



**CARBONATING AND HYDRAULIC MORTARS
- the difference is not only in the binder, aggregates are also important**

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ABSTRACT

In spite of the increasing availability of mortar-less products, mortar has traditionally held walling units together and is still the choice of many builders. Blended lime - Portland cement (PC) mortars are becoming more fashionable and hydraulic, partially hydraulic or carbonating lime mortars are certainly preferred for restorative work. The requirements for proper carbonation when carbonating lime or the new eco-cement magnesian mortars are used are however poorly understood, especially in the English speaking world. This paper compares carbonating and hydraulic mortars and discusses the chemistry of the strength giving reactions involved as well as the impact of physical factors such as aggregate size, grading and moisture. The role of aggregates for proper carbonation is considered from a theoretical point of view and in terms of best practice from the past. The paper concludes that sands suitable for hydraulic mortars are not suitable for carbonating mortars and vice-versa and points out deficiencies in the current standards and codes of practice that do not recognize this. A new direction is suggested that combines the best practice from the past with that of the present.

KEYWORDS: Aggregates, mortars, lime, eco-cement, sand, grading, standards, carbonation

INTRODUCTION

Until the beginning of the twentieth century most buildings were constructed with lime and hydraulic lime mortars and many still stand as testament to their quality. Examples include many Roman lime mortars such as in Hadrian's wall built nearly 2000 years ago (122 AD) and the Tower of London built some 900 years ago. Portland cement mortars until recently had taken over the mortar market in English speaking countries, whereas in many other parts of the world such as Slovenia where PC mortars are banned, lime mortars never went out of use. There is currently a trend back to the use of lime mainly for the plasticity introduced to mixes. There will potentially be a rush towards carbonating lime mortars if carbon credits became available for proven sequestration. The industry needs to prepare itself for such a commercial opportunity.

The requirements of mortars of varying degrees of hydraulicity and carbonation potential are poorly understood and there is considerable lack of scientific knowledge amongst engineers and the trade. The way hydraulic mortars, carbonating mortars or pozzolans are used together is not generally optimised in the English speaking world and there is much controversy. Carbonating mortars are not fairly considered worldwide by standards designed for hydraulic cements. Too often the focus is on ease of use rather than end result. For example, in the most used mixes

(1:1:6 or 1:2:9 (pc, lime, aggregate)), the aggregates used are generally much too fine and well graded for the lime to serve as much other than a plasticiser. Hydraulic limes are rarely used and poorly understood and little advantage is taken of pozzolanic wastes.

The historic record is confusing and a thorough analysis is overdue based on fundamentals that are not clouded by inappropriate standards. Although good mortars from the past have lasted through the ages there have also been many failures¹. The biggest problem in trying to discern best practice from the past is that historic mortar formulations are many and varied, although some common lessons underlie many of them that agree with good science.

Given the increasing popularity of 1:1:6 through to 1:3: 10-12 mortars and the possibility of carbon credits for sequestration it is essential that the industry get its act together. There would be significant potential commercial and technical benefit of cutting through the dogma and providing a scientific basis for formulation. Codes of practice need to recognise the differing requirements of hydraulic and carbonating mortars, particularly for aggregates and curing conditions. The new magnesian mortars developed by TecEco add a new dimension as they are easier to use, and do not appear to suffer the segregation problem of mixed lime PC mortars. As carbonating mortars, they can develop greater strengths including bond strength to bricks because of the unique microstructure attributable to the highly acicular nature of the hydrated magnesium carbonates which form. They develop higher early tensile strengths and are also more acid resistant, yet retain the benefits of self healing attributed to lime mortars. If either lime mortars, PC - lime mortars or eco-cement mortars were optimised for carbonation there would be significant sustainability and other benefits. The new eco-cement mortars should theoretically provide the plasticity required with coarser aggregates and may overcome the tendency in the trade to formulate for ease of use rather than properties.

BINDER TYPES AND MANUFACTURE

There are many binders for cementitious composites and a summary follows. Table 4 is included for reference.

Hydraulic Cements

Cements are 'hydraulic' or partly 'hydraulic' because they set or partially set by chemically utilising water or hydroxylating. This process is known as "hydration" in the industry.

Portland Cement

Portland cements are similar to hydraulic limes as they were derived from them by calcining limestone with clay at temperatures of around 1450°C. The main hydrating minerals present include alite, belite, tri-calcium aluminate and calcium alumino ferrite. As the technology is well known details are not covered in this paper.

Tec-Cements

Tec-cements (5-15% MgO, 85-95% OPC) contain more Portland cement than reactive magnesia. Reactive magnesia hydrates in the same rate order as Portland cement, forming brucite which uses up water and reduces the voids:paste ratio, increasing density and possibly raising the short

¹ The lime mortars in my own house date from 1928 and are failing.

term pH. Reactions with pozzolans are more affective. After all the Portlandite has been consumed, brucite controls the long term pH which is lower and due to the low solubility, mobility and reactivity of brucite, greater durability results. Other benefits include improvements in density, strength and rheology, reduced permeability and shrinkage and the ability to use of a wider range of aggregates many of which are potentially wastes without reaction problems. Tecements are not discussed further as they are not recommended for mortars

Hydraulic Limes

Louis Vicat (1786-1861) introduced the term "hydraulic lime" in place of the earlier term "water lime" used by Joseph Smeaton of Eddystone lighthouse fame and others and classified limes according to their "hydraulicity".

Hydraulic limes are not Portland cement but have many characteristics that are similar as Portland type cements are derived from them.

The decarbonation of lime is greatly favoured by intimate mixing with clay minerals [1]. When heated at moderate temperatures, clay impurities in limestone dehydroxylate forming (in the case of kaolin) metakaolin and generally kandoxi² (dehydroxylated, activated mixed clays). Some reactions also occur between the kandoxi and lime producing calcium silicate hydrate precursors which set when they hydrate including belite, aluminat and ferrite phases [1]. Gehlenite has also been reported. A hydraulic cement contains lime, silica and alumina and hardens by hydration [2]. Most of the minerals formed are therefore "hydraulic".

