REVIEW OF FACTORS AFFECTING THE DURABILITY OF REPOINTING MORTARS FOR OLDER MASONRY

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ABSTRACT

The selection of repointing mortars for older masonry in the Canadian climate is a subject of debate. Repointing mortars should be durable, practical in application (e.g. workmanship, quality control), and not have a negative effect on the durability of the existing masonry. Durability is not only dependent on the mortar mix used but also on how it is installed and cured (workmanship) and on the severity of the environmental exposure, which in turn depends on weather, design, construction, operation and maintenance.

This paper reviews literature dealing with the selection and performance of mortars used in the repair of older masonry. Particular emphasis is given to factors affecting the resistance to frost damage, a major consideration in a cold climate.

Key words: masonry, repointing, mortar, freeze-thaw, durability, heritage.

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INTRODUCTION

There is a need for clear performance objectives for pointing mortars so that an appropriate pointing mortar can be chosen for a particular building. Performance objectives then need to be translated into set criteria which in many cases are still a subject of debate and research. This paper reviews some of the issues particularly those affecting durability with an emphasis on resistance to freeze-thaw action, an important consideration in the Canadian climate.

What is repointing mortar?

Repointing mortars replace the outer deteriorated or damaged mortar in masonry joints. The deteriorated mortar needs to be carefully removed without damaging the masonry units, the resulting gap is cleaned, and then filled (repointed) with a compatible repair mortar to stop further deterioration and water penetration (Fig. 1). Pointing mortar mixes are drier and stiffer than bedding mortars to reduce shrinkage and avoid staining of the masonry. For the repair of older brick and stone masonry walls there is an increasing use of traditional mortar mixes, largely driven by the wish to have compatibility with the original mortar used and the existing bedding mortar (from historic, aesthetic and material property perspectives). Modern, higher strength mortars are often not appropriate and may cause damage. The selection of repointing mortars for older masonry in the Canadian climate is currently a lively subject of debate.

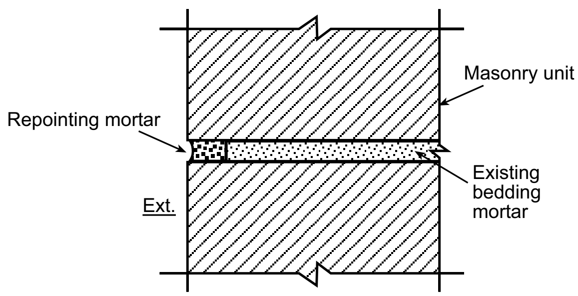

Figure 1. Example of a mortar joint with repointing mortar

Challenges to mortar selection include:

- Original mortar materials are no longer available.
- Difficult to determine the exact composition and properties of the existing mortar.
- Issues of historic authenticity.
- Lack of trades specializing in old materials and techniques. 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.
- Little published information on the performance of traditional mortars in the Canadian climate.
- Traditional mortars, usually weaker than modern mortars, are less forgiving of poor construction practices; good quality control and site supervision are needed to ensure success.
- Hard to correlate laboratory tests to actual field exposure conditions.
- Few standards on use and testing of traditional mortar mixes. Modern standards have

often deleted reference to older mortars but this trend is beginning to reverse.

Mortars are basically composed of a binder, aggregate (sand), water, and additives. Traditional mortars usually have lime as the major component of the binder. Today many restoration mortars have a cement/lime binder usually with more 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. In contrast, binders for modern mortars have cement as the major component with either lime added in equal or less proportion, or with proprietary additives (eg masonry cement).

<u>Possible forms of failure</u>

Potential problems with mortar include spalling, crumbling, efflorescence, biological growth and cracking (within the mortar and at the mortar/unit interface). These in turn are caused by frost action (Fig. 2), salt crystallisation (sulphates & chlorides), movement (settlement, differential, thermal and moisture movement), dissolution, environmental pollution (acid rain), water migration, and biological attack. Moisture is the environmental factor commonly associated with most of these problems, although temperature also has a significant influence on the rate and extent of damage caused by the moisture. Temperature and moisture also directly affect expansion and contraction movements in the masonry. Mortar can also cause problems for the masonry units such as lime leaching out of the mortar and spalling with too strong a pointing mortar.

