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Choosing Mortar Compositions for Repointing of Historic Masonry Under Severe Environmental Conditions

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Abstract The quality of repointing work in historic masonry is to an important degree determined by the composition of the repair mortar. Apart from this, good workmanship is a basic requirement for durable repointing. Over the past decades awareness has grown that the mortar composition of repointing should always be considered and applied taking into account the hygric and mechanical properties of the existing adjacent materials. Often this is easy enough to realize. However, choosing the composition of a repointing mortar there are situations where various damage risks seem to point at opposing materials properties. In the paper this problem is approximated analysing a number of damage cases with the aim to define more precisely which requirements and to what extent should be maintained. Subsequently, from lab studies and experiences with the application of natural hydraulic lime (NHL) in specific repointing projects a set of requirements is proposed. The context of this repointing study is repair of low-strength historic fired clay brick masonry in the coastal area of the Netherlands; environmental conditions: sea salt laden, heavy rain load and freeze-thaw cycling.

Keywords Repointing · Damage · Requirements · Restoration

1 Introduction

Historic masonry in the Netherlands (before 1850) is mostly composed of relatively low-strength bricks held together with a relatively low-strength mortar (often pure lime mortars). In most cases the mechanical strength of the masonry, although low,

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is sufficient to show a satisfactory durability. Low mechanical strength mostly goes together with a high-porosity: 25–40 vol.%.

In the past repointing of historic masonry was often done using shell lime. The shell lime was obtained by burning shells from the sea. This lime was supposed to be weakly hydraulic however more importantly, these mortars (the lime being relatively coarse) showed excellent drying behaviour. For a good quality the preparation of the shell lime mortar was rather time-consuming. With time the use of shell lime mortars for repointing stopped as the production of shell lime came to an end in the Netherlands. The durability of shell repointing often turned out to be excellent.

In the repointing practice of historic masonry, with the disappearance of shell lime, cement as the basic binder was introduced. Speed of production (early strength) and the idea that the use of an, in itself, durable material were important incentives for the application of cement-based repointing mortars in historic masonry. Subsequently, there was amazement at the occurrence of damage as a result of this type of repointing. Mostly the problems are caused by incompatibility between the repair material and the adjacent historic materials. Since the joint material in itself generally remains undamaged, the repointers doing the job are reluctant to adapt their composition, as a change in general will diminish the durability of their joint (it’s about who is responsible for an eventual damage).

From a restoration point of view, however, the repair mortar should not have a negative effect on the durability of the existing masonry and other components in the masonry. With this constraint in mind, the service life of the repair mortar should be as long as possible (be durable).

Service life not only depends on the mortar components but also on how it is installed (workmanship) 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, construction practice, operation, and maintenance.

2 Requirements Related to Damage Risks

Main causes of damage in or as a result of repointing are: (i) freeze-thaw cycling (ii) salts and (iii) thermal/moisture expansion/shrinkage or a combination of these three. These types of damage may be the result of inappropriate materials behaviour and/or unskillfull execution.

2.1 Freeze-Thaw Damage

Freeze-thaw damage may occur *in* a repointing (see Fig. 1) if the binder is an air lime and not sufficiently carbonated at the onset of winter. Under average weather conditions, after 4 weeks, carbonation should have occurred to a depth of at least

5 mm (Tim and Jeff 1997); carbonation depths of 8 mm after 2 months are reported by (Waldum Alf 2009). This means that the application of air lime has to take place in the right season and at least 2–3 months before the frost season. This seasonality also plays a role with regard to the application of Natural Hydraulic Lime (application at least 1 month before the frost season).

For many appliers the use of pure air-lime mortars without the addition of hydraulic components is often considered too risky, especially if the masonry is very exposed. The reason being that non-carbonated lime has a high solubility and is easily leached out by rain. Given the relatively long period of sensitivity to weather conditions pure air lime repointing is in fact not a very favourable option.

Freeze-thaw damage may also occur indirectly: applying a very dense (e.g. cement-based or repointing mortars containing water repellents) repointing on a historic air-lime bedding mortar may have serious consequences for the drying conditions in the masonry. With an open porous structure in the repointing, moisture may easily move from the bedding mortar to the repointing; with a dense structure in the repointing the moisture will necessarily pass through the adjacent brick; this is a slower process, causing longer periods of high moisture content in the bedding mortar; as a result of this the bedding mortar may become frost prone. Cases are known of centuries-old sound bedding mortars showing this type of frost damage caused by the application of the wrong restoration practice (a typical example of an incompatible use of a repair material).