Partially Hydraulic Limes

Partially hydraulic limes have residual lime and are usually slaked with just enough water to convert the quicklime left to calcium hydroxide, but not so much that a chemical set begins³. Hardening occurs by carbonation of the remaining slaked lime as well as reactions between it and unreacted kandoxi forming calcium silicate/aluminat hydrates. At around 40% silica/alumina, maximum strengths are achieved and there is no 'free' hydroxide to carbonate. The degree of hydraulicity of mortars will affect many characteristics. By selecting an appropriate ratio of clay to limestone, the properties of mortars that carbonate or set hydraulically to varying extents can be designed for particular application requirements such as setting time, strength, colour, durability, frost resistance, workability, speed of set in the presence of water, vapour permeability etc.

Hydraulic lime mortars are arguably better than PC mortars and PC non hydraulic lime mortars and are sought after in the restoration industry. However, in the context of global warming it may be better to focus on mortars that can gain strength through carbonation such as partially hydraulic lime mortars, non hydraulic lime mortars, high lime PC blends or mortars made using the new eco-cements developed by the author. All hydraulic cements must be used as soon as possible after opening the bag and adding water.

² The term Kandoxi was introduced by Joseph Davidovits of geopolymers fame for mixed de hydroxylated (dehydrated) clays to get over the rather loose use of the term "metakaolin". See <http://www.geopolymer.org>.

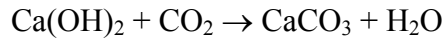
³ in practice, too much water is often used!

Non Hydraulic Carbonating Cements

Non hydraulic cements used in mortars rely on carbonation for strength development.

Lime

When reactive lime carbonates, it follows Ostwald's law forming vaterite, aragonite and calcite in that order [3].

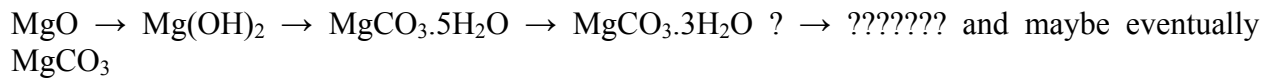


The reaction is thought to be through solution and the first step is the dissolution of calcium hydroxide followed by reaction with dissolved carbon dioxide.

Commonly available lime is generally fired at between 850 and 1100°C and then slaked and is relatively pure as manufacturers tend to pick or sieve out any sintered clinker where it has reacted with impurities. Although it is not the best available for use in lime mortars because it is often slightly hard burned⁴ through the overuse of "flash" calciners, it is what is being used for most blended mortar formulations such as 1:1:6 or 1:2:9 (PC:lime:sand)⁵.

Eco-Cement

Instead of calcium hydroxide as the main ingredient, reactive magnesia (MgO) is used which first hydrates forming brucite (Mg(OH)₂) which then carbonates forming an amorphous phase, lansfordite and nesquehonite. The sequence as so far determined seems to be



The reaction is also probably through solution but favours the formation of hydrated carbonates as the highly charged Mg⁺⁺ ion in water strongly attracts polarised water molecules around it which are not easily removed and are therefore incorporated in the new carbonate molecules when formed.

CARBONATING MORTARS - ADVANTAGES

For many masonry structures modern Portland cement mortars and even some fully hydraulic lime mortars set too hard and do not self-heal. They tend to crack with any movement and let water in. Once the water is in they are so tight they do not let it out again as they cannot "breathe" leading to further problems. Apart from plasticity, the other main advantage of using carbonating mortars is that they are much more forgiving. As all buildings move, especially those built pre 1900, many of which had less solid foundations, this property alone is reason enough to use them. A carbonating component is required for crystalline bridging of cracks that develop through movement.

Global warming is a major issue and the huge potential in the built environment for sequestering carbon cannot be ignored. There is therefore an urgent need to reconsider the merits of properly carbonating mortars in this context. Cementitious materials that go the full thermodynamic cycle

⁴ And therefore may not properly hydrate when "slaked".

⁵ TecEco also have a kiln technology that will get around this problem.

gaining strength by carbonation offer tremendous potential because the CO₂ chemically released during manufacture can be recaptured resulting in significant overall sequestration. To put the tonnages involved into context, in 2004, by calculation from clay brick and concrete block production, Australians used about 300,000 tonnes of Portland cement to make mortars. Roughly only 25% of this cement carbonates, so 225,000 tonnes of CO₂ were released - assuming emissions are taken to be roughly one tonne of CO₂ per tonne of cement [4]. If lime or high magnesian eco-cements had been used the reduction in CO₂ emissions would be a significant 225,000 tonnes. Australia is only about 1.4% of the economic world so globally the figure is significant.

There are other sustainable advantages of self carbonating cements. The bulk density is lower than Portland cement enabling fuel savings during distribution. Buildings constructed with all but the strongest lime and eco-cements can also easily be altered and the recovered masonry reused. In contrast bricks held together with Portland cement mortars usually cannot easily be recycled as the mortar is too strong. The production of bricks and masonry units is an energy intensive process and the savings involved as a result of more efficient recycling would be considerable.

Apart from sustainability there are many other good reasons for using carbonating lime and eco-cement mortars including:

- The accommodation of minor and thermal movement without damage.
- The avoidance of expansion joints.
- Improved insulation and avoidance of cold bridging.
- Reduced risk of condensation.
- Low risk of salt staining.
- Alterations can be effected easily and masonry revised.
- Lower pH
- Masonry life is increased.
- Masonry can more easily be cleaned and reused.
- More resistant to freeze thaw and sulphate.
- Reduced calcium aluminate content & reactions with sulphate in stone.
- Lower alkalinity and reactions with stone, particularly sandstone
- Better bond to acidic or more neutral rocks like sandstone.
- Buildings which themselves “breathe” are healthier to live in.

