Weathering of tuffstone vs. replacement

Background and choices

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Volcanic tuffstone from the Eifel region, Germany, is one of the most important kinds of natural stone used in the Netherlands. These tuffs have, albeit with several hiatuses, been used since Roman times. At several places, original Medieval stones are still present. That does not imply that the stone is completely resistant to weathering: '*The majority of the material that has been used on the oldest churches in the Netherlands ... is Römer tuffstone. None of these buildings still has its original dimensions. Römer tuffstone has a characteristic weathering pattern that after 100 to 150 years the surface layer will detach. The thickness of the spalled layer varies from 6 to 8 mm. A building 800 years of age has become 3 to 5 cm smaller.*' as estimated by Gerard Overeem, then natural stone specialist at the Cultural Heritage Agency of the Netherlands, in an advice dating from 1999. In case the block are large enough, this cause no problem. However, building elements of relatively thin dimensions are not uncommon. The question whether tuffstone has to be replaced in restorations, has appeared a difficult one in recent years (see also Tolboom 2017).

The question whether tuffstone has to be replaced during restorations or not, has shown to be a difficult one over the past years. It is not uncommon that it is proposed to replace the stone, because of the presumption that it will not last till the next restoration campaign. Sometimes, it is tempting, because of costs of scaffolds etc., to replace the stone earlier then necessary. The evident loss of heritage values is apparently accepted without much discussion. The next question arising, after the decision to replacement has been made, is the one of the replacement stone. This contribution gives a brief view on the durability of tuffstone, as background for future choices.

Tuffstone

The historic use, origin and material properties have been discussed in many papers over recent years (see references in other contributions in this volume). Therefore, a brief introduction will be sufficient. The stones in question are volcanic tuffstones from the Eifel region, Germany. Three main groups may be distinguished, viz. Römer, Weibern (including Hoheleie) and Ettringen tuff stone (including Weibern) (Fig. 1).

