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Thaumasite swelling in historic mortars: field observations and laboratory research

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Abstract

The formation of thaumasite in historic mortars was found to be a recurrent problem in cases of conservation of historic masonry in the Netherlands. Several case studies in which mortar swelling occurred were performed. In this paper two case studies concerning thaumasite formation are briefly described, focusing on the damage patterns observed and the analyses performed in order to arrive at the diagnosis of thaumasite formation. Sulfate may come from inside (the historic brick) and from outside (combustion processes from industry or traffic). The second part of the paper deals with laboratory research aimed at provoking the formation of thaumasite in hydraulic lime mortars. A further aim of the laboratory research was to develop an adequate test procedure in order to evaluate the vulnerability of mortars to be used in conservation. A test procedure on mortar, cured between bricks in order to have realistic mortar properties, appears adequate.

Keywords: Historic mortars; Thaumasite formation; Damage; Conservation

1. Introduction

1.1. General

In several case studies carried out in the Netherlands, in the framework of the EU project "Maintenance of pointing in historic buildings: decay and replacement (contract ENV4-CT98-706)", mortar swelling appeared to be the major cause of the damage. This mechanism may lead to

- damage to the masonry as a whole (e.g. cracking and/or bulging) or to the bedding mortar (e.g. layering);
- damage to the masonry unit (e.g. chipping and/or spalling);
- damage to the pointing mortar (e.g. bursting, crumbling and/or sanding).

Mortar swelling always is the result of a reaction between one or more constituents of that mortar and a salt migrating into that mortar. Therefore, this type of swelling is referred to as salt swelling or salt expansion.

The swelling or expansion is caused by the fact that the newly formed compound has a larger volume than the originally present compound. This new compound can be an organic salt (better referred to as ester) or an inorganic salt. However, in most cases the newly formed compound is not a salt but rather a mineral.

All potentially damaging compounds have in common that they form crystals with more or less water incorporated in the crystal.

First some of the cases of swelling bedding mortar are briefly described. On the basis of the damage mechanisms encountered in the case studies, laboratory research was set up and concentrated on the mechanism of thaumasite formation. Thaumasite formation that occurs in the bedding mortar, sometimes over a large part of the wall section, poses a significant problem for the conservation of historic masonry.

1.2. Thaumasite swelling

Thaumasite is a salt with calcareous and siliceous components in combination with gypsum ($CaCO_3 \cdot CaSiO_3 \cdot CaSO_4 \cdot 15H_2O$). Formation of thaumasite in the mortar will lead to an expansion of the mortar, which can lead to damages to the masonry, the pointing and the bedding mortar and to the masonry units.

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Thaumasite can be formed under the following conditions [1]:

environmental conditions
- a high water supply to the masonry,
- a relatively low temperature (<15 °C).

necessary components
- calcium silicate (e.g. C–S–H),
- sulfates,
- carbonate,
- initially reactive alumina (0.4–1%).

Sulfate can penetrate the masonry from outside, when due to air pollution (combustion processes of industry or traffic) the amount of SO_2 is high. Another source for the sulfates can, however, be the brick itself. Low fired brick, as often applied in the inner parts of thick brick walls in historic buildings may contain sulfate (due to sulfate containing clay, low firing temperature and/or type of fuel). Finally, sulfates can also ingress through rising damp.

According to Hartshorn [1], cold and wet conditions are ideal for thaumasite formation; the lower the temperature, the worse the effect.

As in many cases intervening in the sources, like sulfate and/or moisture is not easy or even possible, the conservation question is whether (and if so with what mortar composition) a successful repair could be undertaken. Taking off the decayed mortar, followed by a deep re-pointing could be a possible technique to use. The laboratory research described, concentrated on developing a (quick) procedure, able to provoke thaumasite formation in the laboratory and able to evaluate the vulnerability of possible repair mortars.

2. Case studies

Several cases of swelling salts in mortars, both bedding mortars and pointing mortars were encountered and several types of swelling salts were found. The two cases described here, are concerned with the formation of thaumasite in and swelling of the bedding mortar.