2.1.1 Requirements—Materials Properties

When considering freeze-thaw the most important material characteristics are:

- strength development
- frost resistance
- drying behaviour (moisture transport, porosity)

Fig. 1 Horizontal layering (see arrows) in an uncarbonated air lime repointing as a result of freeze-thaw cycling

2.1.2 Requirements—Execution Techniques

Related damages in addition to the execution technique may play a role in the further occurrence of freeze thaw damage. For instance: a hollow between repointing and bedding, as a result of insufficient filling of the joint may result in push out by frost (where a period of heavy rain is directly followed by a frost period); other causes of damage may be insufficient depth of the repointing, a V-form instead of a rectangular form of the joint etc.

2.2 Salt Damage

Salts may have a harmful influence on the durability of the mortar as well as the brick. The influence of sea salt (containing a high content of NaCl) can be observed in many buildings, especially on the North sea coast of the Netherlands. In Fig. 2 two examples are presented of damage caused by NaCl.

Figure 2 (left), shows damage to a pure air-lime repointing mortar. In this case the highly soluble chemical compound calcium chloride ($CaCl_2$) is formed with calcium from the mortar binder and chloride from the seasalt. Rain, subsequently, causes the leaching out of the mortar. The binder choice is obviously an important parameter in limiting salt damage.

In practice the start situation of the substrate on which the repointing is applied is important: high contents of salt may limit the use of lime-based mortars such that only cement seems to be appropriate. For other reasons this maybe very inappropriate (too dense, too strong). Desalination of the masonry may then be a solution.

Also crystallization-dissolution cycling, especially around 75% Relative Humidity, resulting in swelling-shrinkage cycling, may cause considerable damage (Lubelli 2006).

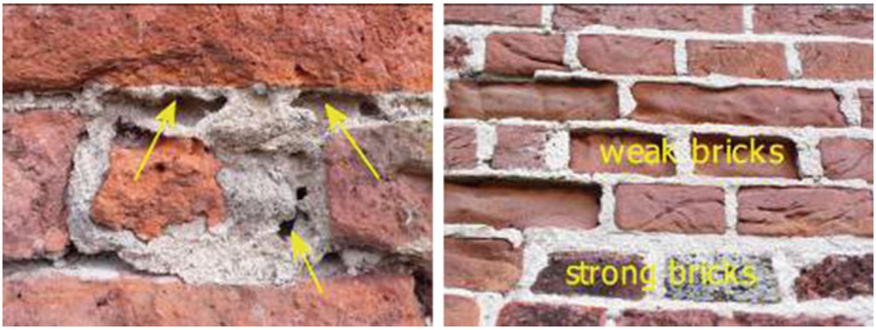


Fig. 2 Cases of NaCl damage. Left: voids in the repointing stemming from leaching of calcium chloride from the air lime repointing. Right: weathering of underfired brick through NaCl crystallization-dissolution cycling

Figure 2 (right), presents damage to fired clay bricks by NaCl. In this case the underfired bricks are apparently not strong enough to resist the crystallization-dissolution cycling caused by NaCl. The stronger bricks don't show damage (compressive strength values of 10–15 MPa are suggested by practice as strong enough to withstand salt damage through crystallization-dissolution cycling).

2.2.1 Requirements—Materials Properties

When regarding salt damage the most important materials characteristics are:

- the choice of the binder
- chemical composition such that no soluble compounds are formed
- resistance against salt crystallisation requires a certain degree of mechanical strength

2.3 Deformation Damage

In practice there is often more of an awareness regarding the risks of damage as a result of thermal and moisture deformation on a macro scale (building element), than there is for that on a meso scale (joint).

Differences in macro deformation behaviour of modern (left) and traditional masonry (right) is shown in Fig. 3. The fear of cracks, apparently a risk in modern cement masonry, is solved by extensively applying dilations. The long wall constructed with a traditional natural hydraulic lime mortar, NHL3.5 type St. Astier, (right) does not need any dilation.

Fig. 3 Left, the yellow lines indicate the dilations applied in a modern masonry. Right, a wall without dilation in traditional masonry (Color figure online)

Fig. 4 Detachment of repointing caused, in particular, by thermal deformation enhanced by a wrong cross-sectional form (V-shape instead of rectangular) of the repointing

At meso scale thermal resp. moisture deformation may as well be a serious cause of damage (see Fig. 4). Not only do material properties such as the (linear) thermal respective moisture expansion coefficient play a role in the detachment process, but so does the execution technique in for example the pointing.

