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Repair mortars for historic masonry; Effects of the binder choice on durability

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Factors affecting the design of repair mortars for historic masonry are: the type of masonry, the condition of the masonry and the exposure conditions. Especially in case of low-strength masonry exposed to heavy rain and high salt contents the design of a repair mortar may be a challenge. The most important problem is obtaining adequate insight into and feeling for the requirements, that play a role with regard to the mortar design. To this end the paper concentrates on materials behaviour of repair mortars in historic masonry. This is done in the context of the analysis of several types of attack on mortar durability: freeze-thaw cycling, salts, thermal movement, rain penetration. From this analysis relevant materials characteristics and technical requirements are derived. The main conclusions are

- **the binder choice may significantly affect the durability of repairs,**
- **a basic and determining condition is a good execution technique.**

Consequently, thorough insight into the characteristics and behaviour of the various available binders is then an important tool to the repair mortar designer. And, practical field experience with the possibilities and limitations of on-site execution practices may be very helpful to ensure good quality of the repair work.

1 Introduction

Repair of historic masonry takes place in the context of a set of requirements, which range from philosophical to purely technical assumptions (see figure 1). As suggested in figure 1, before starting on the building site many aspects have to be evaluated in conjunction with one another. The justification for this is

- Practice has proven that approximating the repair of historic masonry solely from as a technical point of view, will easily lead to interventions, where general aspects such as authenticity and the historical context are grossly neglected.
- In a different, already more technical way, overlooking conceptual requirements may as well lead to serious problems. Examples are damage occurring relatively quickly after repair caused by neglecting compatibility requirements and/or

inadequate repair measures; this may preclude or impede further treatment in the future.

- The functional requirements often provide indications of the technical conditions (structurally and environmentally) of building elements, as they describe the safety, the role or function of the element in the building and the materials of this element that will be restored.
- Ultimately, technical requirements deal with the most decisive technical characteristics for compatibility between new and old material and should be of help to design the composition of the repair mortar. The most important technical characteristics to be mentioned are: composition, strength, elasticity, porosity, thermal or moisture movement, surface features (Groot, Ashall, Hughes (eds) 2004).

In this paper the attention will be focussed on durability: a characteristic in which many technical aspects come together, while taking into account conceptual and functional requirements that have to be fulfilled to obtain durable repairs in historic masonry (the effects of general requirements such as values and authenticity on the restoration will in most cases be brought in by an architect) .

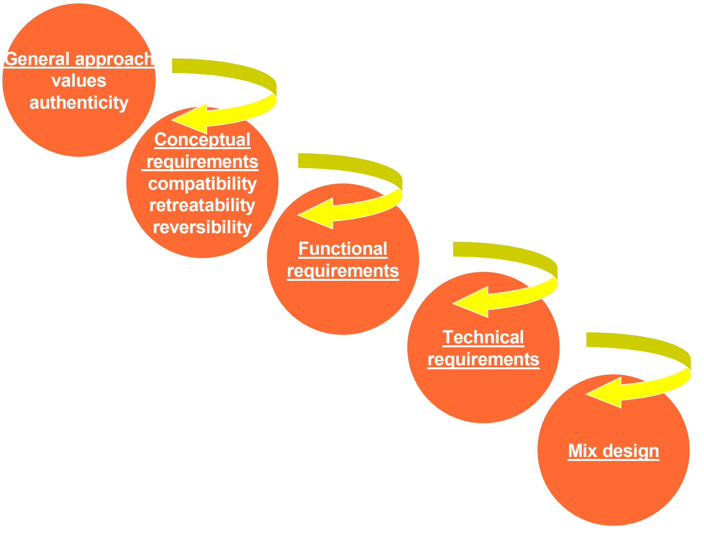


Figure 1. Set of requirements in which repair of historic masonry takes place (Van Balen et al. 2005)

The search for the technical requirements is carried out applying an analysis and evaluation of the most damaging effects on the durability of historic masonry. In the repair practice of historic masonry these are

- freeze-thaw cycles,
- salts,
- movement (thermal, moisture),
- rain penetration.

To enable the development of an adequate set of technical repair requirements the damaging effects on the durability should be related to the application and service life conditions of the repair material. For instance the attention should not only focus on materials characteristics as such, but as well onto what extent the material characteristics of a repair material are compatible with the adjacent materials (type of masonry and condition of the masonry). As well the influence of the exposure conditions (rain, frost, salts) should be taken into account in the analysis of the desired mortar requirements. Often the effects of on-site practices (workmanship), design (influence on exposure) and maintenance (e.g. clogged gutters) are largely underestimated. Elements of the technical context are collected in figure 2.