And last but not least – they are aesthetically pleasing!

CARBONATING MORTARS - DISADVANTAGES & POSSIBLE SOLUTIONS.

Lea's comments that “Mortar taken from buildings many hundreds of years old, if uninjured, is found to consist mainly of calcium hydroxide, only the external portion has been converted to carbonate” [5]. Note however that the lack of carbonation of some old mortars can be explained as a function of low porosity due to poor aggregate selection rather than due to an innate inability of lime to carbonate. Lime type carbonating mortars are considered by many as too weak for copings, chimneys and other exposed work. As minerals such as nesquehonite found in eco-cement mortars are micro structurally stronger, this problem may be overcome by substitution with magnesia as in eco-cements. Currently there is also a danger regarding use in frost prone

months. This is however not so much the fault of the binder but because the fine sands used not only don't let air in for carbonation – they don't let moisture out.

Lime mortars are subject to attack by acid rain. Fortunately eco-cements appear to be much more acid resistant. The thermodynamics and kinetics is complex: however the evidence is that no potholing or caving is ever found in magnesium carbonate country. Chlorides and sulphates attack lime and Portland cement mortars but are rendered chemically inactive and cementitiously useful by the magnesia in eco-cement type formulations. As these salts are common in some rocks and bricks and certainly in city environments, particularly near the sea or where salt is used on roads, eco-cements should be considered for this reason alone.

ADDING PORTLAND CEMENT TO CARBONATING MORTARS.

“The development of mortars containing Portland cement that harden and gain strength rapidly made it possible to place masonry units quickly. Also, thicker joints provided cushions for dimensional variation in the masonry units. The stronger mortars were first obtained by “sweetening” the lime with a small amount of Portland cement. Later, the ratio of Portland cement was progressively increased until the process involved sweetening the cement with a small amount of lime” [6]. In modern Portland cement and Portland cement lime mortars air entraining agents are used to provide the workability previously provided by well slaked lime and the porosity provided by well graded gravel containing a coarse fraction. A problem with this approach however is that bricklayers tend to add too much chemical and air bubbles collect under the uppermost bricks ruining the bond [7].

According to O'Hare who has studied the relative merits of adding Portland cement to lime mortars [8] "the use of cement tends to lead to the user treating the gauged lime mortar as if it were a fully hydraulic lime or cement. Too much reliance on the initial chemical set leads to neglect of the importance of the longer term carbonation of the non hydraulic component present.....segregation is a major hazard. As the mortar sets, the cement colloid tends to migrate into the pores of the lime mortar as they form, clogging them and leading to a greatly reduced porosity. If the proportion of cement is high enough, segregation is much less likely to occur, but the resulting mortar will be hard. If the cement proportion is low, the mortar will be less hard, but segregation is more likely to occur. The resulting mortar will be seriously weakened, with a poorly formed pore structure leaving it very susceptible to frost damage and deterioration, even after carbonation of the non hydraulic lime (components) present has taken place.

The Smeaton Project, a research programme commenced by English Heritage indicates that a 1:1:6 mix, containing a 50 per cent cement binder, is unlikely to segregate, while a 1:2:9 mix, containing a 33 per cent cement binder, is almost certainly at risk. Until recently it was considered good practice to gauge lime mortars with as little as 5 per cent cement, just enough to impart a chemical set but not enough to make the mortar appreciably harder. However all of the Smeaton Project test samples containing less than 25 per cent failed.”

“Given the possible hazards of segregation, an un-gauged lime mortar relying solely on carbonation is likely to be more resilient in the long run than one gauged with a small amount of cement. Doing so requires care in its application and careful nurturing to ensure that it carbonates properly. If a chemical set is required, a safer alternative to Portland cement would be to use a hydraulic lime. In these the hydraulic components are so closely associated with the non hydraulic that segregation does not occur.

Hydraulic limes tend to be hard and impermeable, but not usually as hard as a 1:1:6 mix. Brick dust is a cheap and highly effective pozzolanic additive, providing a useful alternative to cement. Given that it is now widely accepted that mortar should be weaker and more porous than the material that it is jointing or repairing, it is probably better in most circumstances to rely on a good non hydraulic lime mortar using well-matured lime putty and sharp and well-graded aggregate, applied with care and subsequently well tended to ensure correct carbonation.” [8]

Many of the problems referred to by O’Hare are overcome by the new eco-cement mortars in which PC and magnesia work together in a totally complementary fashion.

Hydraulic limes were also superseded by cement because of the need for mass production and lower unit cost. The strength of a hydraulic lime mortar depends on the proportions of clay in the limestone and these varied widely from bed to bed, together with the kiln temperature. As a consequence the vagaries of hydraulic limes meant unpredictable performance. In spite of the evidence that they are not the best, used properly or optimised, 1:1:6 and 1:2:9 mortars are most favoured and commonly used mainly because the manufacture of non hydraulic limes for industry and blending with PC in 1:1:6 and 1:2:9 mortars is a predictable process that at least has the potential of producing a consistent product – essential in a litigious world where construction is ruled by engineers not artisans.

Unfortunately standards in the English speaking world are not very specific about hydraulic mortars and allow a wide range of aggregates to be used (see The Relevance of Modern Standards to Carbonating Cements). Furthermore the current European Standard on hydraulic limes allows compressive strengths within each strength category to vary by a factor of 3. “There is (also) no requirement to specify the amount, if any, of any free lime (calcium hydroxide) available for carbonation. As a consequence many specifiers of hydraulic lime stipulate very high proportions of hydraulic lime. In contrast adding a pozzolan or gauging with cement offers a reliable means of adjusting porosity, structural strength, water permeability and durability.”[9]

The fact that modern lime mortars are so far from optimally formulated and used is no credit to the industry or the scientists that support it. The lime is often slightly hard burned leading to the practice of pre-soaking it for the best result (making lime putty) or it can be carbonated to some extent either when it was manufactured⁶ or by re-absorption over time in the bag. These problems pale in significance compared to the practice of using poorly graded sands that are far too fine to let carbonation properly ensue. To get over these consistency and other problems PC is added and the PC component in blended lime PC mortars is relied on for strength development. The lime is added mainly because of the plasticity it imparts and not because the strength it could develop if it were allowed to carbonate properly.