The first case is a historic canal bridge (1728) in Amsterdam, see Fig. 1. The bridge was built with clay brick (a good quality in the external 40 cm and a low strength orange–red clay brick, most probably rich in sulfate, in the internal part). The bedding mortar was a hydraulic mortar (lime–pozzolana binder).

The damage mainly occurred in the vaults, where push out of the (cement based) re-pointing and chipping of bricks occurred (Fig. 2).

The second case is a church tower (1926) in Noordwijk, see Fig. 6, built in brick masonry, with an external layer being a high strength clay brick and the internal layer a low strength clay brick, rich in sulfate.

Fig. 1. View of bridge 35, Amsterdam (case study 1).

Fig. 2. Damage to masonry in vault intrados (case study 1).

Originally no pointing existed, but a tooled bedding mortar. Part of the mortar joints have been re-pointed with a cement based mortar. The original bedding mortar was mainly lime based, with some addition of portland cement. Damage is visible to the wall as a whole: mainly vertical but also horizontal cracks in the external layer of bricks (Fig. 6); vertical cracks through both joints and bricks, horizontal cracks only through horizontal joints; most severe cracking (width up to 17 mm) occurs in the upper part of the tower. In the case of the historic bridge the diagnosis was that the swelling of the bedding mortar was due to the formation of both thaumasite ($CaCO_4 \cdot CaSiO_3 \cdot CaSO_4 \cdot 15H_2O$) and monochloride ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$). Using polarising and fluorescent microscopy and SEM/EDAX analysis, according to the procedure described in [2], both compounds were found (see Figs. 3–5). Thaumasite was found up to a depth of 10 cm from the surface.

The formation of thaumasite was due to the use of hydraulic lime as a binder and the ingress of water from the bridge deck and of (1) sulfate originating from the low fired brick used in the internal part of the masonry

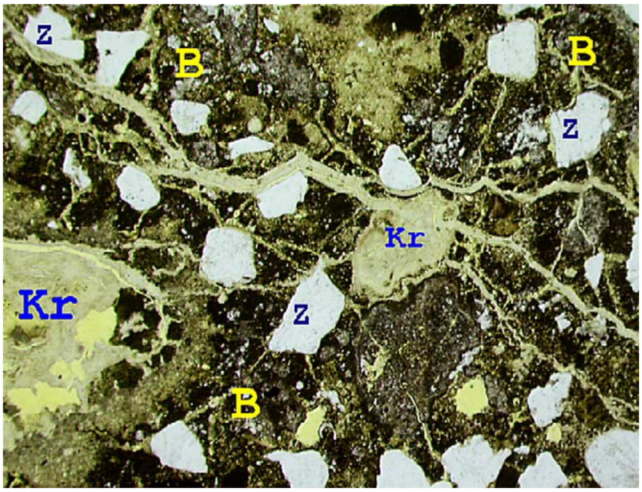

Fig. 3. PFM picture (2.7×1.8 mm) of damaged mortar (case study 1). Thaumasite concentration, cracks are growing from this concentration and are also filled with needle like salt crystals. B = binder; Z = aggregate; Kr = crystal concentration (thaumasite).

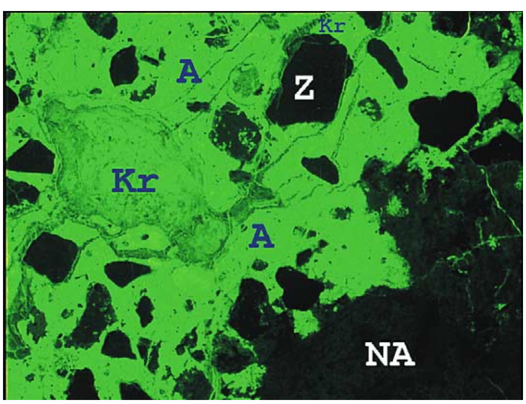

Fig. 4. PFM picture (fluorescence: 2.7×1.8 mm). Concentration of thaumasite. Cracks filled with needle like salt crystals are growing from the concentration. The binder around has suffered from dissolution, which can be seen from the colour (clear difference with the darker colour of the not decayed binder in the right, lower corner of the picture). Z = aggregate; Kr = crystal concentration (thaumasite); A = decayed zone; NA = not decayed zone. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

and of (2) sulfur oxides from the exhaust gases of the diesel-driven engines of the tourist boats; the formation of monochloride was due to the use of hydraulic lime as a binder and the ingress of chlorides from de-icing salts through the bridge deck before it was replaced by a concrete deck.