2 Binders in historic masonry

(For the definitions used in this section, see Groot, Ashall, Hughes (eds) 2004)
Binders used in mortars are materials with adhesive and cohesive properties, which make it capable of bonding mineral fragments into a coherent mass. Mainly, two type of binders are used in restoration mortars;

- air-hardening (non-hydraulic) binders, such as air lime,
- hydraulic binders, such as cements,

where the air-hardening binder slowly hardens in air by reacting with carbon dioxide and moisture in the air to form a carbonate, and the hydraulic binder sets and hardens by chemical interaction with water and is capable of doing so under water.
A binder which shows hydraulic as well as air-hardening properties is Natural Hydraulic Lime (NHL). It is obtained from limestone containing clay materials (e.g. silica and alumina), or a mixture of similar composition, and fired at temperatures up to 1250°C. Natural Hydraulic Lime contains a mix of air lime, hydrated silicates and aluminates. Hardening occurs through direct reaction with water and by carbonatation.

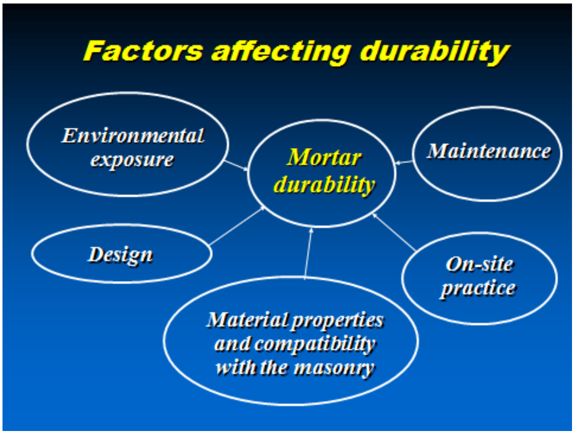


Figure 2. Factors influencing (repair) mortar durability (P. Maurenbrecher)

Before the invention of cements, in particular pozzolans were used, to obtain mortars with hydraulic properties. A pozzolan is defined as a siliceous or siliceous and aluminous material which in itself possesses little or no hydraulic property but will, in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing hydraulic properties. Pozzolans can be natural (e.g. trass) or artificial (e.g. fly ash).

It is clear from the differences in the way binders harden that the field of application of a binder will differ as well: for instance, it is appropriate to apply air-hardening mortars in walls and hydraulic mortars may adequately be used in hydraulic works, foundations etc.

3 Requirements related to freeze-thaw resistance

Freeze-thaw cycles are in colder parts of the world a major reason for damage in historic masonry (figure 3). Obviously, if a mortar does not contain moisture no freeze-thaw damage is to be expected. Damage only takes place if, as a result of the presence of moisture, a high crystallisation pressure (expansion) can develop, causing higher tensile stresses than the mortar tensile strength. In terms of materials properties this means that for a mortar the degree of saturation, the total pore volume, the pore size and distribution, freezing rate and the mortar tensile strength all contribute to freeze-thaw durability (Hall and Hoff 2002).

Figure 3. Frost damage of lime-based bedding mortar caused by a high degree of saturation (in West wall of Ruin De Nijenbeek, the Netherlands)

3.1 Materials choice: strength (development)

From the parameters mentioned above it can be concluded that a certain materials strength is needed to avoid frost damage; this is especially the case in situations of outdoor exposure where rain is directly followed by frost. A certain strength means for historic masonry: a relatively low strength; After all, in historic masonry brick and mortar strength usually are relatively low; consequently, the application of a repair material with a too high strength may cause compatibility problems (mechanically and hygrically) (figure 4). A way to avoid high strength levels in the repair materials is the application of traditional binders, such as air lime, lime-pozzolan, natural hydraulic lime. Apart from low strength these binders show as well a slow strength development: this is in particular the case for air lime. The reason is that sufficient strength is obtained as a result of the carbonatation reaction (formation of $CaCO_3$ from the reaction of $Ca(OH)_2$ with CO_2 from the air); the carbonatation penetrates slowly with time from the surface into the repair material. Measurements in a render (exterior plaster exposed to the weather) have shown penetration depths of 8 mm in 2 months (Waldum 2002) and 5 mm in 4 weeks (Ratcliffe and Orton 1998); obviously, the penetration rate will decrease with depth. From this it can be understood that application of air-lime mortars should be done well before the onset of winter. In early ("air lime") times the application season for lime mortars was between March and October.

