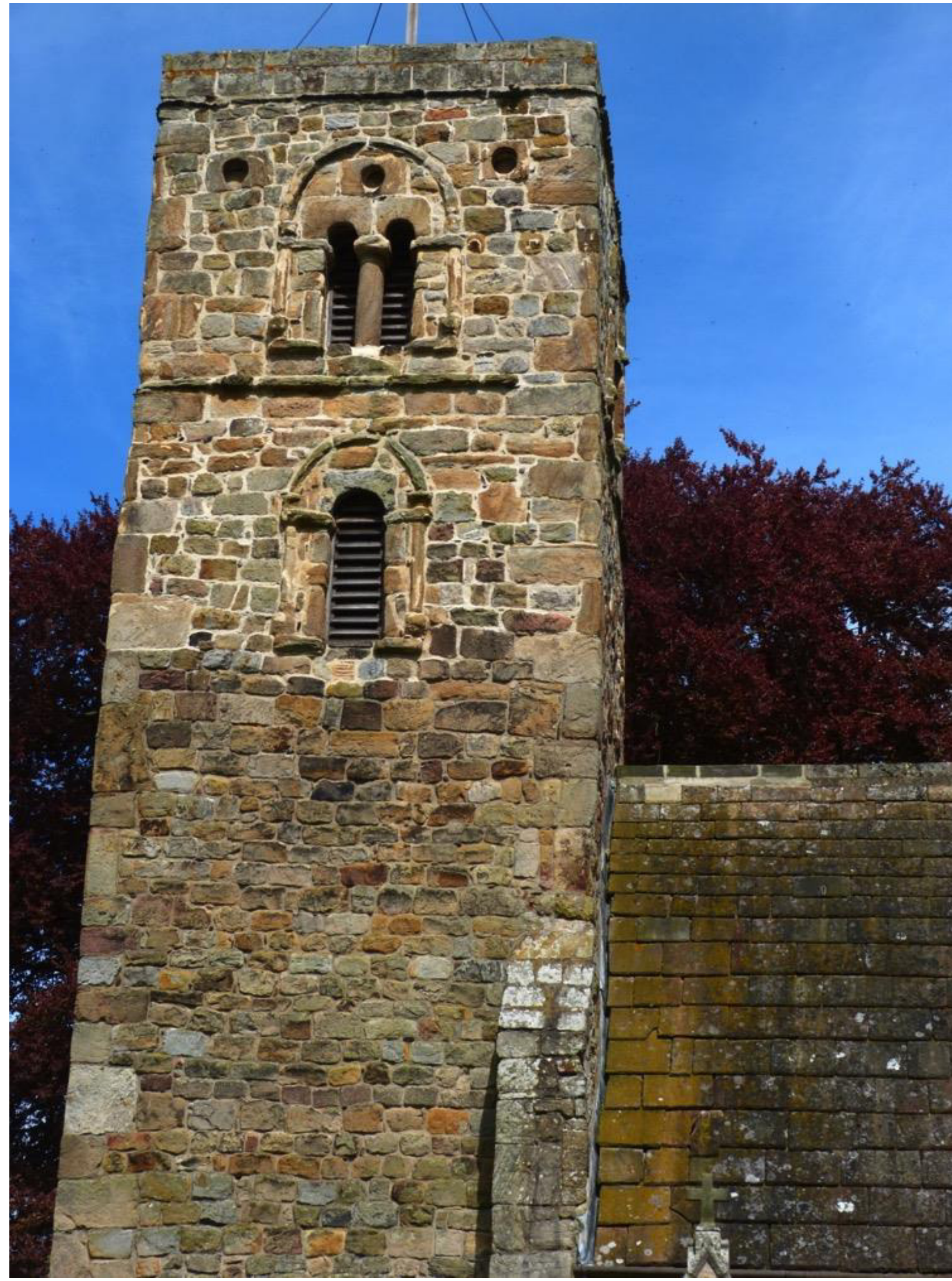
In preparing ordinary mortars, it will be convenient to place the unslaked lime upon a plank floor, under shelter from the sun and rain, and then (without covering) to surround it with the proper quantity of sand. The water, requisite to produce a thick paste, previously ascertained by experiment, should be poured on the lime with the aid of watering pots of known capacity. The lime must then be well stirred, so as to expose every part of it to the action of the water, and afterwards left to itself, until the vapors have ceased entirely. The ingredients may now be thoroughly incorporated by means of the hoe and shovel. If the mixture is made with difficulty, a little water may be added, but only enough to produce a homogeneous mass…. Wright (USA) 1845

<u>If we mix two parts of sand freshly extracted from the river with one part of powdered quicklime, it will create a very fatty and adherent mortar. De la Faye 1777.</u>

A Bricklayer.