2.3.1 Requirements—Materials Properties

- (linear) thermal respective moisture deformation coefficients
- stiffness (E-modulus).

2.3.2 Requirements—Execution Technique

- rectangular cross section of the repointing (no V-cross section form!!)

2.4 Overview—Requirements

In order to facilitate the analysis of the (in)consistency of the materials and execution requirements of the different damage risks, they have been collated in Table 1.

It is quite clear from the table that there is a friction between the required mechanical characteristics relating to frost and deformation risks, when compared to those relating to the salt damage risk.

Table 1 Relative requirements related to major damage risks of repointing in weak historic masonry

	Frost damage	Salt damage	Deformation damage
properties			
strength development	winter proof 1)		4)
drying (porosity)	quick		
strength (compressive)		≥ medium	low
stiffness (E-mod)		≥ medium	low
expansion coefficient			low
frost resistance	+		
salt resistance		+	
execution 2)			
prep,prewett,curing etc	+	+	+
form joint	+		+
depth joint	+		+
filling joint	+		

1) strong enough to pass the first winter without frost damage
2) specialised execution required
3) + high importance
4) empty box: low importance or not specified

The easiest solution seems to be to opt for the stronger and less deformable mortar as required for a better salt damage resistance. This may provide an increase of durability in the repointing mortar; however, such a mortar will also be typically less porous, leading to slower drying of the bedding mortar, and also a higher thermal expansion combined with a higher stiffness, increasing the risk of deformation damage.

In fact a compromise should be reached between the durability requirements of the repair mortar and the compatibility requirements of the adjacent masonry (drying affecting frost resistance) and stresses (resulting from deformation behaviour).

3 Tests in Practice and in the Laboratory

In practice as well as in the laboratory a series of site-mixed and prefabricated repointing mortar compositions were tested. The starting point were recent experiences with repointing mortars used in historic towers and windmills located on the

West coast of the Netherlands. These buildings are composed of relatively weak masonry which is exposed to sea salts, heavy rain and frost. In such cases the choice of the binder is essential, as this determines whether the mortar will be salt resistant, have adequate strength (not too high and not too low, in comparison to the existing masonry materials), is frost resistant, and shows low thermal deformation.

With regard to the needed salt resistance recent experiences in restoration projects with natural hydraulic lime (NHL 3,5) showed such good sea salt resistance, that this binder was chosen as a basis for the site-mixed repointing mortars.

In the laboratory, properties like compressive strength, dynamic E-modulus, free water absorption, drying characteristics, thermal expansion and frost resistance were determined. In this paper the attention is focused on freeze-thaw testing and deformation testing, being of major importance with regard to durability.

3.1 *Mortar Compositions*

Materials used in the site mixed mortars:

- Natural Hydraulic Lime (NHL 2 and NHL 3,5 from St Astier, France).
- BFC: blast furnace cement (HC CEM III/B).
- Pozzolan: Trass (Rheinische Trass).
- Air limes: ‘Lime (Harl)’ (CL70).
- Sand 1: standard repointing (rounded river) sand with Fineness Modulus of 1.8.

The composition of the prefabricated repointing mortars is unknown; from the hardening process it can be concluded that they are Portland cement-based mortars (Table 2).

Table 2 Repointing mortars used in the laboratory tests and their constituents by volume proportions

Site-mixed mortars									Prefab mortars	
VB02	NHL3,5	BFC	Sand 1	VB06	NHL2	add	BFC	Sand 1	VP01	A
	6	1	17		3		1	10		
VB03	NHL2	BFC	Sand 1	VB07	Lime	trass	BFC	Sand 1	VP04	B
	3	1	10		1.3	0.4	0.25	3.2		
VB04	NHL3,5		Sand 1						VP05	C
	1		2,5							
VB05	Lime	BFC	Sand 1						VP06	D
	5	1.5	16							

3.2 Freeze-Thaw Testing

The freeze-thaw tests were based on the test set-up used in the EU-Pointing project (Wijffels et al. 2001). In this test the freeze-thaw cycle is applied from one side of the test specimen, and fresh water is used in the test. Precise details on the freeze-thaw cycle tests are given in (Groot and Gunneweg 2012) (Fig. 5).

The test specimens were evaluated regarding:

- damage of the repointing itself
- deterioration of the bond between mortar and brick
- damage of the bedding mortar behind the repointing
- push out (sound test)

The results are presented within Table 3. None of the repointings of the test specimens were pushed out. Push out may occur in case the depth of the repointing is small (see tests Wijffels et al. 2001); in this testing series the depth of the repointing was greater than two times the width of the joint.