Figure 4. Frost damage in an uncarbonated air lime mortar due to an application of the mortar too late in the season (Brussels, Belgium)

When uncarbonated, air lime is not only frost prone, but also highly soluble. However, as soon as the calcium hydroxide is carbonated the solubility of the formed compound ($CaCO_3$) is more than a hundred times lower (solubility of $Ca(OH)_2$ is ~0.185 g/100 ml; solubility of $CaCO_3$ is ~ 0.0015 g/100 ml). Hence, dissolution and leaching of air lime are real risks in the first months after application: heavy rains on exposed air lime mortars (e.g towers) may cause considerable damage during this period.

All in all, to avoid frost damage and leaching in historic low-strength masonry it is often wise to choose mortars with feebly to moderately hydraulicity (lime-pozzolan, natural hydraulic lime, lime-cement mortars). These moderately hydraulic mortars are often a combination of air lime and hydraulic components. The hydraulic components will cause a more rapid strength developments (compared to air lime carbonatation) and diminish/prevent staining through (partial) encapsulation of the air lime.

3.2 ***Moisture***

Keeping the material as dry as possible is an effective way to prevent frost damage. Moisture uptake and drying characteristics are then important parameters, as well as building details which keep water off the masonry. In practice the moisture uptake of masonry elements may significantly be affected by the exposure conditions. Walls directly exposed to rain, upper parts of walls, soil retaining walls are examples of masonry

elements with regular high degrees of saturation. The exposure rate may also be influenced by the design of the building (no overhang etc.). Mortars under these conditions should be stronger to obtain an adequate durability; the application of air entrainment is another option.
To realise effective drying is not always easy: a good example is a render exposed to rain. On the one hand the render should prevent as much as possible the ingress of moisture, while on the other hand drying should be promoted. This problem can be solved, by designing a render with various layers having different porosities (fineness, pore content, binder content): from coarse porous (inside) to fine porous (outside), see Barbero-Barrera 2014.

*3.3 **Workmanship***

Often underrated are the effects of on-site practices on the durability of repairs. Enumerating the workmanship aspects which play a role with regard to the repair of an historic pointing may give an idea how many things may go wrong in practice: the way the old mortar is removed, depth and form (rectangular) of the new joint, cleaning and subsequently prewetting of the joint substrate before applying the repair mortar. Complete

Figure 5. Push out of a dense repointing mortar caused by frost damage to the bedding mortar. Combination of problems: strong dense mortar (restricts drying, shrinkage cracks allow ingress of moisture); depth of the repointing insufficient (wrong on-site practice). Free-standing garden wall, Ottawa, Canada. (P. Maurenbrecher)

fill up of the joint. Curing by wetting for a shorter or longer period of time depending on the type of binder used. Practice has learnt that a high percentage of durability problems can be attributed to inadequate on-site practices (figure 5).

4 Requirements related to salt damage resistance

4.1 Types of damage

As in the case of frost damage the presence of moisture is an important prerequisite for salt damage to occur. This is applicable to physical as well as chemical salt damage phenomena. In the case of physical salt damage, moisture is needed to transport soluble salts to drying fronts where deposition and subsequent supersaturation create the conditions where deterioration through expansion may take place. For chemical reactions, the presence of water is also essential for the expansive compounds to be formed.

Important with regard to effects of salts on the durability of mortars is the conclusion by Charola (2000) that deterioration caused by salts cannot be explained by a single mechanism; different mechanisms or a combination of these may play a role: crystallisation, hydration, effects of salt on normal hygric dilation. The most damaging salts for buildings are sulphates and chlorides.

Apart from the physical causes of damage mentioned above chemical reactions are known to cause swelling. Collepardi (1990) and Winter (2009) provide relevant information about the most important compounds and factors related to chemical sulphate attack. For the formation of the expansive compound ettringite are needed: aluminium, provided by the binder, sulphate and water. So, with regard to the presence of aluminium the composition of the binder is decisive. (See table 1 for the Al_2O_3-contents of various binders and pozzolans.)

Another less common expansive compound, thaumasite, is formed when there is sufficient supply of sulphate and carbonate + water. The chemical reaction takes place at low temperatures (4–10 °C).

Sulphate sources may be of external or internal nature.

- External sulphate sources for masonry are: seawater, groundwater, clay adjacent to brick work, inappropriate treatment introducing sulphates.
- Internal sulphates are: sulphates present in bricks, sulphate rich aggregate, excess of added gypsum to cement.