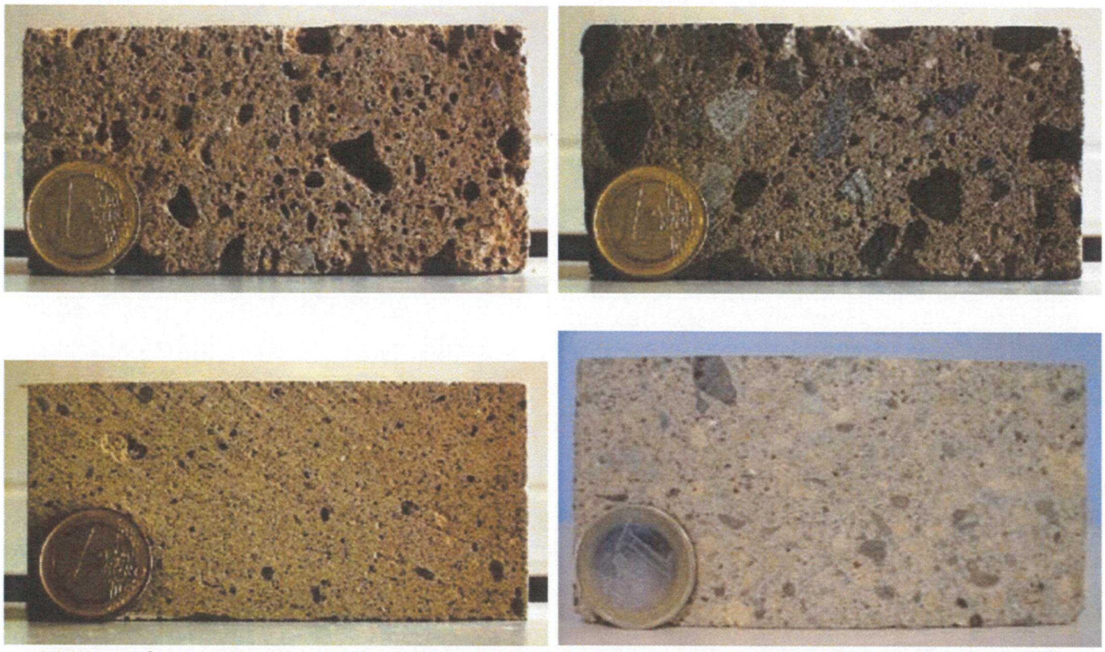

Fig. 1. The main types of tuffstone from the Eifel. Upper left: Römer tuff as used in Medieval times; upper right: Römer tuff with abundant basalt xenoliths, as used in restorations over the past decades; bottom left: Weibern tuff; bottom right: Ettringen tuff.

All Rhenish tuffstones are rocks formed by volcanic ashes, first blown into the air during volcanic eruptions, then deposited on the surface, together with a variable amount of more heavy rock fragments and light pumice fragments. The relative abundance of the components and the thickness of the layers is, amongst others, controlled by the energy of the volcanic eruption, wind direction and speed and gravity. Compaction will be different at different locations, depending on grain size and grading, and thickness of the overburden. This constitutes a variable starting point, even before lithification of the rock. Lithification subsequently occurs under influence of meteoric water, resulting in the formation of zeolites from the volcanic glass. The degree of zeolitization is again variable, depending on the availability of water. It will be clear: in a tuffstone, sources of variation are superimposed on sources of variation. The result is a relatively light and porous rock that has a reasonable strength, easy to quarry, but also with a considerable variation in properties relevant to durability and weathering resistance, such as porosity, pore size distribution, water absorption and drying.

Damages of tuffstone

In Dutch climate, tuffstone may show different types of damage, such as efflorescence, exfoliation (Fig. 2), spalling (Fig. 3), scaling, powdering and cracking. Besides the frequent occurrence of hair cracks, cracking in particular occurs in panels and ornaments with a relatively high length / width ratio. Cracking of panels seems to be a kind of damage mostly associated with Ettringen tuff (Fig. 4), though this may be an artefact of the way different tuffs are used in architecture. Cracking in ornaments with a relatively high length / width ration, such as mullions, occurs in both Ettringen as Weibern tuff (Fig. 5).

Fig. 2. Exfoliation of Weibern tuff directly above the ground level on the Grote Kerk, Oosterbeek (picture R.P.J. van Hees, 2002).

Fig. 3. Spalling of 11th century Römer tuff on St. John's church, Utrecht (picture S. Brendle, 2002).

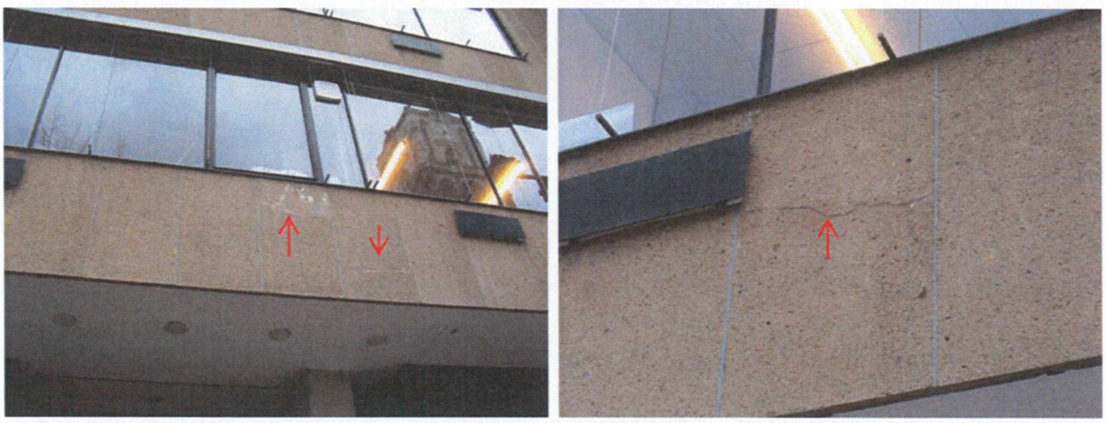

Fig. 4. Cracking in panels of Ettringen tuff at the 1950's office building De Heuvel in Rotterdam (pictures T.G. Nijland, 2006). The panels have been replaced by Muschelkalk during the last restoration.