In addition to the earlier quote, O’Hare remarks with respect to adding PC in relation to heritage work [8] that: “Cement is not in itself harmful, but insensitive and indiscriminate use of it is. It can be used as a useful pozzolanic additive to non hydraulic mortars, but those specifying and using it should be clear why they are doing so, and what its effects are likely to be.”

Note however, that recent work by Beauchamp has demonstrated that “testing the flexural tensile strength of 16 month old lime mortars made with slaked quick lime, slaked hydrated lime and

⁶ this problem will get worse as the partial pressure of CO₂ in the atmosphere increases.

hydrated lime powder showed there was very little difference in the average strength of the mortars. All mortars exhibited increased strength with increased carbonation.” [10]. Chemically there is no difference and it follows that much of the art of slaking on site and making lime putties is only useful if the quality of the lime is questionable as would be the case if it were partially hard burned. Furthermore if lime has carbonated in the bag to any extent it should be used in the vegetable garden, not in mortar!

With all carbonating or partially carbonating mortars, for best results it is essential to optimise the benefits of carbonation and this requires properly graded sands including a coarse fraction (See Aggregates).

The controversy over what mortar is best may well be at an end with the new eco-cement formulations which uniquely appear to optimise all the sought after properties of good mortars from acid resistance and excellent rheology to self healing and strength development. There are other problems that may well be overcome with eco-cement blends including the tendency of both lime and PC mortars to react with salts in stone.

RAW MATERIALS

Lime and Portland Cement

Lime is made from Limestone, hydraulic lime from limestone containing clays and Portland cements are made either from limestone containing clay or limestone mixed with clay. Limestone is a sedimentary rock covering about 7% of the crust. Modes of formation include the decaying shells of marine animals as well as chemical precipitation at specific depths.

Eco-Cements

Eco-cements require a source of magnesium and although magnesium carbonates are less abundant than calcium carbonates, the use of magnesium silicates for sequestration is very seriously being considered because of high molar conversion and the fact that the by-product is magnesium carbonate. Magnesium carbonates can be low temperature fired and are therefore suitable for using waste or solar heat and provide a simple process in which CO₂ can easily be captured for reuse or geological sequestration.

Aggregates

The major problem with nearly all mortars today is that the same sands tend to be used for all of them regardless of the incongruous requirements for proper compaction or carbonation. Carbonating mortars require well graded aggregates with a coarse fraction to carbonate properly. The sort of building sand commonly available from hardware or sand and gravel suppliers today is generally just not suitable. In the past, rough sand would have been cut from a local source and grits with rounded particles were often obtained from rivers. However sharp grits were also used which were waste products from stone quarrying [11]

Carbon dioxide is at about 380 ppm in the atmosphere. It follows that for carbonation to occur in either lime, blended lime PC or eco-cement mortars the mortar must be able to “breathe”. By “breathing” vapors must be able to pass into, through and out of the mortar. Carbonation reactions generally occur in the aqueous phase much more quickly than in the gas phase and thus water vapor is also necessarily present. Reactions will also occur in dry conditions as the

thermodynamics are favourable. Hence the need to seal bags with good liners even in dry storage. For proper carbonation of eco-cement and lime mortars, the sand must result in the mortar being sufficiently porous to "breathe". Coarse sands fractions are required in the aggregates. "Generally specify washed sharp sand with 3-4 mm grit (where the joints allow) and not too high a proportion of fines" [12]. A well-graded masonry sand that has a range of grain sizes from fine to coarse is best. The coarsest grains should be no more than 1/3 the depth of the mortar between bricks for easy laying. Although logical as a ramification of the chemistry this seems to be poorly understood except by a few within the restoration industry.

In contrast, for Portland cement mortars to gain strength the main requirement is for a low water binder ratio. For this, relatively fine sands that are rounded and compact well are required. Such sands are not suitable for carbonating or partially carbonating mortars.

The Historical Record on Aggregates for Hydraulic and Carbonating Binders in Mortars

Most old carbonating lime mortars are a mix of lime putty, lime sand, and grit. Generally a greater proportion of lime was used for sandstone or sedimentary rocks and a harder mortar use for granite or impervious rocks.

According to Benjamin Herring [13], editor in chief of constructor magazine, "The Romans had two distinct types of concrete mortar. One was made with simple lime and river sand, mixed at a ratio of three parts sand to one part lime. The other type used pozzolan instead of river sand and was mixed at a ratio of two parts pozzolan to one part lime."

The oldest record I have on the issue of sands for carbonating and hydraulic cements is book II, chapter IV of the Ten Books of Architecture by Vitruvius Pollio [14]. According to Vitruvius, "the best (sand) will be found to be that which crackles when rubbed in the hand, while that which has much dirt in it will not be sharp enough. Again: throw some sand upon a white garment and then shake it out; if the garment is not soiled and no dirt adheres to it, the sand is suitable" Vitruvius was talking about gritty sand with no fines.