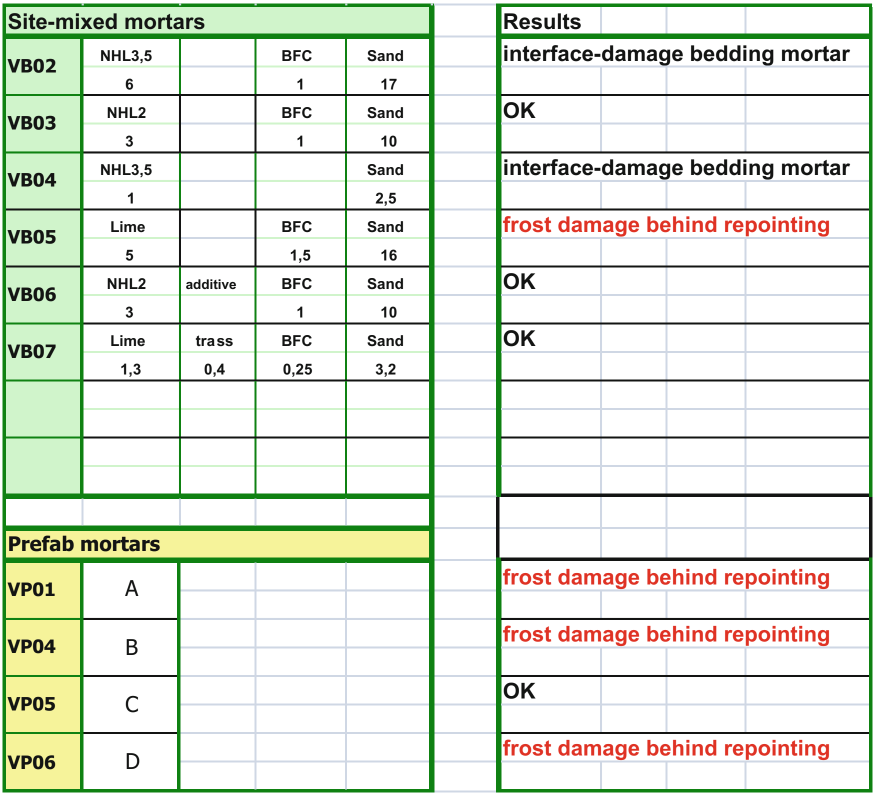
Frost damage behind the repointing (in the bedding mortar) occurred within three of the test specimens of the cement-based prefab mortars and within only one test specimen of the lime-based site mixed mortars: a clear indication that the drying conditions of the site mixed specimens are more favourable than the prefab mortars.

3.3 Thermal Deformation

In the following the effects of stress development in repointing mortars are given in a simplified model considering only a linear deformation and also neglecting the surrounding materials and other boundary conditions.

Fig. 5 The test specimens in the freeze-thaw container

Table 3 Results Freeze-Thaw testing



Site-mixed mortars					Results
VB02	NHL3,5 6		BFC 1	Sand 17	interface-damage bedding mortar
VB03	NHL2 3		BFC 1	Sand 10	OK
VB04	NHL3,5 1			Sand 2,5	interface-damage bedding mortar
VB05	Lime 5		BFC 1,5	Sand 16	frost damage behind repointing
VB06	NHL2 3	additive	BFC 1	Sand 10	OK
VB07	Lime 1,3	trass 0,4	BFC 0,25	Sand 3,2	OK
Prefab mortars					
VP01	A				frost damage behind repointing
VP04	B				frost damage behind repointing
VP05	C				OK
VP06	D				frost damage behind repointing

Thermal deformation may result into stresses in the masonry (Hayen and van Balen 2001; Vermeltfoort et al. 1999). The thermal stress (σ), developing under restrained conditions is given by the following equation,

$$\sigma = \alpha.\mathrm{E}.\Delta\emptyset\ [\mathrm{MPa}] \tag{1}$$

where:

α: linear thermal deformation coefficient [1/K × 10^{-6}]

E: dynamic E-modulus [MPa × 10^{3}]

Δ(T): temperature change [K]

α.E is the materials-dependent stress coefficient, specific for every different type of repointing mortar (see Fig. 6).