Fig. 5. Cracking in Ettringen (left) and Weibern (right) mullions at Eusebius' church, Arnhem and St. Peter's church, Leiden, respectively (pictures T.G. 2009 &2005).

Besides this cracking, that is evidently undesirable, occasionally another phenomenon occurs: an elaborate network of craquelé cracks develops in a relatively hard outer layer on the tuffstone, that seems to protect it from further weathering (Figs. 6-8); this seems to occur in particular on Weibern tuff.

Fig. 6 Example of the formation of a hard, dark crust with craquelé on Weibern tuff at a pinnacle of St. John's cathedral, 's-Hertogenbosch (picture T.G. Nijland, 2006).

Fig. 7. Example of the formation of a hard, dark crust with craquelé on Weibern tuff ornaments on the rampant arches of St. John's cathedral, 's-Hertogenbosch (pictures R.P.J. van Hees, 2003).

Fig. 8. Example of the formation of a hard, dark crust with craquelé on Ettringen tuff at the uppermost part of the tower of the Faculty of Architecture, TU Delft (pictures T.G. Nijland, 2014).

Fig. 9. Ettringen (left) and Römer (right) tuff in an accelerated salt crystallization test with Na_2SO_4 after 4 weeks (from Brendle, 2003).

Fig. 10. Ettringen (left) and Römer (right) tuff in an accelerated salt crystallization test with NaCl after 6 weeks (from Brendle 2003).

Damage mechanisms

The explanation for the formation of the hard, dark crust with craquelé has still to be identified. In the formation of other weathering forms, different damage mechanisms may play a role:

Salt crystallization – In particular Weibern and Römer tuff appear to be susceptible for weathering due to dissolution and recrystallization of soluble salts, both in the laboratory as in practice. In the laboratory, Römer tuff shows damage with both NaCl as Na_2SO_4 (Fig. 9, 10). Damage due to these salts is also shown in practice (Fig. 11). In contrast, Ettringen tuff does not even show efflorescence in the same laboratory tests nor any damage (Fig. 9, 10). This results should, however, be treated with some precautions. It is not likely that in this case, salts accumulate behind the surface (cryptoflorescence), and will cause damage on the long term. Field observations do, however, not suggest that this is the case.

Weibern tuff has so far only been tested in accelerated salt crystallization experiments using Na_2SO_4. In these test, clear damage occurs in the form of spalling and powdering (Nijland & Van Hees 2003). Also in practice, this type of tuffstone shows damage due to salt weathering (Fig. 12, 13).

Fig. 11. Salt damage on Römer tuff due to Na_2SO_4 on St. Peter's church, Utrecht (pictures T.G. Nijland, 2010) and St. Lebuïns church, Deventer (pictures T.G. Nijland, 2013).