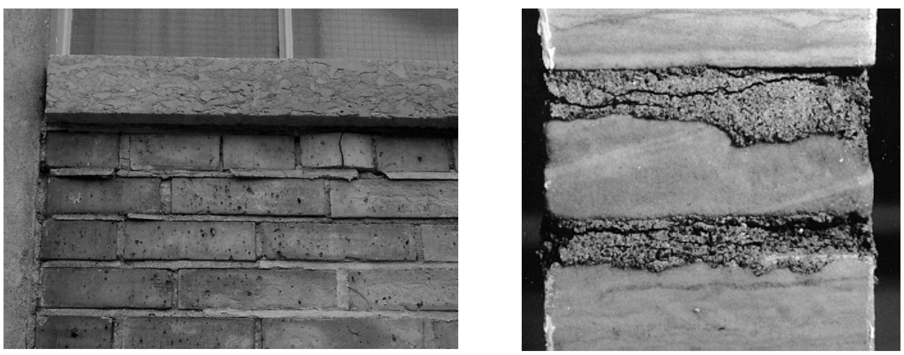

Figure 2. Frost damage

The figure on the left shows damage to brick and mortar below a window sill. The sill is not adequately shedding water away from the wall; this is aggravated by a large window area above this sill. The figure on the right shows damage to a 1:2:8 Portland cement: lime:sand mortar without air-entrainment during a uni-directional freeze-thaw test.

Traditional mortars with a high lime content have more initial flexibility and higher porosity than modern mortars and hence they can better accommodate minor movements in the wall without cracking. Cracks lead to increased ingress of water into the masonry which in turn affects durability. If cracks do occur, they are more likely to occur along the weaker mortar joints and not through the masonry units (this is preferable, simply because it is easier and cheaper to repoint mortar joints than to repair or replace damaged brick or stone). Fine cracks may reseal due to redeposition of lime within the crack.

DURABLE REPOINTING

Repointing mortars should be as durable as possible, without causing damage to the existing masonry (a dense mortar, for example, could retard the drying of the masonry assembly and cause frost or salt crystallisation damage in the bedding mortar or masonry units). It is preferable to repoint mortar joints at more frequent intervals than to have to repair damaged masonry units. A building and its components should be durable enough to perform the required functions in its service environment over the design service life without unforeseen cost for maintenance or repair (CSA 1995). The design service life for masonry is usually 50 to 100 years. A normal expectation for pointing mortar is at least 30 years, but preferably 50 to 100 years (Mack & Speweik 1998). If a weak mix is required in more exposed areas, weathering of the mortar and more frequent repointing should be accepted as part of the maintenance of the masonry (BBA 1999).

The durability of mortar not only depends on the materials used, but on how it is installed and cured (workmanship) and on the severity of the exposure, which in turn depends on the local climate, design, construction, operation and maintenance (Fig. 3).