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.**

[which is to say that, in practice, and craft practice in the US, hot mixing was generally by the first method and taken directly to a mortar and used soon after being made]. Gillmore 1886



Now, while all this precaution is taken in regard to plastering, in making mortar for building the lime is slaked and made up at once, and it is frequently used within a day or two. But this is not all. **Limes which are unsuitable for plasterwork, known as hot limes**, and which, when plasterers are obliged to use them, must be slaked for a period of - not three weeks, but more - nearly three months before using, and are then not quite safe from blistering, ***are the limes mostly used for building purposes.*** Millar Plastering Plain an Decorative 1898

Slingsby N Yorks 2009; Fylingdales 2011-12

Binders routinely used at Chatham Dockyard:

Most building above ground with chalk lime at 1:3; subsequently repointed as necessary with feebly hydraulic (Dorking or Halling) lime or with natural cement (Sheppey or Harwich).

Water limes: Previously fat lime within wharf walls, faced up with fat lime plus pozzalan (from Italy) or trass from Holland. Now (1838), natural cement throughout.

Blue Lias ('the strongest water limes of this country'), necessarily mixed at 1:2; Dorking or Halling lime - Halling from near Rochester.

'Three cubic feet of sand to one of Dorking or Halling lime, will be a good proportion for making mortar with those limes, **which approach very nearly to pure lime'** (Pasley 1838 p15).

Pozzolanic additives identified by John Smeaton in Narrative of the Building of the Edystone Lighthouse (1756).

pumice stone (volcanic ash);
terra puzzolana (ash from Mount Vesuvius);
trass (volcanic ash)
minions - fired ironstone
coal cinders (coal ash);
brick and tile dust
wood ash.

Others: smith's forge ashes; iron filings.

Modern pozzolans: slate dust/micro-silica; calcined china clay (metastar/argical); pfa.

Smeaton concluded the minimum pozzolan for a water lime was one third part of the aggregate so 1 part fat quicklime: 2 parts sharp sand: 1 part pozzolan.

Some feeble hydraulic activity may be achieved with hot mixing of iron-bearing limestone aggregates or clay-bearing sands.

For work in the air, less than 5% of the slaked lime is required. More than 5% is usually unnecessary and no more than 10% should be used.

The typical lime:aggregate proportion of most traditional lime mortars is 2:3 or 1:2. if not richer in lime than this.

'Customary' for specified mortar: aggregate proportions to be expressed in lump lime (before slaking): aggregate, unless otherwise stated (Pasley 1826). In fat and feebly hydraulic limes this will give 2:3 after slaking.

Vicat indicates 1 part of slaked lime to 2 parts aggregate. This might be just slaked hydrate or stiff, dough-like putty made by adding just enough water to the lump lime plus a little more– not putty as we know it – 'drowned' in a surplus of water, which all authors says delivers a weak material with less bond.

Hydraulic, **'WATER' limes were NEVER mixed at 1:3 – typically at 1 part quicklime: 2 aggregate**, hydraulic limes expanding much less than fat limes on slaking, or not much at all. 1:1 was also commonly specified, particularly for eminently hydraulic natural cements.

The objective was to get as much sand into the mortar without compromising workability and performance. WHAT MASONS LIKED TO USE AND DID WHAT THEY WANTED BEST WAS THE STANDARD.

1:3 slaked lime to aggregate never found or specified historically. Became the norm with cement-lime mortars, the cement compensating for the reduced lime content. Even so, 1:2:9 weaker than a 2:3 or 1:2 fat lime: aggregate mortar (but gains initial set much faster) and considerably less strong than a 1:3 modern NHL:sand mortar.

BRICKLAYER. The bricks to be sound, hard, well burned square stocks, equal to a sample to be approved by the Architect and deposited with the Clerk of the Works ; the whole of the brickwork to be laid English bond, and no four courses to exceed 11 ½ inches., and every course flushed up solid in mortar. **The mortar to be composed of stone lime and sharp river sand, in the proportion of three measures of sand to one of lime, the whole well mixed in a pug-mill.** The lime to be kept in an inclosed shed, and no more mixed at one time than is sufficient for the day's consumption.

Signed Charles Barry (Architect), Henry and John Lee 08.11.1837

I adduce the Hull (Ottawa) cement as an instance of this…The Hull cement will not set under water; but when set in air it gradually acquires induration and insolubility (Baddely)

I find that a very important property (is)….that though many of them may set so very slowly as to be quite unfit for tide work, and though they may even go to pieces under water, unless they are kept several days in the air previous to immersion, yet if allowed sufficient time to set in the air before they are immersed, they will become very good, and will not afterwards dissolve under water….so that it is not an indispensable test of the goodness of a cement that it should set underwater unless it be required for tide work, or works of a similar kind. … St Lawrence Canal Office Cornwall 30th May 1837

All the mortar for rubble masonry to be composed of 2 measures of fresh, well-burnt lime to 5 measures of sand. All the mortar used in the brickwork to be of the best fresh burnt brown lime, 1 part lime and 3 of clean, sharp pit sand.

The whole to be properly mixed together dry and a sufficient quantity of water added, the whole to be ground under edge runners or in pug mills.