As a repair measure, in the first place the ingress of water should be prevented. Further all cement based re-pointing mortar and the decayed part of the bedding mortar should be replaced. The use of cement rich in tri-calcium aluminate or hydraulic lime should be avoided in the new re-pointing mortar. Blast furnace slag cement

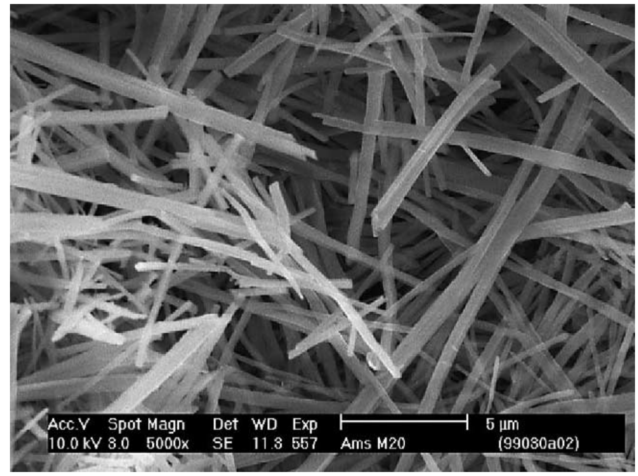

Fig. 5. SEM picture. Massive thaumasite cluster in the binder of the mortar (case study 1).

Fig. 6. Church tower (Noordwijk), case study 2, with both vertical and horizontal cracks.

(bfc) or highly sulfate resistant portland cement could be considered for conservation and the mortar should be applied as a deep re-pointing.

In the case of the church tower the vertical cracks can easily be mistaken for structural cracks. However it was shown that the damaging mechanism consisted of thaumasite formation. The diagnosis was that the backing brick was rich in sulfate. Due to ingress of rain water this sulfate migrated into the bedding mortar of the backing masonry. Here, the sulfate reacted with constituents of the lime-cement to form thaumasite and ettringite.

The presence of those compounds was found using polarising and fluorescent microscopy and SEM/EDAX analysis [2], see Figs. 7–10. These new compounds with large(r) volume made the bedding mortar and thus the backing brickwork expand. The expansion of the backing masonry caused the cracks in the non-expanding exterior masonry.

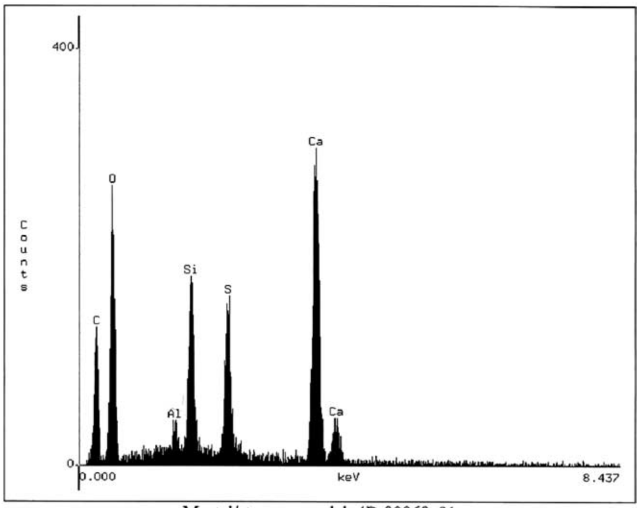

Fig. 7. EDAX-spectrum of mortar-brick interface showing presence of elements of thaumasite, ettringite and maybe calcium silicate (case study 2).