The chemical composition of binders and pozzolans provide info on the possible presence of reactive silica and alumina: see table 1.

4.2 *Materials choice: Binders*

Choosing a binder for a repair mortar, where damaging salts may play a role, should be carefully considered. This is especially the case if the mortar, for compatibility reasons, should be low-strength (low degree of hydraulicity) and dissolution-resistant. As well the service conditions may play an important role with regard to the choice.

4.3 *Pozzolanic binders + cement gauging*

In historic masonry a certain degree of hydraulicity (more rapid dissolution-resistance) of the mortar was often achieved by adding pozzolanic materials (ground materials containing reactive silica and alumina) to the generally used binder: air lime. Well known pozzolans are volcanic ashes (e.g. found in the south of Italy, and on some islands in

Table 1. Chemical composition of several binders and pozzolans

	binders				pozzolans			
	air lime	NHL	OPC	BFSG	MK	trass	Pozz Milos	RHA
	Greece	France	NL	NL	P	D	Greece	T
SiO_2	0.3	13.0	20.9	32.9	54.4	54.1	67.5	93.2
Al_2O3	2.3	1.1	4.8	11.7	39.4	18.1	15.7	0.4
Fe_2O_3	0.0	0.3	3.4	0.7	1.8	5.0	0.5	0.1
CaO	64.9	44.0	65.4	40.5	0.1	2.6	1.8	1.1
MgO	2.8	0.6	1.3	7.9	0.1	1.3	0.4	0.1
Na_2O	0.2	0.0	0.2	0.4		3.7	2.3	0.1
K_2O	0.1	0.1	0.4	0.5	1.0	4.4	3.1	1.3
SO_3		0.0	2.7	0.0				0.9
others		0.8			1.6			
LOI	29.4	40.0	0.9	0.4	1.9	9.4	8.8	3.7

NHL = natural hydraulic lime
RHA = rice husk ash
MK = metakaolin
trass = volcanic tuff
BFSG = blast furnace slag granulate

NL = the Netherlands
P = Portugal
D = Germany
T = Thailand
LOI = loss of ignition

Greece), metakaolin (a highly reactive alumina-silicate pozzolan), ashes of some agricultural products, such as rice husk ash, and tuff (consolidated volcanic ash) known as trass (found in Germany). Also crushed bricks and byproducts of industrial processes such as fly ash are used as pozzolans. Basically pozzolanic materials are latent-hydraulic, needing air-lime to form water-insoluble compounds (figure 6).

Figure 6. Mortar containing crushed brick particles as pozzolana (Istanbul)

Research into properties of pozzolanic mortars and lime-cement mortars has shown that various forms of "competition between hydration and carbonation" may take place (Cizer 2007, Allison and Wood 2012, Santos Silva et al. 2014). This phenomenon often leads to strength reduction of the mortar.

A well-known example is the premature carbonatation of lime in a lime-pozzolan mortar. For the formation of calcium silicate and aluminate hydrates (the pozzolanic reaction), air lime in the form of $Ca(OH)_2$ is needed. If the mortar dries out too quickly (no proper and long enough period of wetting of the slow reacting pozzolan) this will lead to the carbonatation of the lime. Consequently, not enough calcium hydroxide will be left for the pozzolanic reaction. The result will be a mortar with a strongly reduced cohesion. The risk of premature carbonatation is highest for pointing mortars, renders and plasters.

Another form of competition was found by Cizer et al. (2007). She observed a strength reduction at the very early stage for rice hull ash cement lime (RHA-cement-lime) mortars containing 10%-wt cement. Initially hydrated cement phases appeared to be destructed by calcium carbonate phases and subsequently to carbonate, causing negative effects on the mechanical properties.

The negative effect of small amounts of cement added to air lime mortars is also well-known in the UK. Henry and Stewart (2012) recommends, taking into consideration the research carried out by English Heritage in the 90th, that gauging a 1:3 lime/sand mix with cement should have minimally a cement content of ½ part of binder (or < 8%) to prevent a negative impact on mortar strength and durability: this means a mortar composition not leaner than 1:1:6 (cement: lime: sand). This recommendation seems on the rather conservative side as weaker mortars (comparable to a 1:2:9 mortar) in several towers in The Netherlands mortars survive well in practice.

Then as last case the following: During Investigations of lime-metakaolin pastes (Santos Silva et al. 2014) it was found that, dependant of the lime/MK ratio and the curing conditions, the mechanical properties decreased after 180 days of curing. In this case compounds like Stratlingite (C_2ASH_8), contributing to the mechanical strength of the paste, appeared to be unstable.