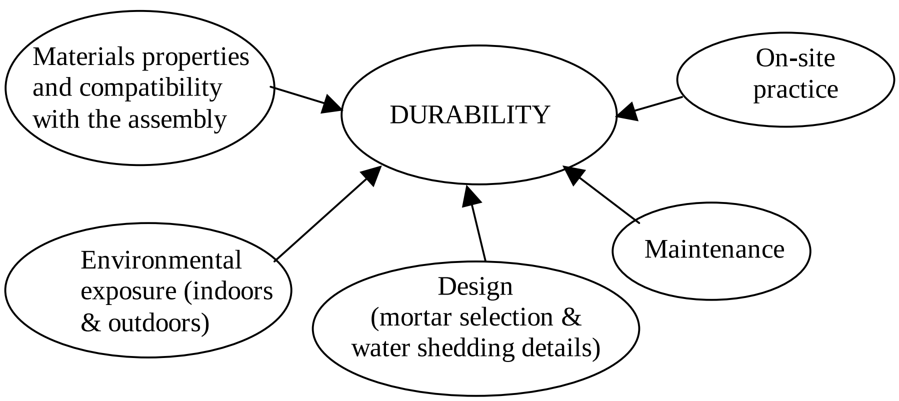

Figure 3. Factors affecting durability

<u>Environment</u>

Mortar selection must take into account the severity of the environment in which it will be used. The severity of the environment depends both on the local weather and the exposure of the masonry elements. For example, relatively weak mortars can survive well in freezing climates provided they are protected from excessive moisture (mortar in a wall protected by a roof overhang has less risk of damage than mortar in a chimney).

Canada has a large climatic diversity. Climates vary from hot summers to cold winters. In winter, some areas can be cold and relatively dry, while others have large amounts of precipitation. Regions with more precipitation (snow & rain) and many freeze-thaw cycles are more severe for the masonry than regions that tend to stay cold or mild over the entire winter. Building orientation affects the local climate (e.g. prevailing driving rain & solar radiation). Not much can be done about the weather but the design of the building, especially building details, can have a large influence on the local environment experienced by the masonry. Attention to water shedding architectural features, including their maintenance, will reduce the risk of occurrence of high moisture levels needed for frost damage (Maurenbrecher 1998). Melt water from snow is a major cause of frost damage in freezing climates (snow melt during the day is absorbed by the masonry underneath which freezes at night; this cycle may be kept up for many days). Cracks, including hairline cracks at the mortar masonry unit interface, will also allow increased water ingress. This highlights the need for regular maintenance and attention to shrinkage and bonding properties of pointing mortars.

Moisture can also come from inside the building. For example, in cold weather, air exfiltration of indoor air of humidified buildings can lead to interstitial condensation in localized areas of the masonry assembly (based on the path and exit locations of the air). In addition to the risks associated with high moisture levels within the masonry, the subsequent outward drying of the moisture may carry efflorescence salts to the surface.

Materials

Sand. Sand is generally selected by what is locally available and what colour and texture are desired for the mortar, but sand cleanliness, grading and particle shape should also be considered for they can have an important influence on overall durability.

Sand grading: Sand is normally made up of particles with a range of sizes, the smaller sizes filling in spaces between the larger sizes. In well graded sands, the void space left over is assumed to be about one-third of the sand volume (the space varies depending on the sand particle shape and grading). Enough binder paste is then added to fill this void space and provide a film between the sand particles to give the fresh mortar plasticity. This explains the binder to aggregate ratio of 1:3 seen in most specifications. This ratio will vary depending on the grading and particle shape, and on the binder. Mortar with too little binder will have poor water retention and workability, while too much binder will lead to higher strengths, increased shrinkage and risk of cracks. The effect of sand grading on durability needs further investigation. Coarser sand gradings for pointing mortars in modern masonry improved frost resistance (Elsen et al, 1993). Grading also influences mortar shrinkage and the bond between mortar and masonry units.

Particle shape: Sands can come from natural deposits or are manufactured by crushing stone. In general, crushed sand is considered most angular (sharpest), while quarry sands vary from semi-angular to rounded. Historic Scotland (1995) recommends a sharp sand with a balanced range of particle shapes (coarse sand is also referred to as sharp). Although sharper sand makes the mix less workable, it provides more interlocking between particles reducing shrinkage. On the other hand, Mack & Speweik (1998) recommend rounded sand particles because it gives the mortar better plasticity, is easier to compact into the joint, and was often used in historic mortars. The easier compaction makes it more likely the joint is filled properly (good contact between the pointing mortar and the existing bedding mortar improves moisture transfer and durability). The need for less pressure to fill the joint is also preferable from the masons' point of view, reducing the risk of repetitive strain injury. Alternatively, vibrating pointing devices can be used which greatly improve compaction of less workable mortars (SBR-CUR 1998).