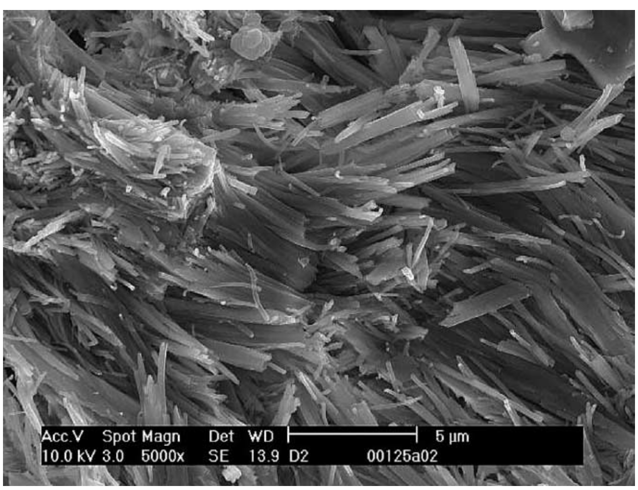

Fig. 8. SEM picture of the thaumasite in the mortar (case study 2).

Fig. 9. SEM picture of the ettringite in the mortar (case study 2).

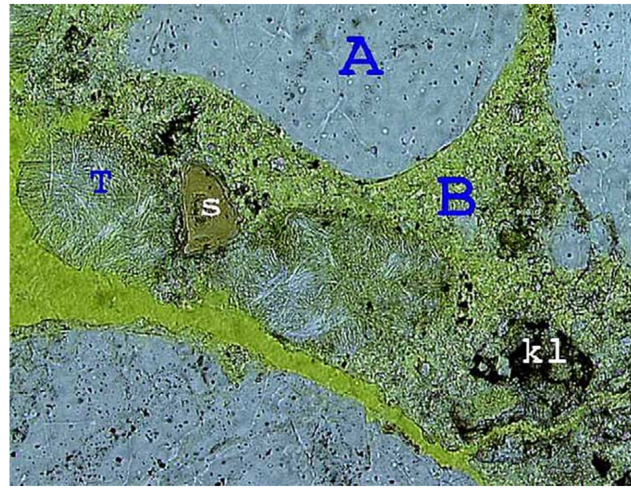

Fig. 10. PFM picture, case study 2. Cluster of thaumasite (T) and crack (solid yellow, i.e. void filled with resin from thin section preparation). B = binder, kl = clinker, s = blast furnace slag, A = aggregate. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

An important consideration for the repair is that the backing masonry is still rich in soluble sulfate and practically no means exist to reduce the ingress of rain water.

3. Laboratory research

There appears to be only limited experience with laboratory research on thaumasite formation in bedding and pointing mortar [3]. The aim of the laboratory research described here was both to investigate the possibilities of the formation of thaumasite in mortars in the laboratory and to develop an adequate test procedure to evaluate the vulnerability of mortars. In this way the risk of thaumasite swelling of specific repair mortars could be tested.

3.1. Criteria test procedure

For the test procedure the following criteria were set:

- The procedure should be able to provoke thaumasite formation in a relatively short time.
- The mortars to be tested should have realistic properties. From [4] it is known that mortar prisms produced in steel moulds show porosity and water absorption values that may greatly differ from those of the same mortar composition, cured on a realistic (for example brick) substrate.

Based on these criteria two different test procedures were followed:

1. *Expansion of mortar prisms*. The expansion was tested by submerging mortar prisms in a 3% sodium sulfate solution. The prisms were sawn from mortar hardened between bricks and had a size of 15×15×160 mm. The temperature of the test solution was kept at 5 °C. The expansion was determined measuring once a week the length of the prisms. This procedure was followed for 15 weeks.
2. *Expansion of masonry*. The expansion was tested on a specimen consisting of a sandwich of two bricks and a mortar joint. The specimen was placed in a climatic cabinet at 5 °C. It was on five sides surrounded by a frame of extruded polystyrene foam, that formed a basin, with the masonry surface as its bottom, that could be filled with the test solution and allowed the absorption of the test solution via the masonry surface. During the first 12 weeks the specimen was allowed to absorb 170 ml of a 3% sulfate solution once a week. After 12 weeks the quantity was increased to 3×170 ml a week. This procedure was followed for a period of 40 weeks.

