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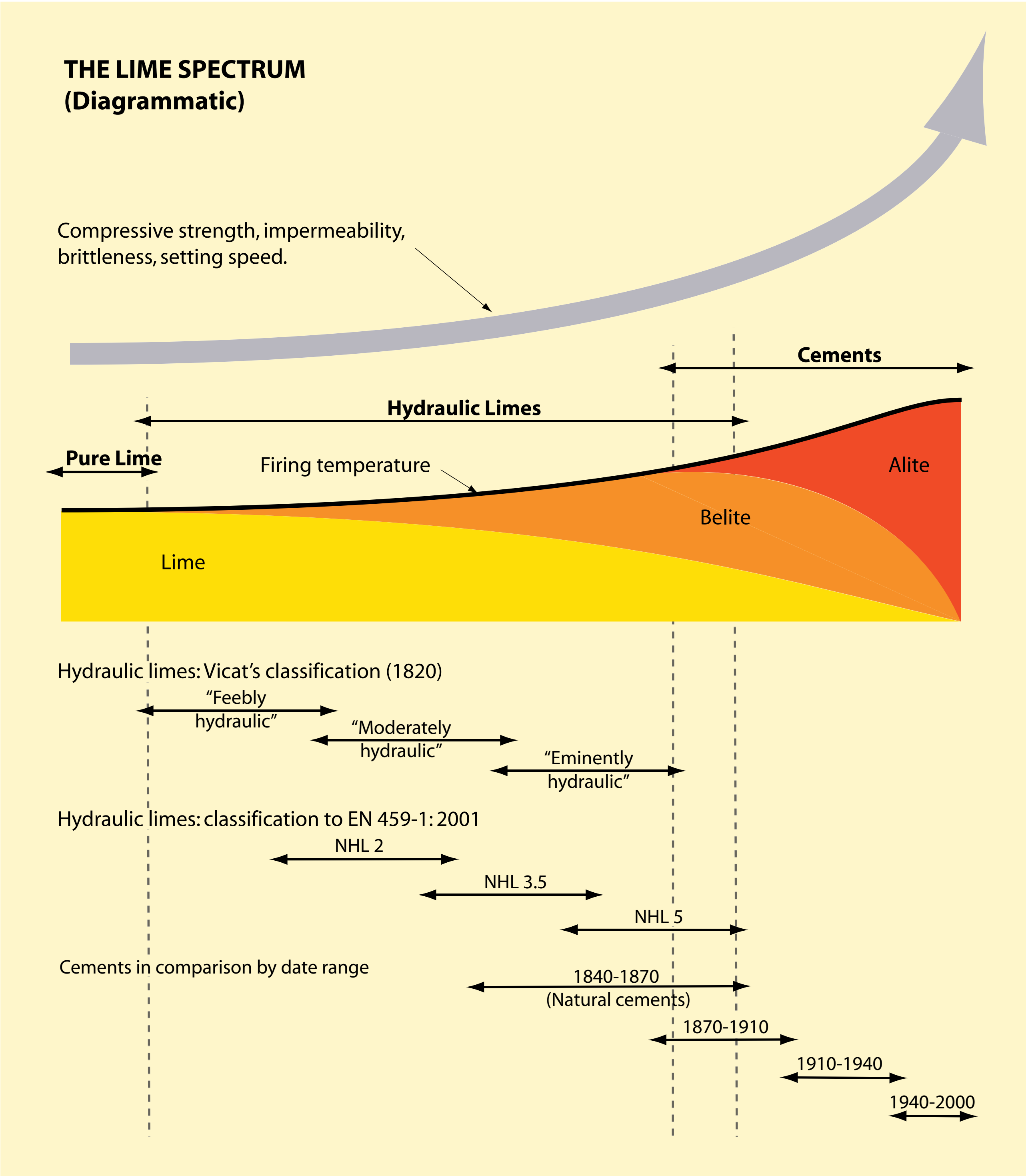

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THE LIME SPECTRUM

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The building conservation community has for many years been fully familiar with the importance of lime in the repair and maintenance of historic buildings of all ages, as well as with the danger of using cements inappropriately, but this is still often regarded as a simple dichotomy between two opposed materials - *lime:* good; *cement:* bad. In reality, however, pure lime and modern Portland cement lie at the two extremes of a broad spectrum of materials with essentially allied characteristics, and the materials which are appropriate for use on any particular historic building may well be found from anywhere within this range. The accompanying diagram is a simplified representation of the spectrum of limes and cements which have been historically available, based on the principal setting chemistries at work, as it is from this factor that their various qualities arise.