<u>The mortar to be used as hot as possible</u> and no more mortar to be mixed in one day than can be used on the same.

The pointing mortar – 1 part best brown lime, 1 part sharp forge ashes, 1 part iron scales.

Mixed and ground under the edge runner to a fine paste as required **for immediate use.**

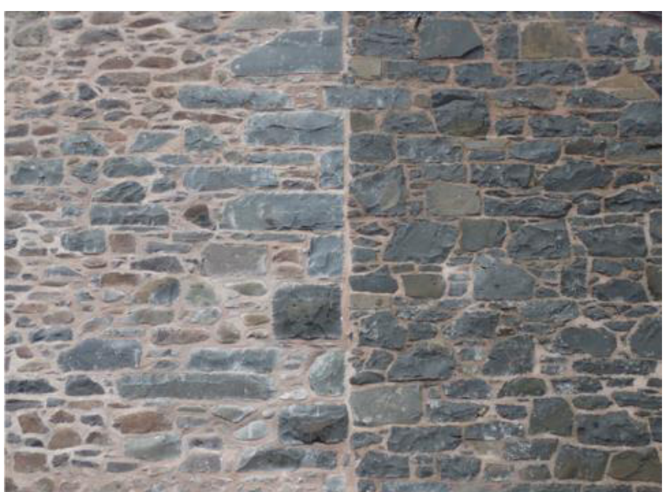
Contract and Specifications for the Parliament Buildings Ottawa Fuller & Jones Architects 1859. (Toronto Public Library)

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

Repointing(left) and rebuilding (right) of hard Pennine sandstone, NHL 3.5 1990s

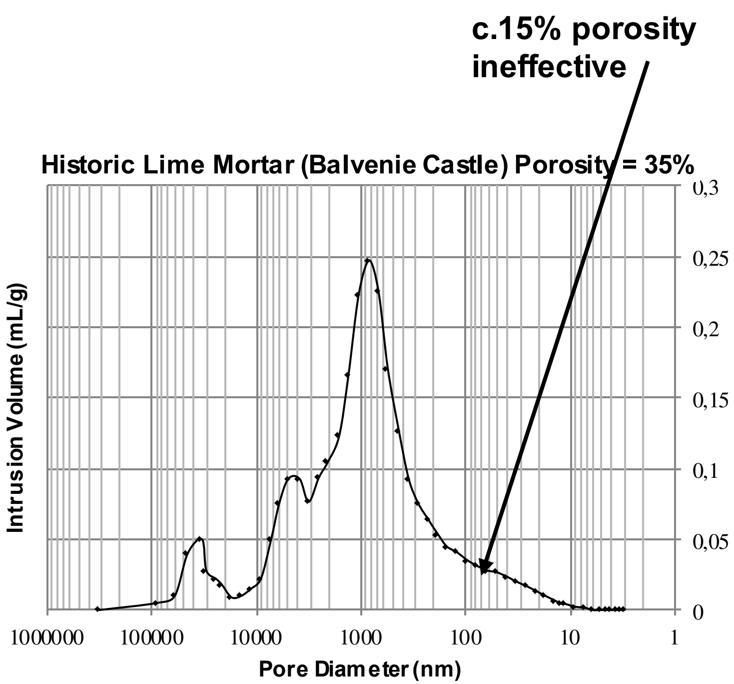
Archbald Moffat House, Moffat, Dumfries & Galloway.

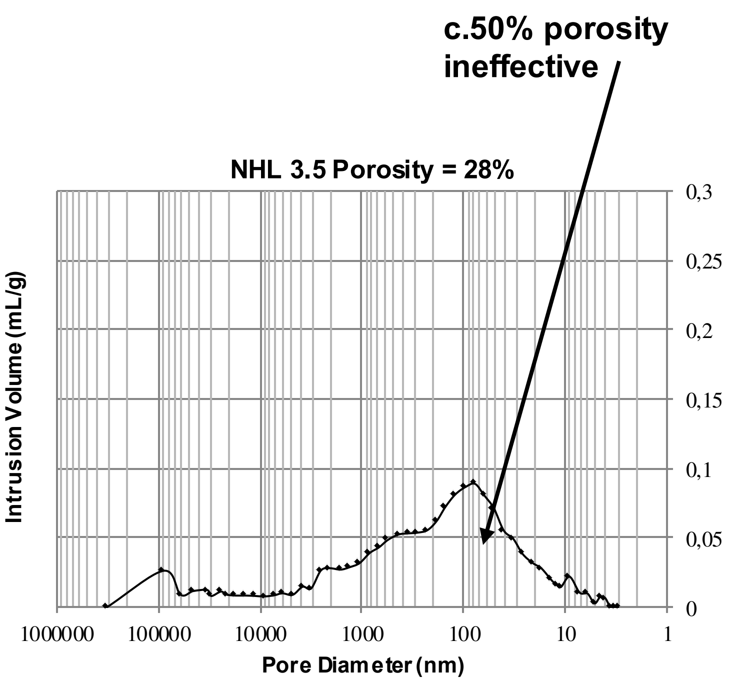
NHL 5.0 (left); hot mixed air lime (below)



Bleeding of calcium carbonate from NHL 5 used to bed ridge stones in late September. None from hot-lime mortars emplaced at same time. Fuller and more rapid carbonation. Straw Builders for Natural England.