The effect of the exposure was followed both by visual inspection and by measurement of the prism or specimen length at suitable time intervals. Prisms showing expansion were analysed using SEM/EDAX in order to assess which compounds had formed.

3.2. Types of mortar investigated

Procedure 1 was performed for two different mortar types:

- Hydraulic lime, St. Astiers (1:2.5 by volume). This mortar was expected to be sensitive to thaumasite formation.
- Hydrated lime (bfc:air lime:sand = 1:4:12 by volume), fully carbonated. Blast furnace slag cement was added to create initial strength and for the reason that this type of cement is considered sulfate resistant. Therefore, this mortar was expected not to be sensitive to thaumasite formation.

Procedure 2 was only followed for the St. Astiers, hydraulic lime.

4. Results and discussion

The results of the test on the prisms are shown in the Figs. 11–13. Fig. 11(a) and (b) shows the prisms after 15 weeks of submersion in a 3% sodium sulfate solution; the prisms made with hydraulic lime showed an expansion and a deformation as well as cracks. After 15 weeks of submersion in the sodium sulfate solution, the hydraulic lime prisms started to crumble. The cause of the crumbling was the formation of thaumasite. The presence of thaumasite was assessed, using X-ray analysis and SEM (see Fig. 13).

Fig. 12 gives the increase of length of the prisms over a period of 11 weeks. After 11 weeks the prisms made with hydraulic lime showed an expansion of up to 7‰. The prisms with hydrated lime and blast furnace cement did not expand.

Fig. 13 is a SEM picture of the thaumasite as it was found in the hydraulic lime prisms; it shows the thick needles of thaumasite present in the pores of the crumbled mortar.

The expansion of the brick masonry sandwich was assessed by measuring the distance between 2×3 steel points that were attached to the surface (see Fig. 14). In this case the increase was purely due to the expansion of the bedding mortar.

Fig. 15 gives the results of the test. The given line is the average of the three measurements. The experiment took 40 weeks. After 25 weeks the expansion of the mortar became clear. But after 40 weeks still no cracks were visible in the mortar.

There is a clear difference in expansion between the first (prism) and the second (masonry) test. The prisms had an expansion of more than 1‰ in eight weeks, while the masonry only expanded ≈1‰ in 25 weeks. Therefore, the procedure using the prisms seems quite adequate, the procedure using the sandwich would take too much time.

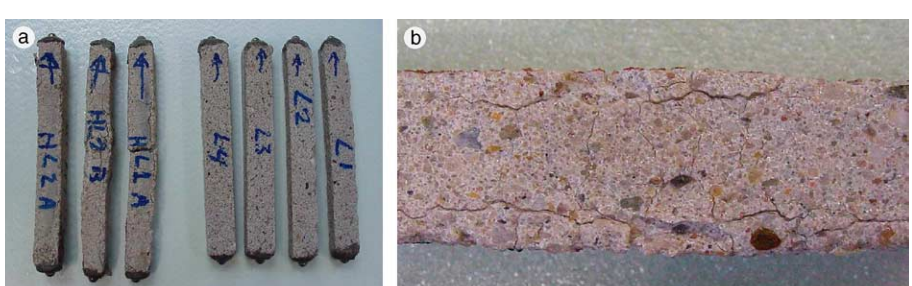

Fig. 11. (a) Mortar prisms after 15 weeks in a sulfate solution. Hydraulic lime based specimens showed expansion and deformation. Hydrated lime in combination with bfc did not show any expansion. HL = hydraulic lime, to the left; L = hydrated lime in combinations with bfc, to the right. (b) A detail of one of the hydraulic lime specimens is given.