Lime (shown yellow in the diagram) sets by the carbonation of calcium hydroxide ($Ca(OH)_2$) to calcium carbonate ($CaCO_3$: the principal material of limestone) through a slow reaction with atmospheric carbon dioxide. This reaction, however, can only take place in the presence of water, which is why slow curing is vital: for the most effective result the mortar, plaster or render needs to be kept damp for weeks to enable the reaction to take place thoroughly. A balance is essential, as too rapid drying will lead to incomplete carbonation, but excessive wetting will cause saturation of the pores in the material and prevent the carbon dioxide reaching beyond the surface. This necessity for dampness is the reason lime work must not be carried out when there is any danger of frost.

Materials which cure by carbonation alone are pure limes or air limes (at the left end of the spectrum), and are generally available either as lime putty or as "bag" lime from builders' merchants. These materials are chemically almost identical, but their different methods of production give them different physical properties. In a putty the calcium hydroxide is produced by slaking calcium oxide (CaO) with an excess of water, and then allowing it to mature over time, whilst bag lime is produced industrially by hydration using exactly the correct amount of water for the amount of CaO. The maturing process in a putty allows the calcium hydroxide to break down slowly and thoroughly to achieve the characteristic smoothness, workability and "stickiness" of a fine putty, whilst hydrated lime is a dry product sold in paper bags, giving a powdery, gritty texture to mixes. The latter may not be much of a problem when mixed with sharp sand and cement on a modern building site, but it cannot be used for fine masonry jointing, plasterwork or limewash, for which putty is ideal.

Hydraulic limes and cements are produced from mixtures of limestone with clays, either occurring naturally in impure limestones (giving rise to natural hydraulic limes: *NHL*s in EN 459-1:2001), or by deliberate addition in measured quantities before firing (*HL*s in the same standard). The clays, when activated by the firing, combine with the water and the free lime in the mix to produce a set primarily based on calcium silicate. Critically, this reaction can occur in the absence of air, such as under water, giving rise to the terms "hydraulic lime" and "water lime". Generally, the greater the proportion of clay in the original material, the stronger the hydraulic set resulting.

There are, however, two principal types of hydraulic component, imaginatively christened "alite" and "belite" by cement chemists. Alite (shown in red on the diagram) is composed primarily of tri-calcium silicate (C_3S), whilst belite (shown orange) is based on di-calcium silicate (C_2S). In both cases aluminates and other chemicals are present in smaller quantities. Both types of hydraulicity may be derived from the same initial material, but the active compounds resulting depend on the firing temperature, with the alite only being produced above 1260°C. Belite is formed between 950 and 1200°C, which is the normal range of firing temperatures for limes. Alite sets harder and faster than belite, and gives cement its particular qualities, whilst hydraulic limes are characterised by a set based entirely on belite. Recently a product claiming to be a "belitic cement" has been under discussion, but this is a potentially confusing misnomer, and the material should for practical purposes be regarded as an artificial hydraulic lime (*HL* to EN 459).

Hydraulic limes always consist of a mixture of lime and belite acting in parallel. This dual curing process should be taken into account whenever they are used, ensuring that both the initial hydraulic set and then the slower carbonation of the free lime can take place, although for practical purposes the latter may now be less critical. When the proportion of belite is low the mix is more workable, and cures slowly and softly to give a very permeable and flexible finished material, whilst a higher proportion of belite gives a faster and harder set at the expense of workability, permeability and flexibility. Carbonation continues to follow the hydraulic set at its own natural pace until the material reaches its finished, cured state, so protection and tending are required on site with even a relatively strong hydraulic lime.