Damp versus dry sand: North American standards assume a binder to damp sand ratio of 2 ¼ to 3 (ASTM 2000 & CSA 1994). The sand is assumed to be damp because that is usually the condition of sand on building sites. On the other hand, in Europe similar ratios are used but based on dry sand (BRE 1991). Damp sand (2-6% moisture content) occupies more volume than dry sand. If a 25% increase in volume (bulking) is assumed, then the ASTM/CSA ratios in terms of dry sand become 1.8 to 2.4. A mix based on damp sand is therefore likely to be stronger and potentially have more shrinkage than a mix with the same proportions of ingredients using dry sand. The discrepancy needs to be resolved. It points to the need for performance specifications to assess appropriate ratios for mortar ingredients.

Other aggregates: Crushed limestone, crushed low-fired brick and expanded vermiculite materials are among other aggregates which are sometimes added to mortar (Historic Scotland 1995).

Binders. The most common binders in mortar are lime and Portland cement. Lime is obtained from limestone ($CaCO_3$) when it is burned at 900°C to drive off the carbon dioxide (CO_2) resulting in quicklime CaO (lime is also obtained from magnesium and dolomitic limestone; dolomitic contains 35 to 46% $MgCO_3$; common in North America). Water is added to the quicklime to produce lime putty or, in modern production, a dry hydrated lime powder, $Ca(OH)_2$. Lime in a mortar mix hardens by carbonation; the lime recombines with CO_2 in the air and reverts back to limestone (to harden, lime mortars need access to both air and moisture). Lime mortars take much longer to gain strength than Portland cement based mortars. Pozzolanic additives can be added to the mortar which react directly with lime and water allowing part of the lime to harden faster without the need for carbon dioxide from the air (hydraulic property). In the late 1700s it was discovered that burning limestone with clay impurities resulted in limes which could also gain some of their strength by reacting directly with water (hydraulic limes). This also required increased firing temperatures (up to 1250°C). Hydraulic limes range from weakly hydraulic to eminently hydraulic (they are still made in Europe and by one manufacturer in the USA). Further increases in clay content and firing temperatures resulted first in natural cements and finally Portland cement (named after its resemblance to Portland limestone). Portland cements require a firing temperature of around 1450°C. They gain nearly all their strength by reaction with water. Mortars using these cements are stronger, and gain their strength more rapidly which also meant construction could proceed faster. As binders become more hydraulic, mortars made using them become denser and less porous. They are therefore better at keeping water out, but should water get into the masonry it will also take much longer to dry out. Portland cements come in a variety of types (normal, white and sulphate resistant Portland cements, and Portland cement based masonry cements have been used in pointing mortars in Canada).

Lime proportion: Hydrated lime powder from different manufacturers can have different bulk densities (largely due to particle size). Thus in volume batching different weights of lime result. The finer the lime, the less weight for a given volume. Will the lower weight of the finer lime still provide the same workability to the mix because of the increased fineness? On the other hand, will the long-term strength of the mortar be less because of the lower weight of lime? In the case of lime putty, it usually contains more lime than an equivalent volume of dry hydrated lime. Lime putties made from hydrated limes from different manufacturers were found to have 16 to 56% more lime than the equivalent volume of dry hydrated lime (Phillips 1994, Maurenbrecher et al 2000). If no attention is paid to these aspects, the quantity of lime in a mortar can vary leading to mortars with differring properties. The significance of this needs to be resolved.

Admixtures. Ingredients may also be added to the mortar to change its colour, or improve workability, water retentivity, water repellancy, bond with masonry units, and frost resistance. Additives are usually discouraged in restoration mortars except for pigments for colour and air entraining agents in frost susceptible areas. Air entraining agents can enhance frost durability (hydrated lime can be obtained with an integral air entraining agent; masonry & mortar cement and most pre-mix mortars have it added too). These agents do not work well in very dry pointing mortar mixes. Excessive air-entrainment reduces the bond to the masonry unit (normal recommended range is 10-15% air).