There is no doubt that sand grading is one of the most important parameters for mortar design. 16th century architect Andrea Palladio is renowned for "The Four Books of Architecture" which were translated into English in the early 18th century and used as a principal reference for almost two centuries (Palladio, Isaac Ware translation, 1738). In the first book he says, "the best river sand is that which is found in rapid streams, and under water-falls, because it is most purged". In other words, it is coarse. Compare this with most sand for use in mortar today [15]. Waldum [16] states, "in the "good quality" ancient mortars relatively coarse sand is often found. Grains up to 6 - 8 mm were often used for renders 20 - 30 mm in thickness and for masonry mortars." However, this experience from the past is ignored to a degree when taking a bet both ways, the author on the same page further states, "Preliminary laboratory tests with lime putties and the compositions in question did not indicate that a more coarse aggregate gives mortars with improved durability properties. The "to-days" recommended grain size distribution was therefore used in the test mortars. In principle, however, sand for repair mortars should be selected to match the sand grading in the various coats of the original render or of the masonry mortar".

Regardless of the variability of mortars in old buildings, "historically, references back through the centuries suggest that the sand mix should be 60% sharp sand, 40% fine sand for mortar and

render mixes.” [17]. “When matching the aggregate of an historic mortar it may be necessary to mix several types of sand and/or fine gravel. Therefore it is essential to have a good knowledge of available sands in a particular region. Take particular care about the grading of the replacement mortar’s aggregate. It should be clean and well graded, ranging from fine to coarse, and be gritty in texture. This produces a stronger mortar with less risk of shrinkage. Beware of artificially crushed stone dusts (especially limestone). These cause shrinkage problems, are weak and have poor adhesion. The size of aggregates will depend upon the thickness of the mortar joint. Fine joints will not be able to accommodate large particles.” [18]

OPTIMISING BY BLENDING OLD AND NEW MORTARS AND TECHNIQUES.

“Modern buildings tend to rely on an impervious outer layer or a system of barriers to prevent moisture penetrating the walls, whereas buildings constructed before the mid 19th century generally rely on allowing the moisture which had been absorbed by the fabric to evaporate from the surface, The thickness of the wall alone may have been relied upon to achieve acceptably dry conditions internally.....Under normal circumstances, older buildings will function well if they are allowed to work as they were intended. Mortars, plaster, renders and finishes should all be of relatively permeable materials allowing moisture to pass through them and evaporate from the surface. Traditionally mortars, plasters and renders were usually lime-based...” [19]

It is important not to use dense hydraulic mortars over older walls or renders as doing so will prevent them from breathing causing all sorts of damp related problems.

The Relevance of Modern Standards to Carbonating Cements

According to Henriques and Charola [20], “lime mortar standards were being developed at the time that Portland cement was being introduced as a key material in mortars. Hence, most of the curing conditions were established on the basis of the hydration requirements of the latter material. It is obvious that lime mortars cannot perform as well under these conditions. The loss of centuries of experience with this material resulted from a combination of their poor performance in laboratory tests with the ease of application as well as increased construction speed possible with cement mortars⁷.”

Standards around the world vary and these authors state further, "the aim of this study was to emphasize large differences in performance of the same mortar mix prepared and cured under different conditions." Henriques and Charola correctly conclude their findings when they say at page 11,"it is significant that standards for mortars developed at the time Portland cement was introduced requiring standard tests to assure its quality control. These tests were then adapted, or not, to test lime mortars. Since the design of the testing procedures [21] mechanical testing at 28 days, it is obvious that lime mortars would fail under these conditions. The poor laboratory performance and the lengthier application procedures required by traditional mortars lead to a decline in their use. This resulted in the loss of the practical knowledge of their preparation in the field which only recently has been regained in part through lengthy studies and tests. It is important that the correct use of lime mortars for the preservation of historic structures be assured through testing procedures. These should be developed specifically taking into account the nature of the material in question so as to provide a meaningful evaluation. As has been pointed out, this means that adequate and comparable procedures should be used. As clearly

⁷ By “cement Henriques and Charola mean Portland cement.

demonstrated by this study, current standard procedures are not comparable. Although the call for international standardization has been made repeatedly over the past [22],[23], [24] and more recently during the ICCROM International Colloquium of Methods of Evaluating Product for the Conservation of Porous Building Materials in Monuments, Rome 1995, and the Dahlem Workshop, Berlin 1996 [25], only the recent CEN effort promises progress. It is to be hoped that this will serve to inspire other nations world-wide to join the international standardization effort."

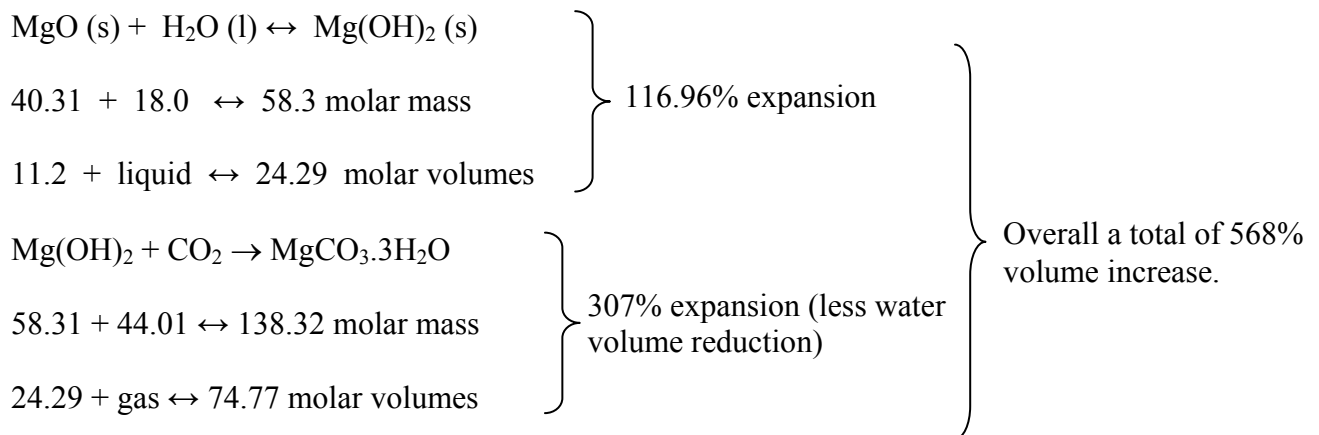
There is still a lot to be learned from the better historic carbonating mortars as the record shows. The advent of magnesium technology overcomes many problems and will only improve carbonating mortars because of the micro structural strength and improved bond added by the more acicular magnesium carbonates.

