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RILEM TECHNICAL COMMITTEES

RILEM TC 167-COM: 'Characterisation of old mortars with respect to their repair'

Characterisation and damage analysis of old mortars

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1. INTRODUCTION

The scope of RILEM Committee TC167-COM is the characterisation of old mortars, with respect to their repair.

For damage analysis of historic buildings, the characterisation of the old mortars may represent an essential part of the investigations. This statement can also be inverted, keeping in mind the scope of the committee and more specifically the second part 'with respect to their repair'. It is essential to have knowledge of the condition of the old mortar and of the causes of any decay that has occurred [1].

The aim of this paper is to underline the importance of knowledge on the factors that influence the way in which degradation of materials- and especially mortars in monuments - occurs. The most common forms of degradation of mortar in monuments, as well as the type of investigation, which is necessary to understand the cause of the damage, are described. On the basis of the assessed decay form and decay process, the most adequate repair method and the most suitable repair mortar can be chosen.

The diagnosis of the damage is very often forgotten *in practice*, even though this is a fundamental step to guarantee a compatible and durable restoration. Such negligence can lead to major incompatibility problems in the case of repair mortar application. The approach discussed in this document can result in a better understanding of the causes of incompatibility and in guidelines for compatible repair mortars, based on the specific conditions of the individual monument.

This article describes the approach, as proposed by RILEM TC167-COM.

2. FACTORS AFFECTING DEGRADATION PROCESSES

The most important factors affecting degradation processes are related to:

- environment
- materials
- design
- workmanship and construction procedures
- maintenance

The principal factors related to *environment* are:

- moisture supply: rainwater, moisture penetrating from the ground or surface water, snow melt, floods, …
- salt supply from the ground, ground or surface water or from usage of the building (stable, salt storage) or via the air (aerosol), floods, de-icing salts
- air pollution
- variations and extremes in temperature
- exposure to fire
- dynamic load (earthquakes, wind, traffic, vibrations, …)
- soil settlement

The principal *material* factors are:

- composition of the mortar (type and quantity of binder, grain size distribution of the sand,..)
- properties of brick, stone and mortar and their interface (capillary transport, adhesion,..)
- presence of salts in the materials

The *design* factors are:

- original structural design of the building and / or subsequent modifications
- choice of (combinations of) materials
- detailing of the building (especially water shedding details like gutters, downpipes, window sills, copings, flashings, roof overhangs, …)
- choice of repair methods and materials (treatments, cleaning operations, ….)

The factors deriving from *workmanship and construction procedures* are:

- quality of execution
- mortar mixing on site
- the way materials are cured and curing circumstances
- protection of (fresh) mortars
- lack of knowledge on traditional workmanship

The factors related to *maintenance* are:

- prompt repair (Lack of maintenance: no prompt repair of water shedding elements, damaged mortar joints, …)
- Inappropriate maintenance programme (time span, monitoring)

The environmental factors, strongly connected with material factors, exert influence on the development of degradation processes.

Orientation and architectural details finally determine the extent to which moisture supply and drying may play a role [9].

Table 1 summarises all the important factors.

Table 1 - Important factors for damaging processes

Environment	Moisture supply	Rain, snow
		Ground water
		Surface water
		Floods
	Salt supply	Soil or surface water
		Use (stable, salt storage)
		Air (aerosol)
		Floods
		De-icing salts
	Air pollution	
	Temperature factors	Variations
		Extremes
	Exposure to fire	
	Dynamic loads	Earthquakes
		Wind
		Traffic
		Vibrations
	Differential settlements	
Materials	Mortar composition	Binder type
		Binder quantity
		Grain size distribution sand
	Properties brick/stone and mortar system	Porosity
		Capillary transport
		Adhesion / bond
	Presence of salts in the materials	
Design	Original structural design of the building or modifications	
	Choice of combinations of materials	
	Detailing of the building	
	Choice of repair methods and materials	
Workmanship and construction procedures	Quality of execution	Quality of execution Mortar mixing on site
		Way materials are cured and curing conditions
		Protection of fresh mortars (masonry)
	Lack of knowledge on (traditional) workmanship	
Maintenance	Lack of maintenance	
	Inappropriate maintenance programme	

Processes

All building materials are to a different extent prone to degradation processes. These are up to a certain point natural processes, which can be more or less influenced by man or man's activities.

Degradation processes exert a stress on the building materials (physical, chemical, physico-chemical, mechanical), which, under certain conditions or after a certain time leads to damage. Degradation is the more or less gradual increase of damage, as well as the decrease of quality.

Damage can be defined as 'a form of degradation of the building material, which becomes evident at a certain moment' (varying from *e.g.* discoloration to complete loss of cohesion). Damage can be both an esthetic and a functional matter.

The degradation process is not by definition identical to the cause of the damage [2, 3]. There are in general a number of essential conditions, without which nothing can happen, notwithstanding the presence of the process.