These examples show that the application of pozzolans can be tricky, and largely dependent on the choice of lime/pozzolan ratio of the mortar and the curing conditions: high moisture content for a longer period of time are needed to obtain a high degree of hydration. In a way this conclusion brings us back to the rationale behind the original use of pozzolanic mortars in the old Roman times, where these type of mortars preferably were used under continuously wet conditions (hydraulic works, baths etc.)

4.4 Natural Hydraulic Lime

For low strength repair mortars natural hydraulic lime (NHL) turned out to be a useful alternative as binder. With the new production techniques the variation in properties of this natural product is such that standard requirements (e.g. NEN-EN 459) can adequately be met. From chemical analyses it is clear that aluminum and alkali content is very low. Testing the sulphate resistance of natural hydraulic lime mortars led to the conclusion that NHL 3,5 mortars exhibit good sulphate resistance (Allen 2015). However, analysis of damage in a NHL-plaster in the South West part of the Netherlands showed that young NHL-plaster may disintegrate as a result of very high salt content in the substrate (the very

high salt contents (NaCl) originated from a sea water flooding in 1954). The disintegration was caused by crystallization expansion of the NaCl in the still weak young mortar (slow strength development of NHL).
Remark. Testing of salt resistance is usually done on test specimens, which are hardened for 28 days. NB the test results are then not applicable to the situation where the fresh mortar is applied on a salt laden substrate, which is normally in practice the case.

As already noted, NHL mortars, like pozzolanic mortars show a slow strength development. The reason is that the binder contains the slow reacting calcium silicate belite (C_2S). So, like in the case of pozzolanic mortars, wetting of the masonry after brick laying for a longer period of time (e.g. for NHL 3,5 mortars 1 week) is necessary.

Interesting as well is that NHL-mortars, compared to lime-cement mortars, show a lower risk of lime leaching. Several possible reasons can be provided: The main reason for this is that during hydration C_2S produces 3,2 times less $Ca(OH)_2$ than C_3S, the main calcium silicate of cement (see http://www.stastier.co.uk/nhl/testres/mineralogy.htm). It can be assumed that $Ca(OH)_2$ from the hydration reaction is an effective staining source as it is released as ions: the finest particles possible to leach out. Moreover, air lime present in NHL-binder is rather coarse: comparison of specific surface of NHL (±10.000 cm^2/gr) with air-limes (up to 50.000 cm^2/gr); so this as well is a reason why less leaching is to be expected from the NHL-binder.

*4.5 **Salt damage and soluble salt transport***

Transport and deposition of soluble salts in the porous masonry determines to a high degree the type of damage which may occur. Basic to where the damage will the take place is the position of the drying front. Differences in porosity of the original material and the repair material, imperfect connection between old and new material and the application of water repellents may significantly affect the position of the drying front.

The drying front may be situated within or at an exterior face of the wall. Crystallisation will cause the serious damage of spalling (cryptoflorescence) when it takes place within the wall; at an exterior face the less serious damage of sanding (see figure 7) will occur.

The examples in figure 7 illustrate the effects of the position of the drying front to the damage. A treatment with a water repellents applied to the exterior face of wall (figure 7, left) results in a drying front within the wall. The reason is that liquid moisture transport from within the wall to the exterior has to transform into vapour transport at the transition zone of untreated material or water repellent layer. This means that deposition of salts will occur at the transition zone, within the wall, resulting in cryptoflorescence (see as well Ioannou and Hoff 2008, Falchi et al. 2016). If the porosity of the substrate does not deviate too much of that of the repair material (and no application of a water repellent) deposit and crystallization of salt solution will take place at the outer face of the wall (figure 7, right), causing minor damage (sanding).

Figure 7. Left: Spalling of brick caused by salt crystallisation (Netherlands). The brickwork had been treated with a water repellent: concentration of salts and crystallisation-dissolution cycling under the water repellent layer. Right: Sanding of surface layer of plaster caused by salts.

Porosity of mortars can to a certain degree be related to the application of a type of binder. Assuming a “normal” mortar composition: a 1 to 3 (by volume) binder/aggregate ratio; a well graded rounded river sand 0–2 mm; without additives, experience learned in The Netherlands that indicatively the porosity increases from cement-blended mortars (10–12 vol %) → trass-lime mortars (15–25 vol %) → NHL 3,5 mortars (25–30 vol %) → air-lime mortars (30–35 vol %). Application of fine sand, additives like air entraining agents may significantly influence the porosity of the mortar.