What the Standards Say about Aggregates and the Ability of Lime Mortars to Breathe

Henriques and Charola also show some insight into the need for carbonating mortars being able to breathe when they say at page 9 "lime mortars require carbon dioxide for the carbonation reaction. Although the presence of moisture will facilitate the carbonation reaction of the lime and crystallization of the resulting calcite crystals, too much moisture, as under the BS conditions, will slow down the reaction. This can be explained by considering that all the exposed surfaces of the lime mortar are covered with a layer of liquid water and that the CO₂ has to diffuse through it before it can reach the lime surface."

Although permeability tests by Fernando and Charola were variable, associated compression testing certainly indicated the long time periods required for strength development with lime mortars which is to some lesser extent is also the case for magnesium mortars. The strong attraction for water of Mg (once bound) however results in greater efficiency of the binder as much more is formed in situ. Consider the molar volume relationships.

When magnesia hydrates it expands:



In Figure 1, particle size distribution curves are shown for the sand of a successful permeable mortar sample compared with the BS 1200 recommendations and the recommendations of the earlier edition of the Australian Masonry Structures Code (AS 3700 -1991). The current Australian standard (AS 3700 - 2001) leaves out any specification of sand grading and the old

British BS 1200 Code grading recommendations tend to be used for the design of replacement and new work lime mortars as well as modern mortars. The standards are compared in Table 1- A Comparison of the American ASTM and British Standards.

Mortar sand grading

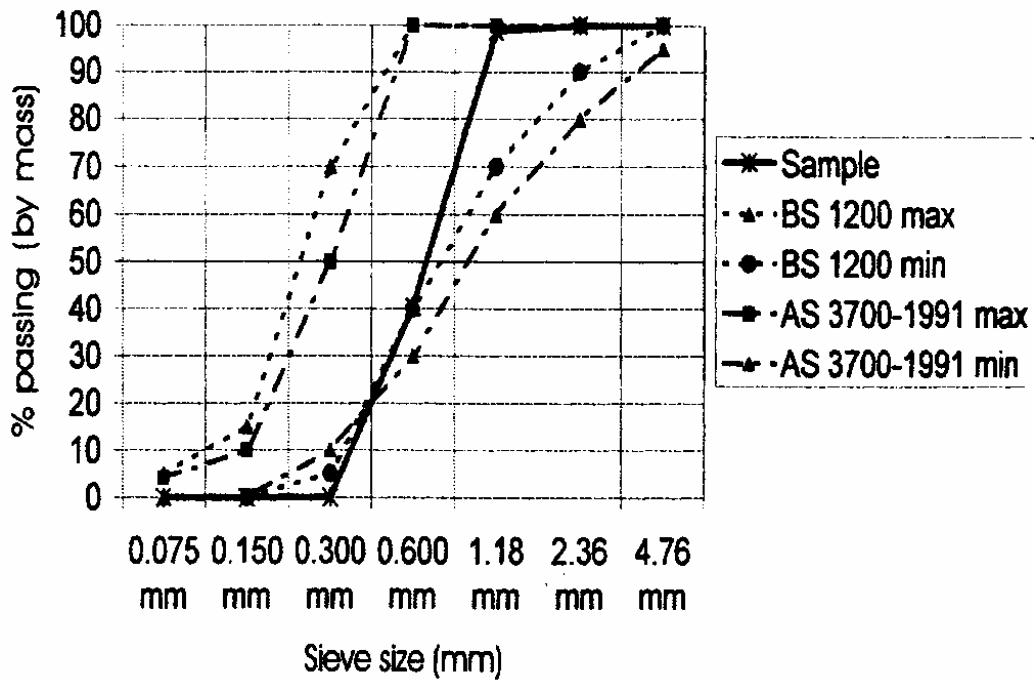


Figure 1 - Sand grading for permeable mortar compared to BS 1200 and AS 3700-991 recommendations [15] (Note that a mortar for successful carbonation barely falls within the ranges specified by the standards. A more suitable mortar would most likely fall without.)

BS EN 13139-2002 Aggregates for Mortar is the new European Standard effective 1 January 2004 and uses a completely different concept to the closely prescribed treatment of the British Standard. The British National Guidance Document is PD 6682-3:2003. A sand grading is not given in either. Sand is defined in terms of two sizes, d and D.

The ASTM American and old British standards are compared in Table 1.

Table 1- A Comparison of the American ASTM and British Standards.

| Graduation specified, percent passing ASTM C144 ⁸ | | | | BS EN 196-1 CEN Reference Sand (Not for mortars) ^{9,10} | | BS1200 (superseded 1 Jan 2004 by BS EN 13139-2002 – see below) | | |
|--|-----------------|--------------|-------------------|--|---------|--|--------|--------|
| Sieve ASTM size No. | Sieve ASTM (mm) | Natural sand | Manufactured sand | Sieve | CEN | Sieve | Type S | Type G |
| 4 | 4.75mm | 100 | 100 | 2.00mm | 0 | 5.00mm | 98-100 | 98-100 |
| 8 | 2.36mm | 95 to 100 | 95 to 100 | 1.60mm | 7+- 5% | 2.36mm | 90-100 | 90-100 |
| 16 | 1.18mm | 70 to 100 | 70 to 100 | 1.00mm | 33+- 5% | 1.18mm | 70-100 | 70-100 |
| 30 | 600 µm | 40 to 75 | 40 to 75 | .50 mm | 67+- 5% | .6mm | 40-100 | 40-100 |
| 50 | 300 µm | 10 to 35 | 20 to 40 | .16 mm | 87+- 5% | .3mm | 5-70 | 20-90 |
| 100 | 150 µm | 2 to 15 | 10 to 25 | .08 mm | 99+- 1% | .15mm | 0-15 | 0-25 |
| 200 | 75 µm | -- | 0 to 10 | -- | | .075mm | 0-5 | 0-10 |

⁸ Additional requirements of ASTM C144: Not more than 50% shall be retained between any two sieve sizes, nor more than 25% between No. 50 and No. 100 sieve sizes. Where an aggregate fails to meet the gradation limit specified, it may be used if the masonry mortar will comply with the property specification of ASTM C270 (Table 4).