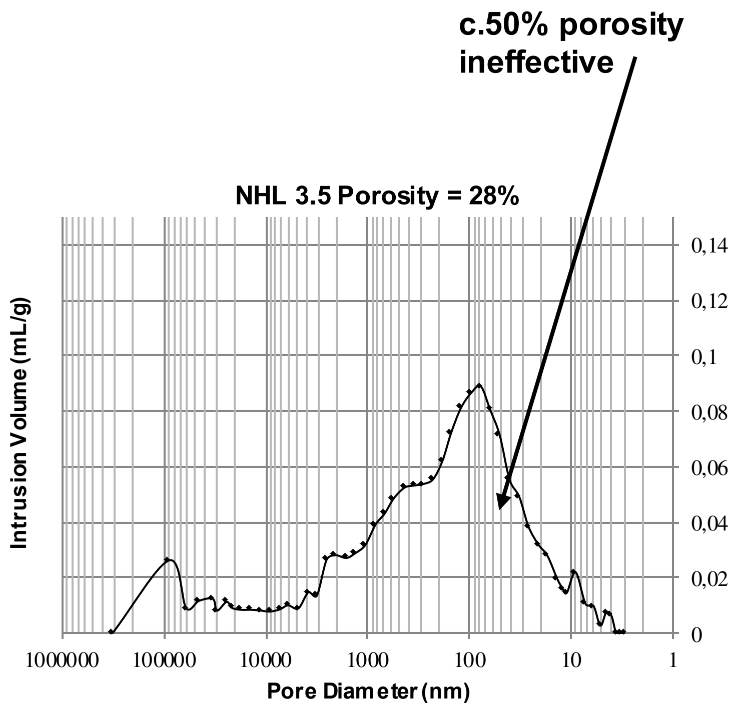
Modern mortars and sick buildings

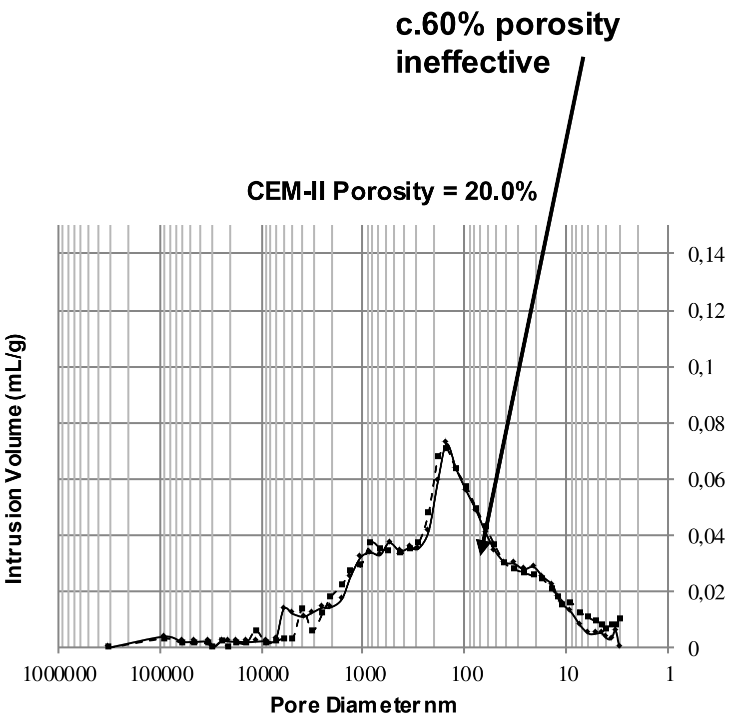




Historic lime and NHL… Spot the difference! DAVID WIGGINS 2016. CURTINS

Modern mortars and sick buildings





NHL and G.P. CEM-II… Spot the difference?

DAVID WIGGINS 2016. CURTINS

Mortar strength…is often greatly over-emphasised to the detriment of other **essential mortar properties**, such as **workability, water retentivity, and bond-strength**…and those builders who strive for high or maximum mortar strengths usually obtain inferior mortar for normal, above-grade masonry construction.

Before the advent of Portland cement in the United States…(1886 on), all of the masonry mortar was a straight lime-sand mix that inherently possessed very low compressive strength. True, some of the lime produced was derived from impure limestone that had varying (but usually faint to moderate) hydraulic qualities; other pure limes were mixed with crude, unwashed sand containing clay that acted like a mild pozzolan with lime. While both of the latter types of mortars possessed slightly more strength than the pure ('fat') lime- clean sand mixes, all would be regarded today as extremely weak in compressive strength (ranging between 50 to 300 psi *.34 – 2.0 Mpa)(*in 28 days).