Modern Ordinary Portland Cement (OPC) does still contain belite and lime, but the speed and strength of the alite set is deliberately designed to swamp the effects of either of the two weaker, slower processes. Such a material is extremely well suited to the production of modern reinforced concrete, and it can be used with little protection or curing on site, making it very tolerant of poor workmanship. Although convenient and economic to use, however, it is debatable whether OPC is at all appropriate to even modern masonry construction in the long term, and finished work is inevitably of inferior quality. In order to improve the economy and environmental sustainability of their production modern OPCs now tend to be manufactured from a wide range of extracted and waste materials, introducing complex and sometimes undesirable chemistry, about which the manufacturers are not always entirely open. Gypsum is often added to retard the speed of the natural set (which can otherwise take only seconds), resulting in a material which is not only unnecessarily hard, brittle and impermeable, but also introduces a significant load of soluble sulphates, causing at best efflorescence on facework when these are mobilised by water, and at worst severely degrading adjacent brick and stone by re-crystallising within their pores. The latter is a very common failure mechanism where modern concrete or cement have been introduced into historic masonry. Most mass-produced bricks are now manufactured with an exaggeratedly high resistance to salt damage, partly in order to cope with the cement, and this is a principal reason for the difficulty in matching their historic softer-fired predecessors.

Pozzolans are separate activated silicates, usually derived from fired clays, which increase the hydraulicity of a mix by combining with the free lime during the curing process to form belite (ground brick dust and natural volcanic earths such as those from Pozzuoli near Naples, and trass, from Germany) and sometimes even alite (ground granulated blast-furnace slag, pulverised fuel ash, and similar high temperature materials). Thus any material containing a proportion of free lime can be moved to the right on the spectrum by the addition of suitable pozzolanic additives.

Vicat's classification of hydraulic limes into "feebly", "moderately" and "eminently hydraulic" classes was widely adopted from 1820 until the demise of most of the traditional lime industry in the UK, as it was both practical and appropriate to the end uses of the materials. This classification has now been superseded by the natural hydraulic lime classifications of NHL2, 3.5 and 5 enshrined in the Euronorm EN 459-1: 2001. It should, however, be noted that these tripartite classifications are not equivalent. The weakest modern class of NHL2 is more closely equivalent to Vicat's "moderately hydraulic" class, whilst NHL3.5 is nearer to "eminently hydraulic". NHL5 limes can easily reach strengths equivalent to natural cements. As can be seen from the diagram, there is now a critical gap in the modern classification between pure limes and NHL2, where Vicat's "feebly hydraulic" class used to comfortably sit.

This gap is particularly important within the UK as many of the limes which were highly regarded historically, and greatly sought after, were classed by Vicat as “feebly hydraulic”. Chief among these is perhaps the Dorking lime from the grey chalk of Surrey which was used to build so much of London, from the British Museum to the West India Docks, as well as being exported far further away. These “lean” limes (as opposed to “fat” or putty lime) are also a particularly interesting category for their working characteristics. Whereas modern NHLs are invariably produced by hydration like bag lime, and sometimes even ground as modern cements, the feebly hydraulic limes were traditionally slaked on site and used as young putties, giving a crucial mixture of the workability of putty with the convenience of a slow hydraulic set, and it is particularly for this mix of qualities that they were so highly prized. Normal working practice within London was to slake lime on a Friday for use during the following week. It is galling that EN 459-1 omits this class not because there is no use for these limes, but because the test method used to assess compressive strength (the crushing of a standard cube) is derived from cement testing methods, and is simply unreliable below a crushing strength of 2 N/mm^2.