We shall try to name degradation processes on the basis of environmental factors:

- process of freeze-thaw *cycles*
- process of salt crystallisation *cycles*
- process of chemical conversion leading to the formation of expansive compounds (including chemical air pollution components activity, *i.e.* dry deposition and wet deposition)
- process of dissolution and leaching
- process of wind and water erosion
- process of hygroscopic moisture absorption due to salts
- process of biological deterioration (bio-deterioration)
- process of swelling and/or shrinkage, due to temperature and/or moisture variation
- process of differential movements and crack propagation (static or dynamic load, settlement of soil, creep phenomena)

The presence of water is a necessary condition for many of the degradation processes.

In this article the general approach, described before is illustrated with one example of a case-study. The complete work, including many examples of practical case studies, ranging from frost damage to structural damage, is described in [Book: RILEM TC 167-COM, to be published in 2004].

In each of the cases the (analytical) investigation techniques that may be used for the diagnosis are mentioned and the results shown. Techniques include for example SEM, XRD, PFM, assessment of moisture profiles and (indicative) salt profiles.

All cases are built up in a similar way: first a description of the type of damage or the damage pattern is given, then the investigations are described, that are necessary to achieve a sound diagnosis, the conditions that are favourable for the damage mechanism are given and a conclusion is drawn on the cause of the damage. Finally a first approach for the repair is given.

3. EXAMPLE

The approach given, is based on the way of reasoning of an expert. This means that in a structured way the cause of damage is assessed [2]. Although it may seem obvious, it is stressed here that any investigation should include an evaluation of the environmental circumstances that might be essential for the damaging process, as well as an assessment of the type of construction involved.

Reference is made to analysis techniques that may be useful in diagnosing the problem. For sampling, often necessary for reaching a sound diagnosis, a general procedure can be found in [6]. Finally a description is given on how the damage and repair could be dealt with.

3.1 Formation of expansive compounds, like thaumasite in the original bedding mortar

Sulphate may form expansive compounds such as ettringite or thaumasite with components of mortars. In case of hydraulic lime or trass lime mortars mainly thaumasite may be formed (VAN HEES, 2002). The sulphate may derive from the atmosphere (SO_2) or from the brick (due to low firing of sulphate containing materials).

Thaumasite ($CaCO_3.CaSiO_3.CaSO_4.15H_20$) is a compound that can be formed by the reaction of mortar components with calcium sulphate and water. Thaumasite itself has no binding capacities. For the conversion to take place, a (very) high moisture content and a relatively low temperature (generally < 5 ºC is mentioned; however, indications exist from some of the examples shown in this section that also higher average temperatures are possible) as well as a high sulphate content are necessary. The reaction leads to swelling of the mortar.

The mortar needs to contain calcium carbonate and calcium (mono)silicate. Sulphate is necessary in the form of calcium sulphate (gypsum). A high moisture load is necessary, not only because the compound itself contains water), but also in order to allow sulphate transport from the brick into the mortar. More information is to be found in [1, 10].

3.2 Description of the damage

A typical damage is the spalling of masonry (brick and mortar). Sometimes the damage is showing in the form of pointing that is being pushed out and goes together with swelling of the bedding mortar. The damage pattern may be very similar to frost damage.

In other cases severe vertical (and sometimes horizontal) cracks may show in the masonry and that may be confused with structural cracks (Fig. 1).

In the example of Figs. 2 and 3 spalling of both brick

Fig. 1 - Wide (vertical and also horizontal) cracks, on the first sight looking like structural cracks, were found to be caused by swelling compounds in the inner part of the masonry.

Fig. 2 - Damage in the passage(way) of a historical arch bridge: spalling of brick and pointing is pushed out.

Fig. 3 - Start of damage visible in the hole left by the drilled core (see arrow for location): a layer of the brick begins to detach, the bedding mortar shows loss of cohesion.

and mortar in the masonry of the passage(way) of a historical arch bridge is shown.

3.3 Investigation

This damage type can be due to frost damage or to the formation of swelling salts. Sampling is always necessary to find out the origin of the damage and to understand what moisture source(s) play a role in the process. In Fig. 4 the moisture distribution is shown. The moisture content is extremely high, whereas the hygroscopic moisture content is relatively low, and surely in the exterior 25 cm of the masonry.

Besides powder samples, taken to measure the moisture distribution, cores were drilled over the wall depth; during this operation it could be seen that a soft red brick was used from a depth of ca. 40 cm. These bricks, fired at a low temperature, could have a high sulphate content.

Petrography (using polarising and fluorescence microscopy) applied to thin sections of the material is a proper method to gain understanding of the named compounds as well as of the composition of the mortar [7, 8, 11]. The compounds found can be further investigated by means of SEM/EDX. If thaumasite or ettringite are found it is important to find the source for the sulphates.

The thin sections showed concentrations of crystals from which cracks start (see Fig. 5); this sample came from a core taken at a distance of -/- 200 cm (See fig. 4). The crystal concentrations are situated at a depth of 5-10 cm from the surface.

The picture in Fig. 5 shows the transition between a decayed zone (A) and a non decayed zone (NA). In the decayed zone the binder is partly dissolved, resulting in a higher porosity (lighter colour) than in the non decayed zone (darker colour).