Boynton & Gutschick 1964

(US) National Bureau of Standards Circular No.30:

“This question of the strength of a mortar is apt to be given undue weight. Since masonry is assumed to weigh 150 lbs/cu ft, then the compression load at the bottom of a wall will be 150 over 144 times its height in feet. A mortar with a compressive strength of 100 psi should, according to this reasoning, be able to carry a wall 100 x 144 over 150 = 96 feet or about 9 stories. A mortar joint in a wall may possibly be 9” wide by 30’ long by ½ “ thick. In the joint the ratio is 9 divided by ½ = 18. If a mortar has a strength of 100 psi when tested in the form of a cube, it should theoretically have a strength of 1800 psi when laid up in a wall.

Quoted in Boynton & Gutschick 1964

Where walls of greater thickness are used or where 8-inch walls are used for a one-story building and where reasonable care is taken to prevent undue loads, the use of straight lime mortar should be made optional.

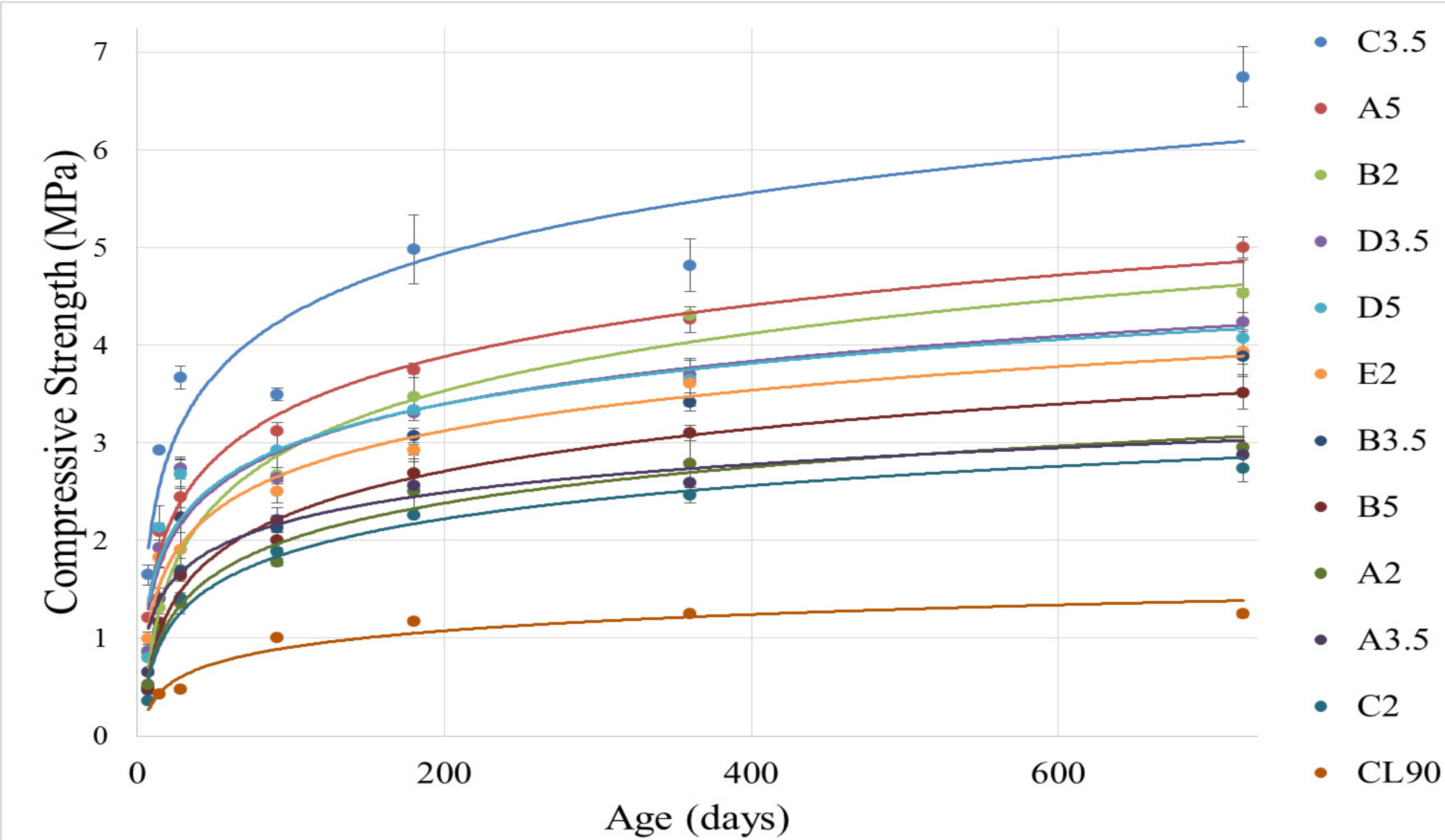
Recommended minimum Standards for Small Dwelling Construction. Report of the Building Code Committee. 1923. Government Printing Office, Washington.