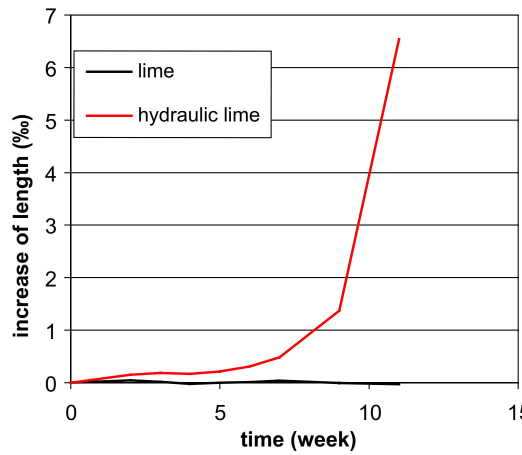

Fig. 12. Increase of length of mortar prisms over a period of 1–11 weeks. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 13. SEM picture of thaumasite in mortar prism based on hydraulic lime.

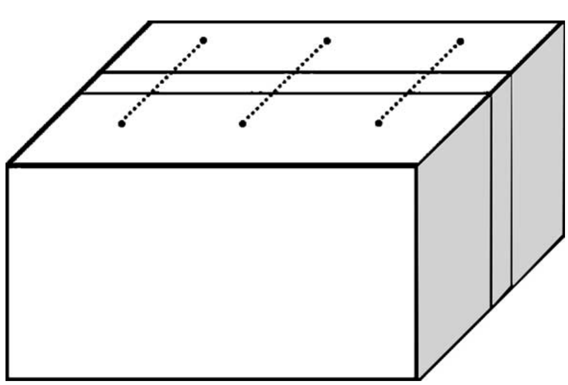

Fig. 14. Masonry specimen. Expansion was measured perpendicular to the joint.

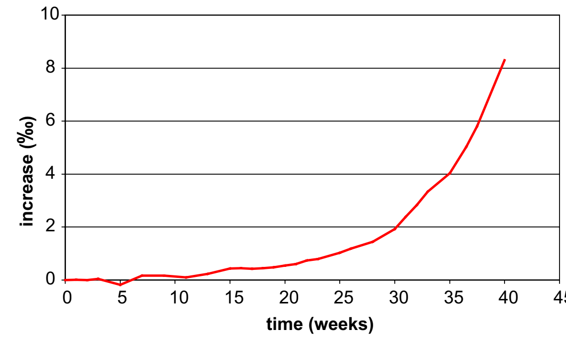

Fig. 15. Swelling of mortar in masonry panel measured perpendicular to the joint and expressed as ‰ of the width of the mortar joint.

The difference in expansion is most probably due to the difference in sulfate and moisture content in the specimens. In the case of the masonry specimen, the moisture and sulfates penetrate from one side, while in the case of the mortar prisms, the moisture could penetrate from all sides.

5. Conclusions

The phenomenon of mortar swelling due to the formation of thaumasite was found to be a recurrent problem in Dutch monuments. The mechanism of thaumasite formation may lead to cracks in masonry, spalling or chipping of brick and bursting and crumbling of mortar. Although measures like prevention of moisture and sulfate penetration should always be considered first, in many situations this is not completely possible. Especially in those situations the choice of a compatible repair mortar is essential for a sound conservation of historic masonry.

The sensitivity of a mortar for thaumasite formation can be tested in the laboratory. A test procedure based on mortar prisms from mortar cured between bricks appears adequate. A test procedure based on masonry sandwiches appeared too time consuming.

Using the procedure based on mortar prisms a hydraulic lime mortar showed a strong expansion and deformation and the formation of thaumasite was assessed; this is in line with the expectation. A hydrated lime, combined with blast furnace cement, that is considered sulfate resistant, showed no deformation in the test, which can be considered a positive indication: This type of mortar could offer a compatible solution for several situations in practice.

5.1. Further research

The experiments performed, showed thaumasite damage on one type of mortar. Further research may give more information on the vulnerability of different mortars (different composition) to thaumasite damage.

A second interesting field of research is the relationship between the amount of sulfate in the brick and the formation of thaumasite. In practice, it may be important to know if, with a given sulfate content in the brick, the risk of thaumasite formation exists.

Acknowledgement

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