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Mortars for repair of traditional masonry

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Repair mortars are needed for replacing mortar in damaged or severely weathered masonry mortar joints (repointing), for reconstruction of deteriorated masonry, and for renewal of rendering. The main components in a mortar mix are sand, binder and water. Additional materials may be added to modify the properties or appearance of the mortar. The intention of this article is to raise awareness of issues involved in the choice of mortars for the repair of mortar joints in traditional masonry (usually with thicker walls and weaker mortars than modern construction) by providing a brief overview of mortar binders, performance requirements, and mortar mix types. Work is ongoing to assess performance requirements and how to achieve them.

Binder materials

Lime (non-hydraulic)

Lime was the most common binder in mortar until late in the 19th century. It is still used, together with Portland cement, in binders for mortars in modern masonry. It is also regaining its role as a major or only binder component in mortars for the repair of traditional masonry. Lime is derived from the Latin limus (mud) and linere (to smear). The material itself is obtained from limestone, a sedimentary rock composed mainly of calcium carbonate. Limestones are defined by their magnesium carbonate content: dolomitic limestone with 35-46% magnesium carbonate, magnesium limestone with 5-35% magnesium carbonate and high calcium limestone with less than 5% magnesium carbonate. Other sources for lime are chalk, coral rocks and shells. When high calcium limestone is heated to 900°C, carbon dioxide is driven off leaving quicklime, a reactive alkaline material to be handled with care [$CaCO_3$ -> $CaO + CO_2$]. Water added to the quicklime causes a strong exothermic reaction to produce calcium hydroxide, or slaked lime, for use in mortar [$CaO + H_20$ -> $Ca(OH)_2$]. In Canada & USA, the slaked lime used in mortar today is often obtained from dolomitic limestone (dolomite). When dolomite is heated the following reaction occurs: $CaCO_3 + MgCO_3$ -> $CaO + MgO + 2CO_2$. The carbon dioxide is driven off from the magnesium carbonate at 725°C. Further heating is needed for the calcium carbonate, but this added heat causes the magnesium oxide to become less reactive to water. When water is subsequently added, the calcium oxide converts easily to calcium hydroxide at atmospheric pressure, but generally less than 25% of the magnesium oxide converts (Boynton 1980; Oates 1998). In modern manufacture, an autoclave is used to ensure conversion to magnesium hydroxide.

Slaked lime for mortar is available as a dry powder (hydrated lime) or a wet paste (lime putty). Hydrated lime is sold under four designations (ASTM C207): N (normal), S (special), NA and SA. The latter two have an integral air-entraining agent. Type S lime putty is also available. Type S or SA is recommended because it confers higher plasticity and water retention to the mortar, and has a limit on unhydrated components (unhydrated components may hydrate at a later stage causing expansion and damage to the mortar). Type N hydrated lime from a particular manufacturer should only be used if shown by test or performance not to be detrimental to the soundness of the mortar (no limit is placed on its unhydrated components). Lime in mortar gains strength slowly by recombining with carbon dioxide in the air to revert back to calcium carbonate, a process called carbonation [$CO_2 + H_2O$ -> H_2CO_3; $H_2CO_3 + Ca(OH)_2$ -> $CaCO_3 + 2H_2O$]. The rate depends on environmental conditions and the permeability of the mortar and the masonry units (the depth of carbonation is generally proportional to the square root of time). Lime therefore needs access to both air and moisture. The slow carbonation rate means free lime is available for an extended period and may be a benefit in healing of small cracks that may develop in the mortar. Carbonation of lime at these cracks can help seal them. On the other hand it may also allow uncarbonated lime to leach out of the mortar if excessive water leakage occurs through the masonry.