*4.6 **Repair on salt-containing substrates***

Historic buildings may gather, over time, substantial quantities of soluble salts (Groot, van Hees, Wijffels 2009). The presence of salts in historic buildings means that repair interventions are often applied on salt-containing substrates; this may be harmful especially for renders, plasters and repointing mortars. As the original mortars are generally lime-based, for compatibility reasons (porosity, deformability) it is recommended to apply as well lime-based repair mortar. The problem is then to resist salt attack of the young lime-based repair mortar. Often this is achieved by choosing a binder with a higher amount of hydraulic components than the original one, to obtain a more rapid strength development. Care should be taken not to overdose the hydraulic components, as this will lead to low porosity of the repair material, causing compatibility problems (e.g. blocking or slowing down of moisture transport) resulting in damage in the original material.

Above reasoning describes in fact one of the main challenges of designing/choosing a repair mortar namely to find an equilibrium between the durability of the repair material and the protection of the original material (figure 8).

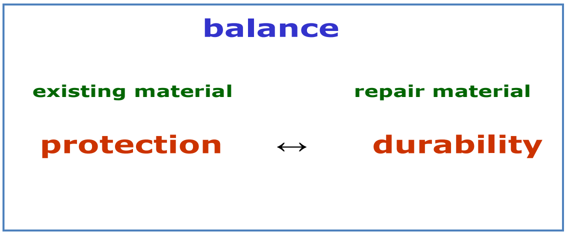


Figure 8. Compatibility expressed as a balance between protection of the existing historic material and a compatible degree of durability of the repair material

5 Requirements with regard to thermal and moisture movement

Thermal and moisture expansion/shrinkage cycli are normal phenomena in masonry walls; usual practice to take expansion into account is the application of expansion joints. Figure 9 shows examples of the application of expansion joints in modern masonry (see figure 9, left) and in historic masonry (see figure 9, right): a striking difference in number of expansion joints between the first and the latter. On the basis of an evaluation of a damage case and an analysis of the relation between materials characteristics and potential

Figure 9. Left: many expansion joints in modern cement mortar masonry (see the yellow lines). Right: in this wall built with a natural hydraulic lime (NHL 3,5) only one expansion joint was applied at the top of the door opening at the rear of the wall.

stress development in masonry some conclusions can be drawn on preferred material choices for repair.

An example of the damage one may encounter in practice is shown in figure 10. Figure 10a provides a clear indication that expansion/shrinkage cycling may be cause of the loosening of the mortar joint. The repointing consists of a cement mortar. It can as well be understood that, apart from the material composition, the joint form, V-form instead of rectangular, will play a role in the loosening of the joint: see figures 10b and 10c. So, in this case, materials properties and on-site practices may be assumed as the determining factors

a *b* *c*

Figure 10. Loosening of joints as a result of thermal or hygric deformation and a wrong joint form

with regard to the occurrence of expansion or shrinkage damage. Focussing on the materials properties and specifically on thermal expansion the thermal stress σ developing under restrained conditions can be given by the following equation,

$$\sigma = \alpha E \Delta\phi \quad [\text{MPa}] \tag{1}$$

where

α	linear thermal deformation coefficient [1/°K]
E	dynamic E-modulus [MPa]
$\Delta\phi$	temperature change [°K]

The product αE is called the materials-dependent stress coefficient, which is specific for every different type of repointing mortar. This means that thermal deformation and dynamic E-modulus data can provide insight into the influence of the mortar composition on the potential stress development in masonry. From literature research and tests carried out by Groot and Gunneweg (2012a), some thermal deformation coefficients are given in table 2. It is clear that the thermal deformation coefficients of cement-based mortars are twice as high as those of lime-based mortars. Subsequently, analysing the E-moduli of cement-based mortars and the NHL-mortars in figure 11 (St Astier internet publ), the following can be observed: For the mortar combinations with a comparable compressive strength (1:1:6 and NHL5; 1:2:9 and NHL 3,5) the E-moduli of the lime-cement mortars are moderately to significantly higher than the associated NHL-mortars:

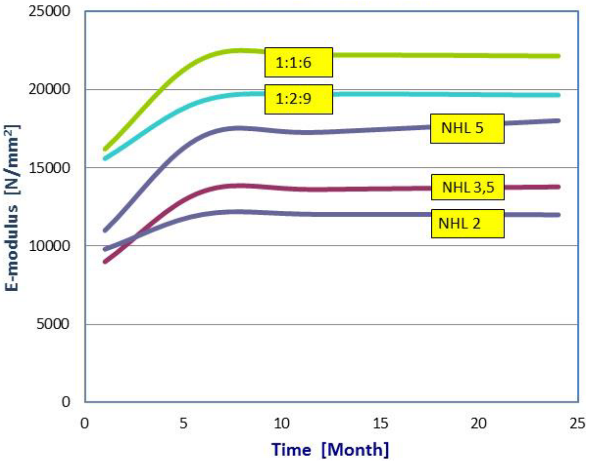
E-modulus 1:1:6 is ~ 20% higher than NHL5
E-modulus 1:2:9 is ~ 50% higher than NHL 3,5

This means that the stress coefficient αE, and with that the potential stress development under restrained conditions, of the cement-based mortars is 2.5 – 4 times higher than those

Table 2. Thermal deformation coefficients

Material	Thermal deformation coefficient (m/m 10^{-6})/°K
Brickwork	5-7
Lime-base mortar	4-6
Cement-based mortar	10-14

of the NHL-mortars. It may be concluded that there is significant influence of the binder choice on the potential stress development in the masonry, as a result of thermal expansion.



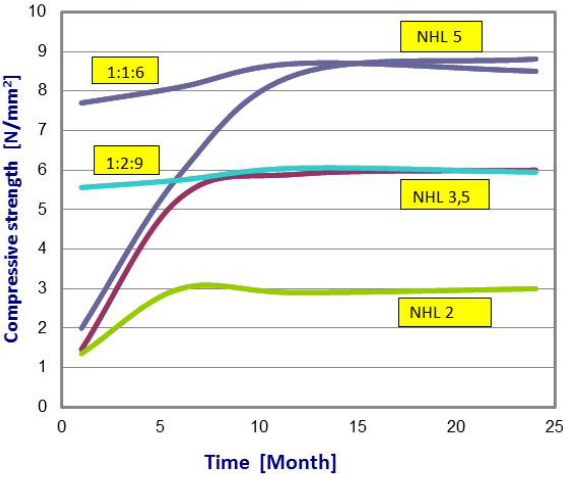


Figure 11. The graphs show that the NHL-mortars, like pozzolanic mortars, have a slow development of strength and stiffness. The test specimens have been cured under high-moisture conditions (RH 90%,T 20 ⁰C), leading to relatively high values. (1:1:6 or 1:2:9 (cement : air lime : sand by volume)) (http://www.stastier.co.uk/nhl/info/hydraul.htm)

6 Requirements with regard to rain penetration

Leakage problems in historic solid fired clay masonry are regularly observed. Materials choices, exposure conditions and workmanship (at the building site) are usually the main reasons for leakage. The most unfavourable combinations of the 3 main leakage causes may be met in traditional windmills, which are intentionally exposed to rain and wind (figure 12). Different leakage patterns can be distinguished. Unexpectedly, uniform leakage over an inner surface rarely occurs. In most cases there are defined spots where water pours from the wall. It is observed as well that the leakage is often enhanced by wind. What does this mean? Interpreting leakage in terms of porosity characterization one may argue that there are no leakage problems to be expected if the capillary pores in the wall range from 0.1 to 100 µm. Then there is no contribution to moisture transfer (see Thomson et al. 2004). The capillary pores of bricks and hardened mortars fall within this range. If, by using the appropriate brick laying technique (figure 13), every brick is fully surrounded by mortar the only remaining weak spot is the mortar-brick bond interface. To ensure a good quality interface mortar and brick should hygrically be compatible: moisture transport from brick to mortar such that a dense and well hardened and connected interface is formed (Groot and Larbi 1999).

Figure 12. Water mills built in 1738 at Kinderdijk, the Netherlands. They are almost identical in design, but built by different contractors. Striking are the differences in quality of these mills. From the beginning several of them are suffering from serious rain penetration problems. Others show no problems at all.

Figure 13. A basic requirement for water tightness is that during execution no voids are left; to avoid this every brick should be fully surrounded by mortar. This is only possible if the brick laying is done carefully brick-by-brick.