⁹ The CEN reference sand according to the standard should be well rounded and rich in quartz

¹⁰ The BS EN 196-1 CEN 196-1 reference sand is not a sand necessarily recommended for mortars. It is a sand specified for compaction and strength. It has been included for the purpose of comparison only.

BS EN 13139-2002 Aggregates for Mortar is the new European Standard effective 1 January 2004 and uses a completely different concept to the closely prescribed treatment of the British Standard. The British National Guidance Document is PD 6682-3:2003. A sand grading is not given in either.

Sand is defined in terms of two sizes, d and D.

The requirements of the European Mortar Sand Standard are shown in Table 2 of the specification for nominal size 0 - 2mm.

Table 2: Masonry Mortar Sand

| Type | Oversize | | |
|------|----------|--------|-------|
| | 2D | 1.4D | D |
| 0/2 | 100 | 98-100 | 85-99 |

There also exists a requirement for a 1 mm nominal size and 4 mm nominal size but the 2mm covers the vast majority of current sources in use. Perhaps the 4mm nominal sand may be more suitable, particularly for carbonating mortars.

There is also a requirement to state a declared grading, with permissible deviations as shown below in Table 3 of the specification.

Table 3: Tolerances on Producer's Declared Typical Gradings for General Use

| Aggregates | | | |
|---|---|-------------------|-----|
| Sieve Size Mm | Maximum Tolerance in Percentage Passing By Mass ¹⁾ | | |
| | 0/4 | 0/2 | 0/1 |
| 2 | - | +5% ³⁾ | - |
| 1) Notwithstanding the tolerances listed above the aggregate shall confirm to the requirements of Table 1 and Table 2. 2) For special purposes the supplier and purchaser can agree reduced grading tolerances. 3) If the percentage passing D is > 99% by mass the supplier shall document and declare the typical grading including the sieves identified in Table 4. | | | |

The European concept of d, D and declared grading is more realistic and practical in light of the variability of known sands than the alternative historic prescribed treatment. However in terms of guidance it is a failure. Following the introduction of European standardisation, CEN Technical Committee 125 produced 2 mortar standards, pr EN998-1, Plastering and Rendering Mortars, and pr EN998-2, Masonry Mortars.

These new European standards differ fundamentally from the British Standards in that they are to some extent performance standards and define compressive strength minima and other performance characteristics rather than prescribed mix proportions. Performance standards are

better than prescription standards but leave a vacuum in an industry already lacking skilled artisans. There is an opportunity to get it right by developing new practice guides that properly consider carbonating and non carbonating mortars.

Another reason for developing practice guides is that regardless of the compliance system used it is still possible for sand to comply with the standard but remain deficient. For example it is possible for complying sands to be excessively single sized with concomitant tendency to bleed or segregate.

IMPROVING THE STATUS QUO

The Forces for Change

One has to consider why in the face of science and the historic record the standards allow the use of such inappropriate aggregates for carbonation and apply such unfair advantages in tests to hydraulic cements. Perhaps the answer lies in a misguided belief that the only answer is Portland cements and that the only sand sold should optimise hydraulic setting. It is time cement companies dropped the philosophy of “if its grey it’s great and all we make goes out the gate.” A small number are now making lime as well as Portland cement and at least one has become involved in the development of geopolymers. As “The only enduring business is the business of change”[26]. Perhaps the cement industry needs to understand that they are in the mineral composite business and that some minor diversification could actually be more profitable, particularly if there were opportunities for carbon credits through sequestration in the built environment. Adopting new technologies will result in new products and may mean new resources are defined many of which are wastes. New products create new market share.

To move forward, the industry needs to:

1. *Realise that the sands required for hydraulic binders are different to those required for carbonating binders*

People in the industry need to understand that the requirements are quite different. Specifiers need to specify the right aggregates for either hydraulic binders or carbonating. The right sorts of sands need to be commercially available and this may mean production from industrial wastes or rock.

2. *Fix the Standards*

Make them Relevant

Lime and eco-cements mortars are different to PC mortars and require different standards that take into account the slower strength development of carbonating mortars and different aggregates that are required. Standards in major countries around the globe do not take into account these differences.

Performance rather than Prescription

It is essential that there are standards to protect purchasers and owners however arguably the one size fits all prescription approach is not the way to go. Standards based on performance will do all that is required of them in terms of providing a measure of adequacy to protect the purchaser, user and public.

A change from prescription to formula based standards however leaves a vacuum of knowledge and practice in an industry already suffering from lack of training and skills of participants.

Non mandatory codes of practice are a possible solution. There are good economic reasons that a more efficient modus operandi in terms of producing the desired result will emerge as in the future the bulk of the work in walling will be done by companies as a total service for which staff are trained adequately to use the corporate product. Responsibility would lie with such contractor companies which would need to gain approval for their methods, possibly by an organisation similar to the British Board of Agreement. There would be less risk of failure all round as the legal responsibility would ensure proper training is provided for staff and approval would give confidence to the user builder. At the moment it is a case of everybody blaming everybody else when things go wrong!

For those few left outside this corporate responsibility umbrella there could be room for better descriptive language in the codes of practice.

MEETING THE SUSTAINABILITY CHALLENGE

There are new demands for sustainability being placed upon the industry. With the advent of Kyoto as a treaty there could even be money to be made from carbon credits if mortars containing lime or magnesia (as in eco-cements) were allowed to carbonate properly.