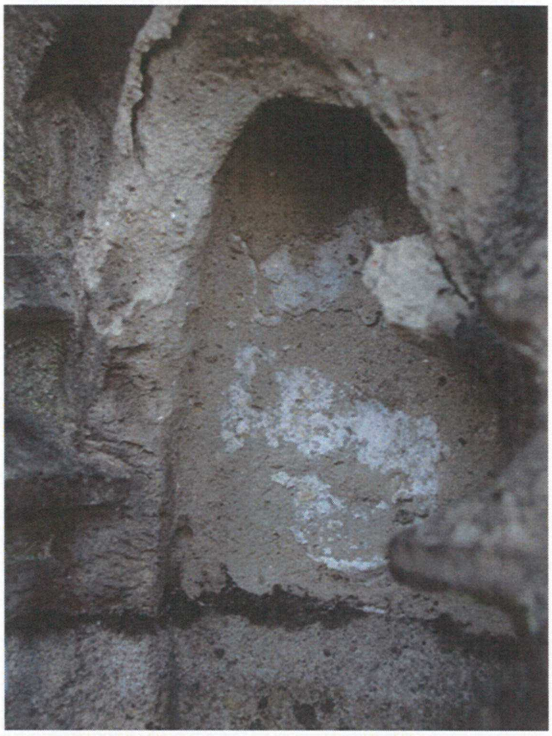

Fig. 12. Salt damage on Weibern tuff due to Na_2SO_4 on a pinnacle on St. John's cathedral 's-Hertogenbosch (picture R.P.J. van Hees, 2002).

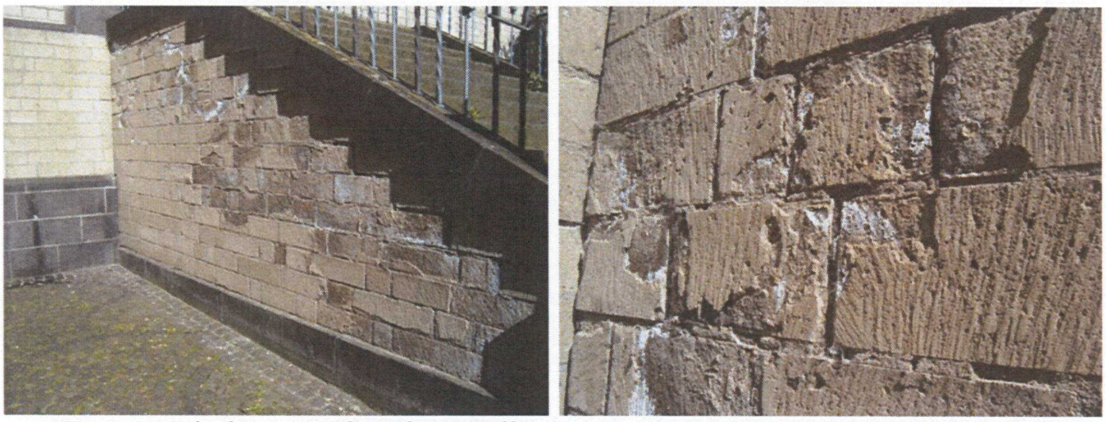

Fig. 13. Salt damage of Weibern tuff, St. Maria im Kapitol, Cologne (pictures T.G. Nijland, 2009).

Freeze-thaw – The occurrence of damage to natural stone due to freeze-thaw cycles depends on several factors, including the number of cycles, the amount of moisture in a stone, the possibilities of a stone to dry, and porosity, pore size distribution and water retention of a stone. TNO has performed several freeze-thaw tests on both Weibern and Römer tuffstone over the years, using the so-called *zandkistvriesproef* according to Dutch standard NEN 2872:1989. Figure 14 shows a compilation of the results of these tests in which also water absorption and density of the stone have been determined. From figure 14, it appears that a relationship exists between the ratio of water absorption versus density and the occurrence of frost damage