The decay appears from the formation of needle like crystals, that are present as concentrated pockets (KR). By means of SEM/EDX it was found that these are mainly thaumasite. Thaumasite is not hygroscopic, which explains the low hygroscopic moisture content (Fig. 4).

3.4 Cause

The formation of thaumasite in the bedding mortar (a lime mortar with hydraulic, trass like components), led to micro cracks; on a macroscopic scale this is visible in the spalling of the masonry.

N.B.: Spalling is the consequence of the increase of volume caused by swelling salts forming near the surface of the masonry. This leads to a compressive stress there. In the case of thin masonry this could lead to bulging. In the case of thicker masonry, bulging of the masonry is generally not possible and thus spalling occurs.

3.5 Factors

Water penetration, through the bridge deck on top and the bridge vaults downwards) is the first important environmental factor. The presence of sulphate is the second factor. This can come from the masonry materials themselves, namely from the soft red brick and from the environment, namely from the diesel engines of the canal touring boats. A determining material factor is the presence of a hydraulic lime mortar or of certain hydraulic components in the lime mortar.

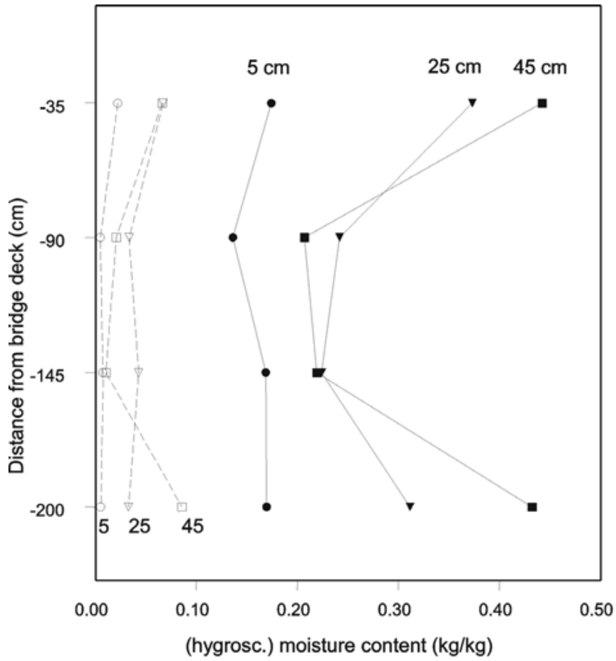

Fig. 4 - The moisture content (and distribution) in one of the bridge pillars as a function of the distance from the bridge deck and as a function of drilling depth (5, 25 and 45 cm). The continuous lines indicate the moisture profile. The dotted lines represent the hygroscopic moisture content at 93% RH and give an indication of the salt profile.

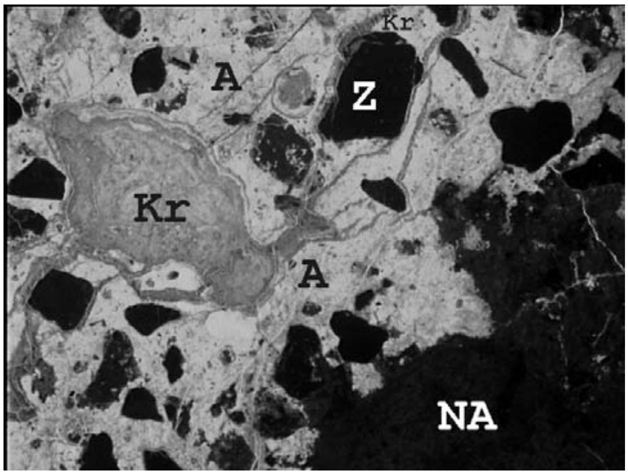

Fig. 5 - PFM picture (fluorescence) of decayed mortar. The dark not decayed zone has lower porosity. In the left part (light colour) the porosity is clearly higher; this is due to the dissolution of the binder; 'A' is used to indicate the decayed zone, 'NA' for the not decayed zone. The decay is shown by this phenomenon as well as by concentrations of structures in crystal form indicated by 'Kr'. Dimensions of the section shown are 2.7 x 1.8 mm (magnification: 50x). Location -/- 200 cm below bridge deck, depth 5 to 10 cm from the wall surface (see Fig. 4).

3.6 Restoration – repair

Reduce moisture penetration as much as possible (by means of hindering the ingress of moisture through the bridge deck and the bridge edges).

The production of the SO_2, originated from the diesel engines of the canal touring boats, should possibly be limited.

For the repair mortar a low strength mortar with characteristics similar to the old bedding mortar should be considered. One should however be aware of the possible consequences (similar damage!) if the elimination of moisture were not successful. The use of a sulphate resistant mortar might then be a possibility to reduce risks.

Further requirements are: i) achieve a good contact between the repair mortar and the old mortar, aiming at making moisture transport (and possibly salt transport) towards the exterior possible (drying of construction and transport of salts to the surface) and ii) aim for rather low adhesion of the repair mortar to the brick, so that in the case of salt crystallisation, the new mortar can be pushed out, without causing damage to the surrounding brick.

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