Hydraulic lime

Lime mortars can be given hydraulic properties by adding pozzolanic materials containing reactive silicates and aluminates. Pozzolans possess little or no cementitious value but in finely divided form in the presence of moisture react with slaked lime forming compounds with cementitious properties without the need for carbon dioxide. Romans made use of brick dust and volcanic ash (the term pozzolan is derived from the Italian town Pozzuoli near Vesuvius). Many limes used in the past naturally had slightly hydraulic properties because they were made from limestone containing clay with reactive silicates and/or aluminates. In the late 1700s it was recognized that limestones containing clay minerals fired at higher temperatures (up to 1250°C) could produce limes with hydraulic properties. They are known as hydraulic limes. Hydraulic limes were traditionally classified as feebly, moderately or eminently hydraulic which refers to the degree by which they gain strength by reacting with water. A new European standard for building limes (British Standards Institution 2001), classifies hydraulic limes into three different strength ranges (it also makes a distinction between natural hydraulic limes and hydraulic limes with added ingredients). ASTM also has a standard for hydraulic lime but it needs to be updated (C141). Hydraulic limes still contain a high proportion of (non-hydraulic) lime, which gains strength by carbonation. The strength gain by hydraulic reaction is much slower than for Portland cement; after a year the mortar strength could be three times the 28-day strength. Testing for compressive strength at 28-days is therefore not appropriate for non-hydraulic and hydraulic lime mortars (Portland cement-lime mortars also continue to increase in strength but the proportionate increase is much less).

Natural and Portland cements

Further increases in clay content of the limestone and higher firing temperatures resulted in natural cements which were common in the latter part of the 19th century. The higher temperatures led to sintering and partial fusing of materials which had to be ground after firing. These cements set more quickly and gained strength at a more rapid rate (mainly the result of a more reactive component produced by the higher firing temperature). Natural cements could be quite variable in their properties because limestone varied at different quarries or within the same quarry. Natural cements were displaced by Portland cement made from a blend of clay materials and limestone fired at a temperature of around 1450°C (patented in Britain in 1824; manufactured in USA and Canada from the 1870s onwards). Standards were later developed to ensure cements from different suppliers would have similar properties. The blending of raw materials is continually adjusted to ensure a uniform product. A small amount of gypsum is added to the cement to lengthen the time to initial set. Portland cement and other modern cements gain nearly all their strength by reaction with water. They gain strength at a faster rate which meant construction could proceed faster. Portland cement comes in a variety of types: e.g. normal (types I, II, ASTM C150), white and sulphate resistant (type V). Portland cement as the only binder component produces a very strong mortar with poor workability. Lime was therefore added as part of the binder to improve workability (ensuring better contact between the mortar and masonry units) and water retention. The higher the proportion of lime in the binder, the better the workability and the lower the compressive strength. The 1930's and the 1980's saw the introduction of masonry cement (ASTM C91) and mortar cement (ASTM C1329) respectively. They are specially blended binders containing Portland cement and proprietary ingredients such as ground limestone, set retarders, and air-entraining agents. They are often used in modern masonry mortars instead of Portland cement and lime.

Mortar selection

Repair mortars should be durable, practical in application, and not have a negative effect on the durability of the existing masonry (mortar should be considered 'sacrificial'; it is easier to repair mortar joints than replace masonry units). Durability is not only dependent on the mortar mix but also on how it is installed and cured, on the compatibility between the masonry unit and the mortar, and on the severity of the environmental exposure, which in turn depends on weather, design details, construction practice, operation, and maintenance.

Challenges to mortar selection for traditional masonry include:

- Original mortar materials are no longer available.
- Difficult to determine the exact composition and properties of the existing mortar.
- Issues of historic authenticity. How close should the repair mortar correspond to the original? Should only traditional binders be used?
- Many of the materials and techniques for producing and applying traditional mortars were lost and substitutes may have to be found and techniques learned again. New publications with guidance are beginning to appear.
- Traditional mortars, usually of much lower strength than modern mortars, are less forgiving of poor construction practices. Construction and curing procedures are therefore more important, together with good quality control.
- Appropriate laboratory and site test procedures are needed for the evaluation of repair mortars.
- There is little published information on the performance of low strength mortars in areas subject to significant freeze-thaw cycles (most of Canada). Blockley (2001) also addressed the lack of performance data: “why is construction one of the few industries where in-service measurement is seen as a weakness and not a strength? …we are not as good at learning from projects and from the way our structures behave in use as we should be”.