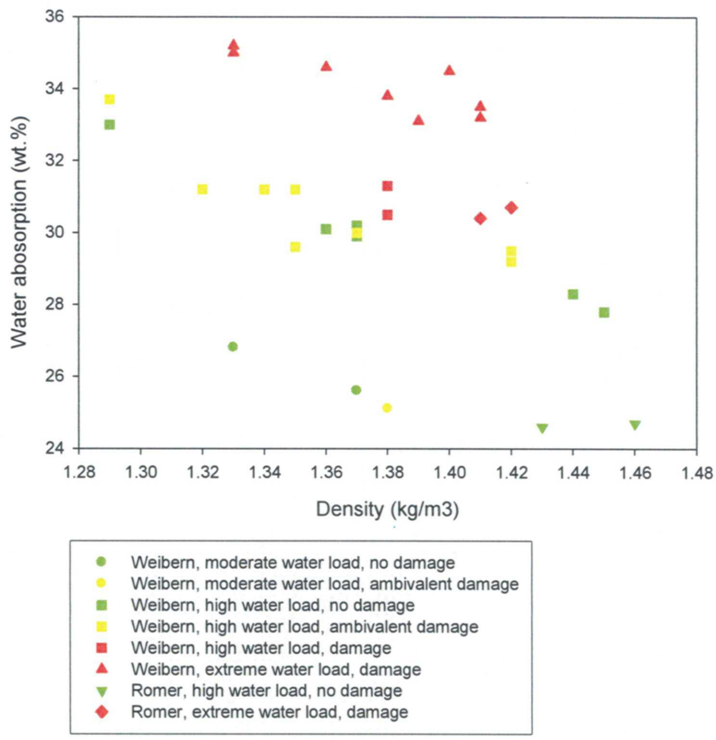

Fig. 14. Compilation of TNO's results with respect of freeze-thaw resistance of tuffstone according to NEN 2872:1989.

Test specimens have been preconditioned at moderate, high and extreme moisture loads according to the standard. At extreme moisture load, both Weibern and Römer tuffstone show typical frost damage (Fig. 15). As far as Römer tuffstone is concerned, damage occurs in the variety with abundant xenoliths, as used in restorations over the last decades. Tests on classical Römer tuff show that, even when preconditioned at extreme moisture load, this tuff can be frost resistant (Nijland & Van Hees 2003).

At high moisture load, Römer tuffstone does not show any damage. Weibern tuff shows sometimes no damage, sometimes ambiguous damage; ambiguous in the sense that evidently, the damage does not follow the typical pattern of frost damage, but, for example, after testing a very narrow vertical hair crack occurs. The same holds for Weibern tuff preconditioned at moderate moisture loads. Given experiences in practice, this ambiguous damage is not considered as frost damage. Weibern tuff in particular has, compared to Römer tuff, a relatively high number of small pores combined with a high porosity (Nijland et al. 2005b). It seems likely that the difference in frost resistance is related to these different pore characteristics.

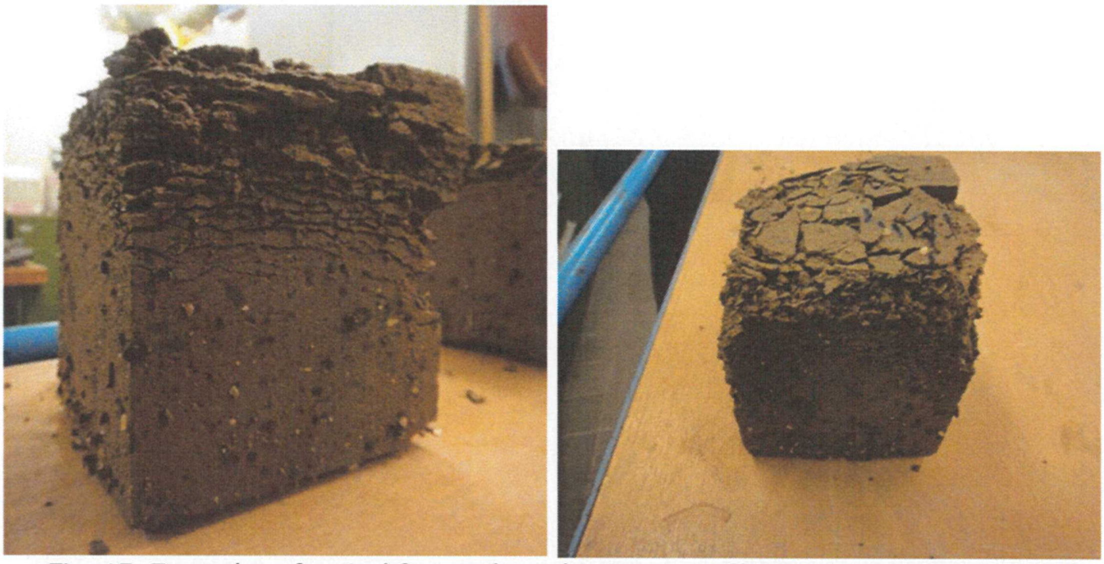

Fig. 15. Examples of typical freeze-thaw damage on tuffstone preconditioned by an extreme water load (pictures T.G. Nijland).