Pre-mixed mortars. Use of pre-mixed mortar ingredients to which only water needs to be added gives the greatest control over mortar consistency on site. Such mixes are more expensive. The exact components are often proprietary.

On-site Practice

On-site practice includes mortar joint preparation, and mortar mixing, pointing and curing (BRE 1999; Mack & Speweik 1998; Historic Scotland 1995). All have an important influence on the long-term performance of the mortar. Supervision and quality control will help ensure the performance standards are reached.

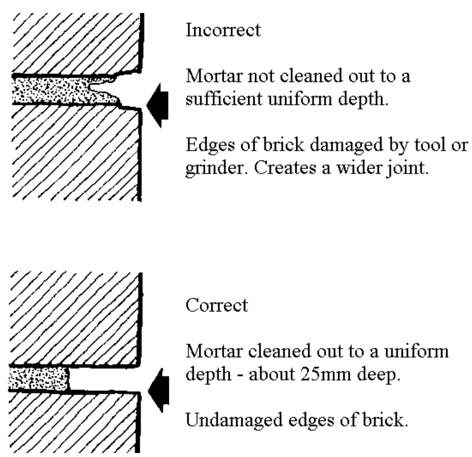

Figure 4. Raking out mortar joints in brickwork (Mack & Speweik, 1998)

Joint preparation. Raking out and cleaning of the joints must be carefully done to ensure no damage to the masonry units, and ensure a clear rectangular space for the repointing mortar (Fig 4). Then there is more likely to be a good contact between the pointing mortar and the masonry unit and the existing bedding mortar. Poor contact inhibits moisture transfer. Before pointing, the joint is usually pre-wetted to limit its water absorption rate. How best to do this is still a subject of debate. At the time of pointing, water is absorbed from the mortar by the masonry unit (depending on type of unit, amount of pre-wetting and the water retention capacity of the mortar). This can affect the bond of the mortar to the masonry units. A study on modern bricks and pointing mortars found the water remaining in the mortar affected the frost durability: too much water in the mortar decreased frost resistance, too little water affected hydration and reduced strength (Elsen et al, 1993).

Mortar mixing. Batching (measuring) of mortar ingredients by weight gives better consistency than batching by volume, but batching by volume is still the most common procedure. Volume batching introduces larger variations in quantities because the level of compaction in measuring containers varies with the individual doing it. In addition, the volume of sand can vary with moisture content. Pre-mix mortars avoid most of the batching problems.

When lime is used in the mix, it can be added in the form of hydrated lime powder, lime putty, or 'coarse stuff' (lime, sand and water mixed ahead of time). The latter two give the best workability because the lime particles are fully wetted beforehand. The difference in lime content in dry lime and putty lime mentioned earlier must also be taken into account.

Mortar may be mixed by hand (only suitable for small amounts), in a standard paddle mortar mixer, or a mortar mill. The mortar mill is often used for high lime mortar mixes. Mixing time must be controlled especially for mortars containing air entraining agents (to avoid excessive air content). After mixing, the mortar is often allowed to stand for a while before use. Pure lime mortars can be kept for months before use provided they are kept damp and air is excluded (Historic Scotland 1995). Mortars with hydraulic binders have to be used within a certain period. Mortars with Portland cement need to be used within 2 to 3 hours of mixing. The mortar may also be allowed to stand for a period after mixing to allow pre-hydration (and thereby reduce shrinkage and improve workability). ASTM C270 recommends 1½ to 2 hours after mixing with sufficient water to produce a damp mix. After that period, further water is added until the right consistency is obtained. Another document does not mention this waiting period (BRE 1999). The cement content and type of lime may also affect the need for a waiting period.