Of the numerous factors contributing to sound masonry, bond between the units and the mortar is generally recognised as a very important factor, perhaps *the* most important…***bond strength and extent of bond…*** Principal reasons for lime's superiority over portland cement in producing intimate and durable bond are its higher degree of plasticity and water retention, and its greater fineness and inherent stickiness, which permits joints to be filled more readily and completely. Its ability to heal minute cracks and fill minute voids (autgeneous healing) also contributes to better bond.

Boynton & Gutschick 1964

(high free lime content in the binder is crucial to this effect)

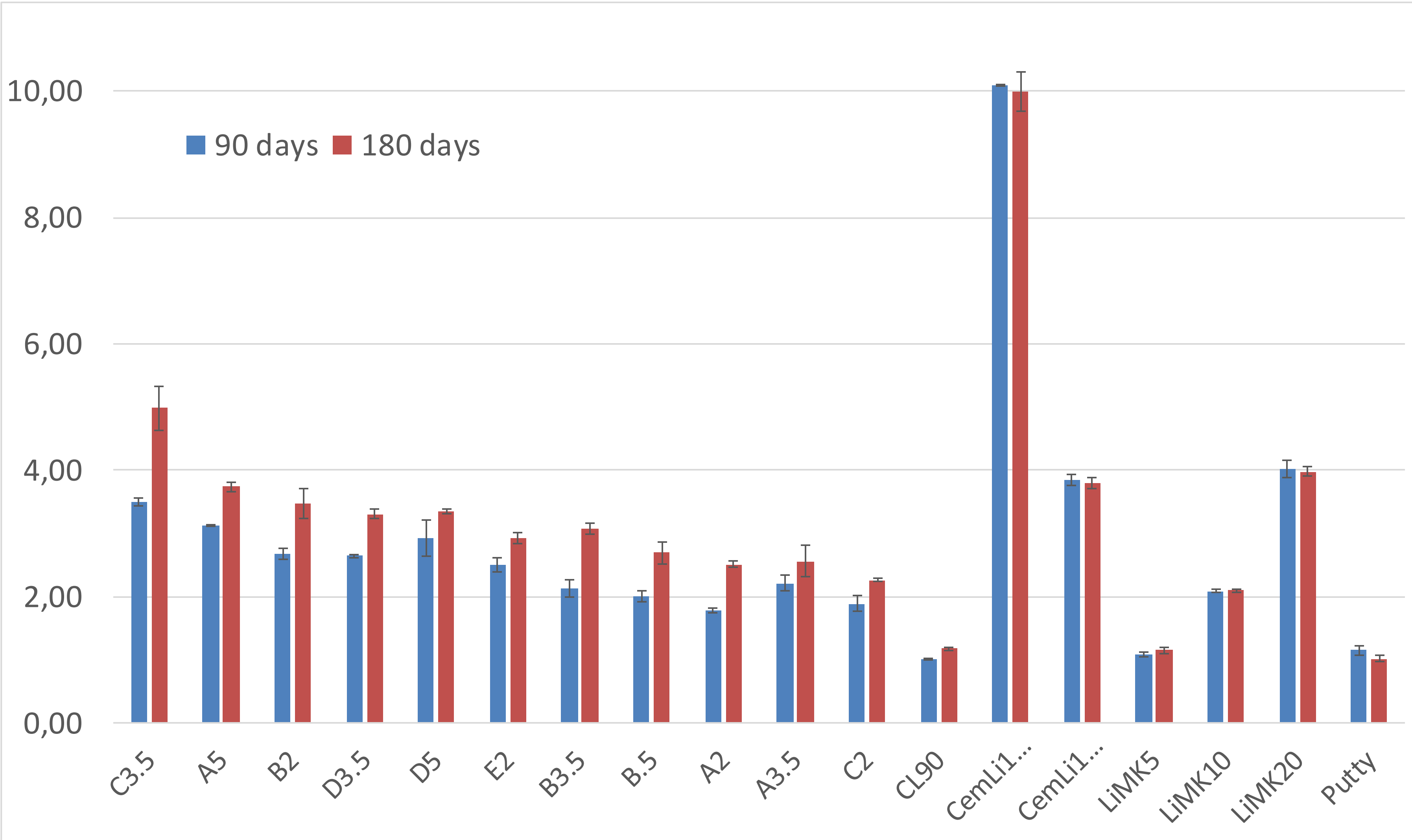
720 day compressive strengths. Mixed by volume.