In recent years the practice of specifying NHL3.5 hydraulic limes as a middling solution for general use in almost any circumstances has become widespread, and is often even advocated by official agencies, usually without adequately considering the circumstances of any particular building. This does have the practical advantage of providing a material which is relatively easy for the inexperienced to use, and which has a conveniently quick initial set. Prior to c.1870, however, limes of this strength would have been quite rare throughout much of the UK, and would normally have been reserved for civil engineering works including bridges, tunnels, docks, canals etc., and they can be much stronger than necessary for masonry or render on historic buildings. This frequent error is compounded by another misleading characteristic of EN 459-1: the establishment of compressive strength of mortars only at 28 days old. This is also derived from cement chemistry, as an alite set will be substantially complete at this age. A belite set, however, will often continue gaining strength for 90 days or more, so all of the NHL classes of hydraulic lime tend to produce finished mortars which are much stronger, harder, and less permeable or flexible than are generally recognised. In spite of the widespread acceptance of the lime revival, therefore, we are still often using materials which are significantly harder than those originally used on historic buildings, and the consequences of this rather sloppy approach remain uncertain.

In the unfortunate absence of any feebly hydraulic limes on the market, it is possible to obtain comparable results by adding NHL to a pure lime putty, although this approach was called into question by English Heritage’s moratorium on the use of “hybrid” mixes some years ago. It is crucial to recognise under these circumstances that the first proportion of hydraulic lime added will be inert; thus a putty + NHL3.5 mix will give actual results close to those expected of a putty + NHL2 mix. In all cases, however, other variables can cause problems, and site-specific trials are strongly recommended. One can only hope that a manufacturer of a good quality feebly hydraulic lime will once again materialise before long.

As with the limes, there has historically been a wide range of different types of cements, characterised by varying proportions of alite, belite and free lime. Another conspicuous gap in the spectrum of available limes and cements is that between NHL5 and modern OPC, which is particularly significant for the conservation of buildings in the later 19th century and the first half of the 20th, including those from the early Modern movement. Although these often used cement as a critical component in their construction and appearance, the actual material available was very different from that found in builders’ merchants now, and few present equivalents exist. An NHL 5, perhaps with added pozzolan, can be used to closely match the compressive strength of pre-WW1 cements, although matching of other qualities, including appearance and long-term behaviour, is not always achievable. Masonry cements, which tend to be hybrid mixes of modern Portland cement and hydraulic or hydrated lime (usually with plasticisers and other additives) can be useful in this area, and their continued existence is a tacit admission of the relative unsuitability of OPC for laying brickwork or stonework, but the appropriateness of a specific proprietary mix to an individual historic building cannot be guaranteed, and there is little variety available.

A recent international EU-funded research programme, represented in the UK by the University of Bradford, has been studying the "Roman" cements widely produced during the 19th century, particularly in the UK from septaria occurring in London clay. These natural cements have a highly distinctive appearance, with a strong reddish-brown colour which is notoriously difficult to match, and the project's intention to re-commence manufacture of the material is quite an exciting development. Roman cements were, however, made effectively obsolete by the rise of early Portland cements after 1870, so this only partially fills the gap. Some other natural cements have survived on the UK market, principally to suit the requirements of the potable water industry for low soluble chemical content and rapid set, but the majority of these are supplied as premixed mortars tailored specifically for the repair of water-retaining structures, and are of limited use in conservation. That does not, however, exclude the possibility that suitably formulated products may be developed in the future.

In conclusion: the question of "lime *vs*. cement?" is no longer an adequate model for the specification of mortars, renders or plasters in building conservation, but should instead be replaced by the question: "*which* lime or cement?". A suitable equivalent for many of the materials used historically, throughout all periods, is now available, but there are significant gaps in the overall spectrum which still remain to be filled. This relatively wide availability puts the building conservation community in a position of strength which has never previously existed, although it must be recognised that each of these varied materials does need to be understood in its own right in order to achieve appropriate results. There are grounds to hope that a full spectrum of appropriate limes and cements for both conservation and new build may actually be available in the foreseeable future, although much work still remains to be done.

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Postscript: Since this article was first written, and in response to a proposal put forward by British representatives, the Euronorm committee has agreed in principle to consider the revision of EN 459 to introduce a weaker class of natural hydraulic lime, provisionally designated NHL1. At least one manufacturer is understood to be actively considering the introduction of a suitable product.