Proof for this interpretation was found in a field study (Groot and Gunneweg 2005) where examples were analyzed of well-made historic brickwork constructed with high absorption bricks (Initial rate of absorption (IRA > 3 kg/(m^2.min) and high porous lime mortars without any leakage problem (the most unfavourable mortar-brick combination with regard to leakage potential). In case of a presence of pores > 100 µm and cavities originating from wrong brick laying technique, leakage at defined spots may be expected. The reason is that pores coarser than 100 µm contribute to the water permeability through gravity or wind driven water ingress (see Thomson et al. 2004). Hence, leakage may in these cases be attributed to networks of fine cracks, wide cracks throughout the wall, voids in the interior of the masonry (voids, apart from being water reservoirs in the wall, may also promote leaching of soluble material, such as calcium hydroxide). Generally, the porosity of the mortar is finer than of the bricks in low-strength fired clay brick masonry. This means that the mortar may act as a barrier to water transport in masonry. (For more extensive information what may happen as result of moisture transport from mortar to brick see Groot 93 and Brocken 98). Tests with various mortar-brick masonry combinations showed that the barrier effect of air lime mortars is rather low, and the more hydraulic the mortar the higher the barrier effect.

The function of the masonry may play an important role in choosing an adequate binder with a view to water tightness. Especially, dynamic loading in contrast to static loading appears to significantly influence the binder choice. For instance, in the case of windmills the effect of the heavy dynamic oscillations of the sails on the masonry require a high

deformation capacity of the mortar. This is adequately provided by an air lime mortar. However it should be noted that a feebly-to-moderately hydraulic mortar will significantly diminish the ingress of water in the wall (lower moisture contents in the wall), without losing too much of its deformation capacity.
For repair of lime mortar - fired clay brick masonry, such as usually applied in traditional wind mills, it is recommended to use bricks with similar hygric properties to the weathered old bricks (in practice often 1.5< IRA< 3.0); for the mortars a feebly-to-moderately hydraulic mortar may be used in order to maintain as much as possible the deformation capacity of the masonry and to prevent compatibility problems with the old mortar.
Water penetration problems caused by networks of cracks may in a number of cases successfully be tackled applying grout injection techniques.

7 Conclusions

In table 3 an overview is given of the main technical requirements for repair mortars; these are derived from an analysis of four durability risk factors: frost, salt, thermal deformation and moisture permeability. A distinction is made between materials properties and on-site practices.

7.1 ***Materials properties***

For the repair of low-strength historic masonry feebly to moderately hydraulic mortars (lime-pozzolan, natural hydraulic lime (NHL 2 and NHL 3,5), lime-cement mortars) are in most cases compatible to the existing masonry. These mortars show compressive strengths and stiffness, which do not deviate too much from historic air-lime mortars; the same is the case for the porosity.
Especially for low-strength lime-pozzolan mortars attention should be paid to the risk of mechanical degradation as a result of “competition between hydration and carbonation”. A too low hydraulicity of the binder and unfavourable curing and environmental conditions may then lead to low durability. So, thorough knowledge about binder behaviour is needed to prevent durability problems.
Basically the required minimum strength in case of salt damage risk is higher than for the other three risk factors. Risk of strong salt attack directly after applying the mortar requires a more rapid strength development of the mortar. Most of the traditional mortars (air lime, natural hydraulic lime and lime-pozzolan) will not meet this requirement because of their slow strength development. Then special restoration mortars based on cement and with a

high porosity (e.g. so-called WTA mortars) may be a solution. A low expansion coefficient and low E-modulus are especially appropriate if low thermal movement and a high deformation capacity (dynamic loading) are required.

7.2 *On-site practices*

In the analysis of the risk factors it was shown that poor workmanship is an important cause of failing performance. Wrong on-site practices may for instance significantly decrease frost and thermal movement durability as was demonstrated in the previous sections. And prevention of water penetration in solid brick masonry is simply best served by applying the appropriate brick laying technique.

Table 3. Requirements for repair mortars of low-strength historic masonry

	Frost exp. or shrink	Salt exp. or shrink	Movement exp. or shrink	Rain penetration dynamic loading [5]
strength development	winter proof [1]	rapid [2]	-	-
strength loss [3]	binder choice	binder choice	binder choice	binder choice
drying (porosity)	rapid	rapid	-	rapid
strength (compressive)	low	> medium	low	low
stiffness (E-modulus)	low	> medium	low	low
expansion coeff.	low	medium	low	low
salt resistance	-	+	-	-
on-site execution	+ [4]	+ [4]	+ [4]	+ [6]

1 strong enough to pass the winter without frost damage

2 rapid enough to avoid salt attack

3 risk of strength loss caused by "competition between hydration and carbonation"

4 specialised execution required (e.g. repointing, render)

5 dynamic loading e.g. windmills; heavy oscillations due to the sails on the masonry

6 no air void left; brick fully surrounded by mortar

\+ important

\- not important

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