Historic England

Weymouth College, March 2017

Compressive strengths of formulated mortars



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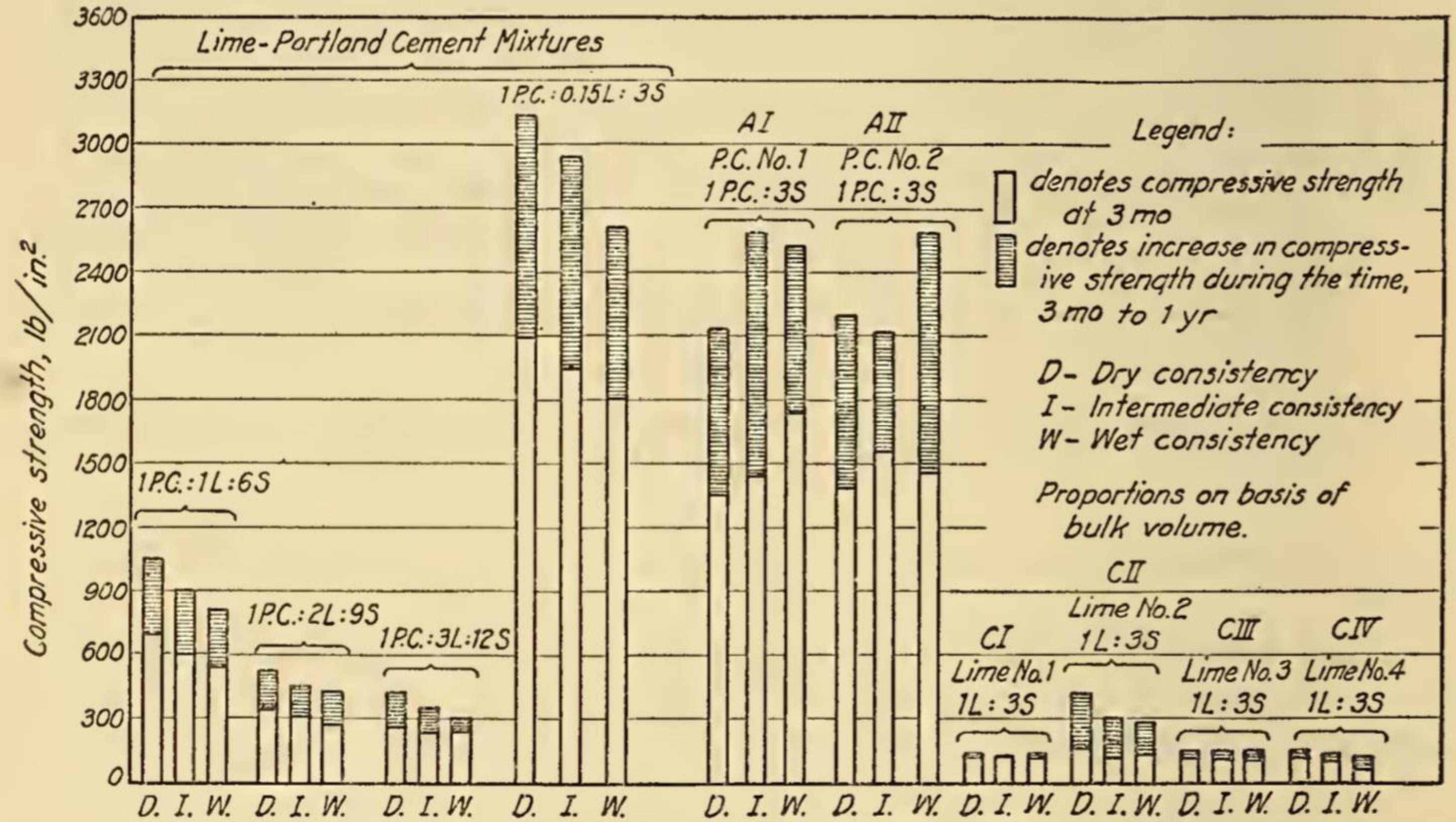


FIGURE 4.—*Average compressive strengths of 2-inch mortar cubes at 3 months and 1 year.*