Mortar application. Good compaction of the pointing mortar in the joint is important to good performance. For deeper joints it is usually done in more than one layer. The final finish of the mortar joint surface affects its water shedding capabilities. The surface should not extend out over the surface of the masonry units (thin sections of mortar extending onto the face of the unit easily crack and collect water). Standard finishes range from a concave finish (best compaction and weathertighness) to a raked joint (worst) (BRE 1999). For historic masonry, many other finishes have also been used.

Curing conditions. Curing conditions for freshly pointed joints have led to much debate especially when there is the risk of frost. (Historic Scotland 1995, Mack & Speweik 1998, BBA 1999, BRE 1999).

Rapid drying out of the mortar should be avoided. It can bring lime to the surface and increase the risk of shrinkage cracks; as well, it may not leave enough moisture for curing of hydraulic components in the mortar (Historic Scotland 1995). Common recommendations include a damp cure of two to four days (longer for pure lime mortars), or protection for seven days (Mack & Speweik 1998; BRE 1999). Actual times will depend on environmental conditions. Damp curing may be achieved by wet burlap covered in plastic. Regular misting is an alternative. Water should not run off the joints while doing this, otherwise staining may result from lime leaching out of the mortar. New repointing should therefore be protected from rain.

Where there is a risk of frost, protection for a minimum of seven days from freezing is recommended for weaker mortars (BRE 1999); air entrainment will provide added protection. The effect of only seven days initial protection on frost durability and long-term strength gain needs further investigation. Pointing should preferably be done well ahead of winter.

High lime mortars will slowly gain strength as the lime within the mortar carbonates. The outside surface of the joint carbonates within a few days, but within the joint, the process is much slower taking a year or more depending on the porosity of the mortar and masonry unit, the depth of the pointing mortar and the environmental conditions. Favourable conditions for carbonation are relative humidities in the range 60 to 75% or repeated wetting and drying. Full carbonation is likely to improve durability including resistance to sulphate attack (Harrison 1990) and frost resistance.

Design

The designer needs to take into account all the factors affecting durability. Performance requirements provide a good base for assessing appropriate repointing mortars. From these, specific criteria can be developed. There is no miracle mortar mix suitable for all masonry; the mortar mix should be adapted to the particular masonry assembly under consideration (e.g. in terms of the existing mortar and masonry units, and environmental exposure). Typical mixes are given by Mack & Speweik (1998), BRE (1999), Historic Scotland (1995), BA (1999). There is little recent documented data on the use of pure lime and hydraulic lime mortars in Canada, so they must be used with caution until more experience is gained with their use. When selecting a mortar mix, the following performance requirements should be taken into consideration.

- Compressive strength lower than that of the existing masonry units, and similar to or lower than the existing bedding mortar (if the pointing mortar is too strong, stress concentrations could cause spalling of the masonry units). In future repairs and restoration, weaker mortars are also easier to remove without damaging the masonry units. Weaker mortars have less stiffness and greater creep allowing accommodation of larger movements without cracking. Recommendations for maximum strength have ranged from 8 MPa (for Nepean sandstone; Suter et al 1998) to 10 MPa (Knöfel et al 1993). This still leaves questions on assessment of strength. Mortar cube strength can be quite different from the strength of the mortar in the joint. In addition, strength varies with age, the high lime mortars gaining strength gradually.
- Water absorption and vapour transmission rates similar to or greater than those of the bedding mortar and masonry units. The pointing mortar should facilitate the drying of the masonry assembly through the mortar joints. This is especially important in masonry with dense masonry units. A more porous mortar will also encourage any salts in the masonry to migrate out through the mortar instead of the masonry units (salts can cause crumbling, spalling or efflorescence).
- Little if any shrinkage after pointing. Well graded, washed sand, with no clay fines, will reduce shrinkage, as will low water-to-binder ratios, and proper curing. Sand

particle shape may also have an effect (see section on materials). Knöfel et al (1993) recommend a maximum of 1 mm/m.