The following gives a list of typical performance requirements. The requirements must be considered as a whole - improvements in one area may reduce performance in another.

- Mortar should be *no stronger than needed* for the structural and durability requirements of the masonry. The long-term compressive strength should be lower than that of the existing masonry units and similar or lower in strength than the existing bedding mortar. Strength specifications should therefore have an upper limit as well as a lower limit. There is a tendency to over specify the strength in the belief stronger is better. Unfortunately although the mortar itself may become more durable it can have a negative effect on the performance of the masonry as a whole. The masonry becomes more rigid and less able to accommodate movement. If any movement takes place cracks may occur through the masonry units as opposed to cracking along the mortar joints. Lower strength mortars will also be easier to remove in future repair and maintenance.

- Water absorption and vapour transmission rates should be similar to or greater than those of the existing mortar and masonry units. Vapour permeability in mortars reduces as the hydraulicity of the binder increases (pure lime mortars are the most permeable and pure cement mortars the most impermeable). A more permeable mortar will encourage drying through the mortar; any salts in the masonry will then tend to migrate out through the mortar instead of the masonry units. Figure 1 shows what can happen when a dense Portland cement pointing mortar retards drying in a wall with a lower strength bedding mortar. The pointing mortar has been pushed out by frost damage to the water saturated mortar behind it. The pointing mortar itself was not damaged. It also highlights the need to pay attention to water shedding details (this was a free-standing wall without an overhanging coping).

Figure 1 Frost damage in a wall with a dense repointing mortar

- Mortar should have little shrinkage. Well graded, washed sand, with no clay fines, will reduce shrinkage, as will low water-to-binder ratios, and curing procedures that reduce initial surface evaporation. Good compaction of pointing mortars into the mortar joint is important. Shrinkage also increases with higher cement contents. Shrinkage away from the masonry units can produce fine cracks allowing water ingress.
- Full contact between repair mortar and masonry units (and existing bedding mortar if pointing) should be strived for (not necessarily strong bond). This reduces water infiltration at the interface between the mortar and the masonry units (significant leakage through masonry walls nearly always occurs along the interface or through gaps left in the mortar not through the mortar itself).
- Resistance to frost action where needed. Great care must be taken in selecting mortars for areas of severe climate exposure such as chimneys, parapets, freestanding walls, exterior steps and pavement, and masonry below or at ground level. Selection should be based on experience and/or testing. Laboratory testing for the freeze-thaw resistance of small-scale masonry unit/mortar specimens can provide useful *comparative* results on mortar performance. Generally speaking the stronger the mortar the more resistant it is. But the performance of low strength mortars can be improved by proper workmanship, appropriate sand grading and particle shape, and air entrainment. Water shedding design details can greatly reduce the risk of damage (Maurenbrecher, 1998).
- Resistance to salts where needed (e.g. sulphates or de-icing salts).
- Thermal and moisture expansion properties compatible with the existing masonry.
- Texture and colour of the mortar are important if they are to blend with an existing mortar, or if required for historic authenticity.
- Mortars should be practical in application to encourage good workmanship. Use contractors and masons experienced in the repair of older masonry. Lower strength mortars are less forgiving of poor construction practices than mortars used in modern masonry. A spiritual approach would help, for according to Longfellow (from his poem *The Builders*): ‘In the elder days of art, builders wrought with greatest care each minute and unseen part, for the Gods see everywhere.’

Mortar mixes

Today many restoration mortars have a cement/lime binder usually with a higher proportion of lime than cement. There is also increasing interest in the use of pure lime mortars, hydraulic lime mortars, and proprietary pre-mix mortars to which only water needs to be added. A few brief comments on mortar mixes are given next.