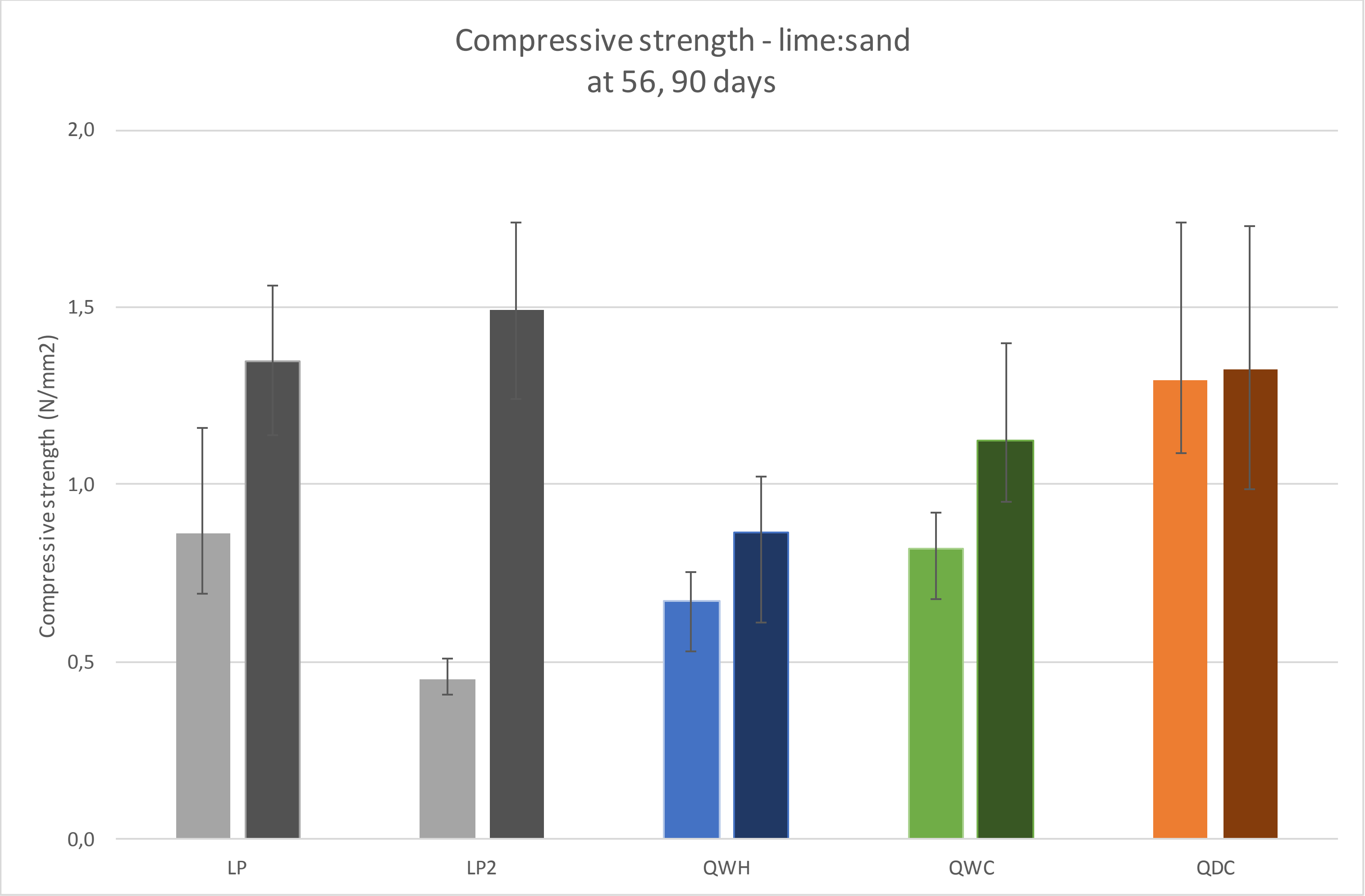
100 psi = 0.68 Mpa

C I	Lime no. 1	High calcium quicklime.	1L:3S	1 dry hydrate [4] 8.12S.
C II	Lime no. 2	Dolomitic hydrated lime.	do	1L:10.52S
C III	Lime no. 3	High calcium hydrated lime.	1L:3S	1L:9.21S
C IV	Lime no. 4	Dolomitic quicklime	do	1 dry hydrate [4] 7.26S.

Palmer & Parsons - US Bureau of Standards Journal 1934

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

Compressive strength



Historic England

& Lucie Fusarde

Coventry, October 2016

Free lime in an air lime: 90 – 96%
Free lime after 5% pozzolanic addition: 80 – 86%
Free lime in historic Blue Lias NHL: 72%
Free lime in a 1:3:12 mortar: 75%
Free lime in a 1:2:9 mortar: 66%
Free lime in a typical NHL 2.0: 35%
Free lime in a typical NHL 3.5: 25%
Free lime in a typical NHL 5: 15%
Free lime in typical new build mortar of 1 part cement: 5 parts sand: ZERO.
Addition of air entrainers compromises bond.
Cement production contributes to 10% of carbon emissions globally.

Optimum effective porosity will only come from carbonated free lime
Only free lime may take back CO2 emitted during firing.

Nidaros Cathedral, Trondheim. Hot mixed mortar 1000 years on; Chris Pennock explaining the rebuilding of the King's Entrance with hot mixed lime mortars 2017

Palmer, as long ago as the early 30s completely discredited (laboratory freeze-thaw tests as a measure of real world durability), claiming it was misleading and unrealistic. He contended, in fact, that the most frost resistant materials are usually the most dense, but that they tend to remain excessively wet in the wall. " The most weather-resistant wall is one hat remains relatively dry even though the materials composing it have poor records in laboratory freezing and thawing tests"…the analogy between a freezing saturated mortar cube and a monolithic wall structure is ridiculous.

Boynton and Gutschick Durability of Mortar and Masonry 1964

Typical compressive strength of an air lime mortar after 3 months: 0.7 – 1.3 Mpa.

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

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