- Good (not necessarily strong) bond with full contact between mortar and masonry units and existing bedding mortar. Good bond and low shrinkage reduce the risk of fine cracks forming at the interface between the masonry units and mortar. Most water infiltration through a masonry assembly occurs at this interface and at poorly filled joints. Examples of minimum recommended flexural bond strengths are 0.2 MPa (Knöfel et al 1993) and 0.3 MPa (with Nepean sandstone; Suter et al 1998).
- Resistance to frost action where needed. High lime content mortars have less resistance to freeze-thaw action when they become saturated (they are most vulnerable early in their life because they take a longer time to harden). On the other hand, the more porous mortars tend to dry faster, thus reducing the risk of damage. An air-entraining agent added to the mortar will improve frost resistance. Great care must be taken in selecting mortars for areas of severe exposure such as chimneys, parapets, free-standing walls, exterior steps, and masonry below or at ground level (base selection on experience and/or testing). Exposure to de-icing salts will further reduce freeze-thaw resistance.
- Resistance to salts where needed (e.g. sulphates). If sulphates are present in existing masonry, they can react with binder components (eg uncarbonated lime & components of Portland cement) when the masonry is damp for extended periods of time (Harrison 1990; BRE 1991). Use of sulphate-resistant Portland cement reduces this risk.
- Thermal and moisture expansion properties compatible to existing masonry.
- Mortars should be practical in application to encourage good workmanship.
- Use contractors and masons experienced in the conservation of older masonry.

Maintenance

Good durability is not only a design and construction consideration. On-going maintenance has a large influence on performance as well. Regular visual inspections coupled with a maintenance guide would be ideal. Failure of water shedding elements, such a gutters and downspouts, can result in rapid deterioration especially in cold climates. Prompt repair of these elements along with the damaged mortar joints will greatly reduce the extent of further damage.

TESTING & STANDARDS

Performance requirements and durability can be assessed by documenting actual performance in buildings, and by tests in the laboratory and in the field.

Pre-construction testing

It is difficult to assess the exact composition of mortars used in the past; compounding this problem, there is also a lack of information on the properties of such mortars and their influence on performance in the Canadian climate. There is a need for standard tests so results from different laboratories and countries can be compared. A RILEM committee on the characterisation of old mortars with respect to their repair is addressing the issues of sampling, analysis of physical and chemical characteristics, damage types, testing and case studies. The committee also sponsored a workshop (RILEM, 2000).

Testing should take into account the performance of the mortar in combination with the masonry in which it will be used. Testing mortar using small masonry wallettes gives a better representation of actual practice. NRC/IRC, in association with the Heritage Conservation Program at Public Works and Government Services Canada, is investigating the durability of pointing mortars for stone masonry. Small masonry prisms are used to assess the freeze-thaw durability of pointing mortars (Fontaine et al, 1998; Maurenbrecher et al, 2000; Suter et al 1998; Thomson et al 1998). Improving the freeze-thaw test to more accurately reflect conditions in practice is also an objective (e.g. freezing from one side only, rate of freezing).

Quality control during construction

There is a need for simple and quick quality control tests on site. One example, which has worked well to assess the workability of a particular mix, is the cone penetration test (ASTM C270).

Performance in service

The performance of pointing mortars in actual buildings should be surveyed, monitored and documented in Canadian conditions.

Standards

The ASTM mortar standard has a short section on pointing mortar (ASTM 2000). The CSA mortar standard includes a reference to the ASTM standard (CSA 1994). More guidance is needed in both these standards on the repointing of older masonry.