The significant influence of the choice of material on the possible stress development in masonry can be shown, by comparing the thermal stresses developed by the cement-based repointing VP01 and the lime-based repointing VB06

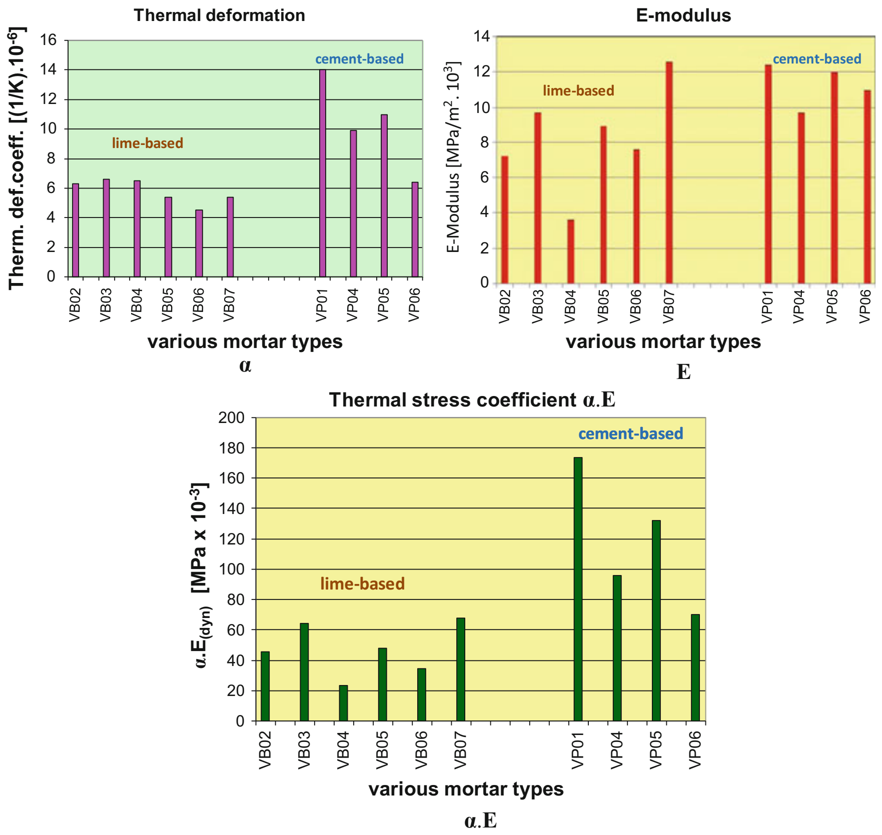


Fig. 6 Materials-dependent stress coefficients **α.E**

(see as well Fig. 6). Note: for the determination of the dynamic E and the thermal deformation coefficient α, see Groot and Gunneweg (2012).

Stress development under restrained conditions, with a temperature increase of 50 K (south or west facade) is as follows:

VP01:

Stress coefficient (see Fig. 6): $\alpha.E = 170 \times 10^{-3}$ MPa/K.
Restrained stress with a temp increase of 50 K: $\sigma = \alpha.E.\Delta Ø = 170 \times 10^{-3} \times 50 = 8.5$ MPa.

VB06

Stress coefficient (see Fig. 6): $\alpha.E = 34 \times 10^{-3}$ MPa/K
Restrained stress with a temp increase of 50 K: $\sigma = \alpha.E.\Delta Ø = 34 \times 10^{-3} \times 50 = 1.7$ MPa

3.4 Guideline Requirements

A series of guidelines with the necessary requirements for a suitable repointing mortar could be developed from the results of the laboratory testing combined with the practical experience obtained in a series of repointing projects.

The guidelines for requirements applicable to the repointing of low-strength historic fired clay brick masonry in the coastal area of the Netherlands where conditions encountered are sea salt, heavy rain load and freeze-thaw cycling, are as follows:

- Workability, evaluated as good by an experienced mason/pointer
- Choose preferably NHL-based binder (or at least lime-based)
- Depth of the joint ≥ 2 times joint width
- Compressive strength 3–7 [MPa]
- Dynamic E-modulus (6–10) $\times 10^3$ [MPa]
- Linear Expansion Coefficient (4–7) $\times 10^{-6}$ [1/K]
- Water Absorption Coefficient (WAC) 0.3–0.9 [kg/(m^2. min$^{0.5}$)]
- Freeze-thaw test: no damage to the joint, no debonding within the joint, no frost damage to the bedding mortar *behind* the repointing (acc. to EU-Pointing Project, see also Wijffels et al. 2001, Groot and Gunneweg 2012).

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