Lime mortars

Lime mortars usually consist of one part of lime to 2 to 3 parts of sand by volume. Lime in the form of putty is usually preferred for mortars as it normally gives the best workability (particularly for mortars with lower water contents such as pointing mortars). Lime putty can be ordered from the manufacturer, or made directly from quicklime or hydrated lime (ASTM C1489). Lime putty usually contains a significantly higher content of lime than the same volume of hydrated lime. This should be taken into account if the lime content in the mortar is based on volume proportions. Lime/sand mortars are more appropriate for repair of older masonry with an existing lime mortar, and where exposure to climate loads is low. Freeze-thaw action together with high moisture levels will damage the mortar. They should be placed well ahead of winter. Although, in principle, simple to use, only experienced practitioners should use lime mortars until more guidance and field experience is available. Mortar performance can vary from excellent to abysmal. Their use should be confined to walls above ground level, where only low compressive and flexural strength is needed, and environmental exposure is not severe. With thick walls they should not be used on the interior because they will take a long time to carbonate if at all.

Hydraulic lime mortars

Hydraulic lime mortars are making a comeback in the conservation of older masonry. They have not gained general acceptance for this use yet because of the lack of published test and performance data in USA & Canada. Research is ongoing to assess their suitability in Canadian conditions. A guide for their use has recently been published in Britain (Allen et al. 2003). The strength of mortars made with hydraulic limes is similar to those obtained with type N, O and K Portland cement/lime mortars, but hydraulic lime mortars gain strength at a much slower rate. In addition, the properties of similarly classified hydraulic limes from different manufacturers can vary significantly therefore it is important to determine the physical and mechanical properties for the particular hydraulic lime used. Mortar mix proportions are usually in the range 1:2-3 hydraulic lime:sand by volume.

Cement/lime mortars

Portland cement / lime mortars are the most common repair mixes. Common mixes are 1:1:6, 1:2:9, 1:3:12 Portland cement:hydrated lime (or putty):sand by volume (known as types N, O & K in ASTM and CSA mortar standards). Air entrainment is recommended for mortars exposed to significant wetting in freezing temperatures. Mortars using masonry and mortar cements, which incorporate an air-entraining agent, have also been used. Of the two, mortar cement is preferred because of its tighter limits on air content and a requirement for bond strength. Restoration practitioners have often preferred Portland cement/lime mortar mixes because of the need to know what the exact materials are in their mix. The ingredients in masonry and mortar cements are proprietary and may change with time. Furthermore with masonry cement there is a danger of too high an air content in the mortar and a resultant large drop in bond strength.

ASTM and CSA mortar standards (ASTM C270 & CSA A179) have two independent options for specifying Portland cement based mortars: use of volumetric proportions (usual option), or specified mortar properties (compressive strength, water retention and air content). If the proportion option is used, these standards assume sand is measured in a damp state. This tends to produce mortars which are much stronger than mortars based on the property specification (if the sand is measured damp, there is less sand in the mix because it occupies more volume than dry or wet sand). The mortar standards specify minimum strengths for mortar mixes designed according to the property specification. The values for site prepared mortars apply to bedding mortars not to pointing mortars. Pointing mortars have a much lower water content thus their strength will be significantly higher. To avoid excessive compressive strength, determine the strength beforehand for any chosen mortar mix.

Pre-mix mortars

Packaged pre-mix mortars are available to which only water needs to be added. Mixes based on Portland cement/lime, on hydraulic lime, and on proprietary ingredients are available. These mixes give the greatest control over mortar consistency on site. They are also more expensive. Manufacturers of premix mortars usually state the minimum compressive strength their mortars will achieve but the actual strength can be significantly higher. Information on the upper limit to strength should also be requested.

Further information

The selection of an appropriate mortar for the repair or conservation of older, traditional masonry is a lively subject of debate. Modern standards on mortar are aimed mainly at new masonry. Work is in progress to provide more guidance for traditional masonry. ASTM is developing a standard on restoration mortars, the Canadian Standards Association is evaluating the possibility of a similar standard, and RILEM has set up a committee to provide guidance on repair mortars for older masonry (RILEM: International Union of Laboratories and Experts in Construction Materials, Systems and Structures. Web site www.rilem.org).

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