The new eco-cements are exciting as they are potentially far more sustainable. They contain relatively high proportions of MgO that will first hydrate and then carbonate. The production of magnesia can be achieved using an efficient low temperature process that can use waste heat or “free” solar energy. The capture of CO₂ during this process would result in sequestration on a massive scale.

The magnesia used is relatively fine and like lime, markedly improves rheology. MgO mortars also appear to also be more tolerant of some clays actually exhibiting more strength in their presence and this could be an advantage in terms of being able to utilise sands without the cost of washing and disposal problems associated with the clay fines fraction. For mud brick manufacture using soils rather than sands it is a definite advantage. A case study on mud bricks using a high clay soil is on the TecEco web site¹¹.

Because Mg⁺⁺ is a small and highly charged ion it tends to cause polar water molecules to orientate in layers around it introducing a shear thinning property improving for example anti sag properties in mortars as would methyl cellulose. Nesquehonite is the main observable carbonate and forms star like acicular growths which adds to microstructural strength. Fibrous carbonate growth may also improve bonding with brick, tiles and various walling substrates.

CONCLUSION

That insufficient intelligent work has been done on the merits of various mortars and aggregates that are suitable for them is evident by the confusion and infiltration of art rather than science in the engineering literature. This sad state of affairs is at its worst in relation to suitable aggregates (sands).

The standards offer little real guidance and as they become more performance based they will not do so and the codes of practice and guides could certainly do with some improving. Sands specified for concrete tend to be used for mortars regardless of whether they are meant to set

¹¹ www.tececo.com

hydraulically, by carbonation or a mix of both. As the requirements of sand for carbonation are quite different to those for hydraulic setting, and because of the increasing popularity and need for carbonating mortars for restoration and sustainability reasons urgent work needs to be undertaken to distinguish sands based on the end use and get away from “one sock fit all” approach of standards and informational literature.

The requirements for totally hydraulic limes and all PC mortars is to minimise the amount of water for hydraulic strength and maximise compaction and for this purpose aggregates that require grading and relatively fine rounded sands to minimise voids are required. For carbonating mortars on the other hand the mortars must “breathe” requiring a coarse fraction to cause physical air voids and some vapour permeability.

Because of the differing requirements of aggregates (sand) it may be better not to mix hydraulic and carbonating mortars. Unfortunately however carbonating lime mortars do not set quickly enough and so PC is added wherein there is a need to compromise. Air entraining agents and plasticisers partially solve the problem but care needs to be exercised in their use as there is a tendency to overdose with air entraining agents in particular as they give workability, but detrimentally form under brick bubble layers and weaken bond. Surely a purely mineralogical and physical approach would be better.

The new TecEco eco-cement magnesian mortars hold the promise of overcoming the problems associated with using only carbonating lime mortars such as rate of strength development, lack of plasticity with coarse sands and bond strength.

Global population is expanding as rapidly as ever, there is a need to build millions of new homes over the coming years; however environmental issues are becoming more important. The introduction of a carbon tax, or legislation setting targets for recycling of buildings could reduce the demand for Portland cement and the new TecEco eco-cements and lime mortars will become more popular.

Current practice is to add lime to mortars for plasticity and no other reason. Given the urgency of doing something about global warming it is about time the industry optimized the benefits of using carbonating and blended carbonating mortars. The best results will be obtained by combining some of the techniques of the past (carbonating mortars and mortars and walls that breathe) with those of the present (vents, vapor barriers, double skin walls and damp courses). More research needs to be done in this area, more work is required to develop the relevant codes of practice, and most importantly, considerable effort will need to be taken to disseminate the findings to people in the industry.

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Table 4 – Properties of Different Types of Mortar

| | PC Mortar | Tec-Cement Mortar | Hydraulic Lime Mortar | PC lime Mortar | Eco-Cement Mortar | Carbonating Lime Mortar |
|---------------------|---|---|--|--|---|--|
| Rheology | Poor | Good to Excellent | Excellent | Good to Excellent | Excellent | Excellent |
| Aggregates Required | Fine to minimize voids. | Fine to coarse as segregation not a problem. Coarser aggregates will allow non hydraulic lime component to carbonate. | Fine to coarse as segregation not a problem. Coarser aggregates will allow non hydraulic lime component to carbonate. | Aggregates used are too fine to allow carbonation. If coarser possibility of segregation. | Coarser aggregates essential to allow brucite to carbonate. | Coarser aggregates essential to allow lime to carbonate. |
| Main Advantages | Quick to set | Acid resistance, durability, excellent rheology, good bond. | Excellent rheology, good bond, tend to more readily self heal, mortar can be cleaned off walling units, breathe for healthier buildings. | Excellent rheology good bond. | Excellent rheology, acid resistance, excellent bond, faster setting, self heal, lower pH, mortar can be cleaned off walling units, breathe for healthier buildings. | Excellent rheology, good bond, self heal, lower pH, mortar can easily be cleaned off walling units, breathe for healthier buildings. |
| Disadvantages | Crack easily, poor rheology. | Currently more expensive. | Variability. | Do not carbonate, can have segregation problems if aggregates coarser to allow carbonation | Currently more expensive. | Slow setting |
| Setting conditions | Hydraulic | Hydraulic | Hydraulic and carbonating | Hydraulic and carbonating | Hydraulic and carbonating | Carbonating |
| Setting requiring | Moist | Moist | Moist and air access | Moist and air access | Moist and air access | Moist and air access |
| Standards | Most based on 28 day strength and hence pass. | Wrong or unfair | Unfair | Unfair, but most still pass | Unfair, will probably pass with coarser aggregates. | Unfair |
| Codes of Practice | Many | None | Many but wrong | Many but wrong | None | Insufficient, wrong |
| Opportunities | | | | | Carbon credits | Carbon credits |