CONCLUSION

This paper highlights some of the issues affecting the durability of repointing mortars. With an increase in popularity of repair and restoration of old masonry buildings, there is pressure to produce design and construction guidelines for practitioners to use for best results. Care is needed in determining which mortar mixes are best for a particular building. It is recommended to use experienced practitioners in the field who manage to negotiate the minefield of new products, on-site practices, and research documentation. This has led to a relatively young research field exploring the interrelation of these factors. There is a need for documented data on performance and testing of repointing mortars in relation to the Canadian climate and on-site practices. Without documentation and analysis, codes and standards cannot be improved to meet the current demands. This paper is a step towards documenting the current issues and, as can be seen, there are many gaps. The Institute for Research in Construction (IRC) at the National Research Council of Canada has made efforts to address these gaps through research and information exchange. A working group of architects, engineers, materials suppliers, material scientists, researchers, contractors and masons meets twice a year to discuss current challenges, and areas requiring further work. To support this effort, IRC has also developed a website that provides information on their current projects on masonry and selected bibliographies on relevant topics (www.nrc.ca/irc/bes/masonry).

REFERENCES

ASTM (2000). C270 Standard specification for mortar for unit masonry. American Society for Testing and Materials. USA.

BBA (1999). h/2 Blue Lias Hydraulic Lime Mortar. Detail Sheet 3. Agrément certificate 99/3581. British Board of Agrément. 5 p

BRE (1991). Building mortar. Digest 362. Building Research Establishment. UK. 8 p

BRE (1999). Repointing external brickwork walls. Good Repair Guide 24. Building Research Establishment. UK. 4 p

CSA (1995). S478 Guideline on durability in buildings. Canadian Standards Association. Rexdale, Ont.

CSA (1994). A179 Mortar and grout for unit masonry. Canadian Standards Association, Rexdale, Ont.

Elsen J., Lens N., Gérard R. (1993). Gélivité des mortiers de maçonnerie dans les façades en briques (Frost resistance of masonry mortars in brick façades). CSTC Magazine. Belgique. Automne. pp 3-11

Fontaine, L., Thomson M.L., Suter, G.T. (1998). In search of durable repair mortar for historic masonry in northern climates: a prologue. APT Bulletin, Vol 29, No 2. Association for Preservation Technology. pp 39-40

Harrison W.H., Bowler G.K. (1990). Aspects of mortar durability. Br. Ceram. Trans. J. 89, pp 93-101.

Historic Scotland (1995). Preparation and use of lime mortars. Technical Advice Note 1. Edinburgh. 60 p.

Knöfel D & Huesmann M (1993). Mörtel zur Fugeninstandsetzung an historischen Bauwerken (Mortar for pointing maintenance in historic structures). Bautenschutz + Bausanierung 16. pp 30-34.

Mack R C & Speweik J P (1998). Repointing mortar joints in historic masonry buildings. Preservation Brief 2. Heritage Preservation Services, National Park Service, US Dept of the Interior. 16 p.

Maurenbrecher, A.H.P. (1998). Water-shedding details improve masonry performance. Construction Technology Update 23, Institute for Research in Construction, National Research Council, Canada. 4 p.

Maurenbrecher, A.H.P., Suter, G.T., Trischuk, K., Fontaine, L. (2000). Contribution to pointing mortar durability. Historic Mortars: Characteristics and Tests. Editors P. Bartos, C. Groot and J.J. Hughes. RILEM Publications. pp 361-369

Phillips, M. (1994). A source of confusion about mortar formulas. APT Bulletin. Vol 25, No 3-4. Association for Preservation Technology. pp 50-53.

RILEM (2000). Historic Mortars: Characteristics and Tests. Editors P. Bartos, C. Groot and J.J. Hughes. RILEM Publications, France. 459 p.

SBR-CUR (1998). De kwaliteit van voegen in metselwerk (The quality of pointing in brickwork). Report SBR299/CUR 98-3. Stichting Bouwresearch, the Netherlands.

Suter, G.T., Thomson M.L., Fontaine, L. (1998). Mortar study of mechanical properties for the repointing of the Canadian Parliament buildings. APT Bulletin, Vol 29, No 2. Association for Preservation Technology. pp 51-58

Thomson M.L., Suter, G.T., Fontaine, L. (1998). Frost durability testing of stone masonry mortars: restoring the Canadian Parliament buildings. APT Bulletin, Vol 29, No 2. Association for Preservation Technology. pp 42-49