Hygric-thermal expansion – Volcanic tuffstone shows several characteristics that distinguish it from most other types of natural stone: porosity and water absorption are high, but at the same time drying is (very) slow due to the considerable amount of small pores. At the same time, hygric expansion is high compared to most other building materials (Nijland et al. 2005ab, Lubelli et al. 2017). This possibly explains the formation of cracks in tuffstone elements with a relatively high length / width ratio like mullions (Fig. 5). The following damage mechanism may be proposed: The tuffstone becomes (to a large extent) saturated, and by consequence expands. Drying of the part sticking out of the wall is faster than the part of the element surrounded by the masonry blocks. Due to the high water retention, this part stays moist. The part of the element sticking out of the masonry shrinks, whereas the part within the masonry stays expanded. The result will be a shear pressure near the boundary between both parts. Due to repeated wetting-drying cycles, expansion-shrinkage cycles will occur, resulting cracking due to fatigue in the zone with the largest shear pressure (Fig. 16). An alternative version of this hypothesis is the one in which the part within the masonry stays dry, whereas the part sticking out repeatedly shrinks and expands due to wetting-drying cycles, resulting in a similar shear pressure. This type of damage is subject of the paper by Lubelli et al. in this volume.

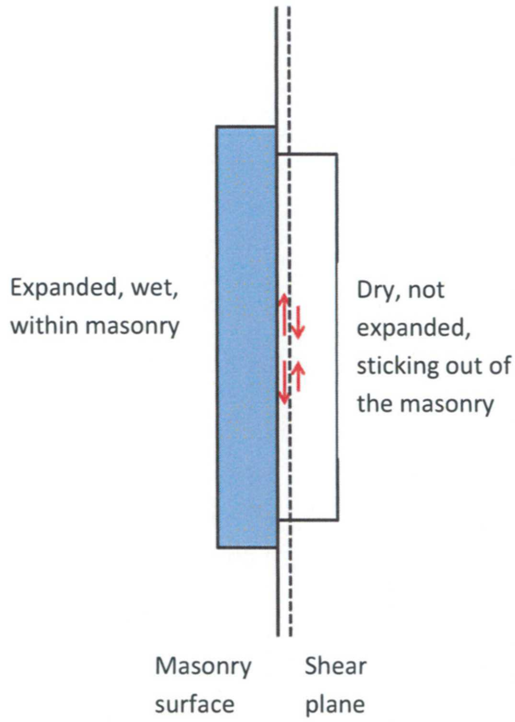

Fig. 17. Schematic picture of the hypothesis of hygric-thermal crack formation in tuffstone.

Discussion and conclusion

Volcanic tuffstone from the Eifel is one of the most important stones of natural stone in the Netherlands. The stone as, albeit with several large time intervals, been used since Roman times. The Netherlands still have several original early Medieval examples of its use. Nevertheless, durability problems are not uncommon. In cases where replacement is unavoidable, the choice whether or not to use tuffstone again is often a difficult one. This is partly due to variation in composition and properties of the stone, which are a consequence of the geological genesis of this type of stone. Nevertheless, the combination of laboratory tests and on site experience give a first practical guidance:

- Römer and Weibern tuff are both susceptible to salt damage; under such conditions, they will develop powdering, scaling or spalling. This seems not, or to a lesser extent, to be the case with Ettringen tuff.
- Römer and Weibern tuff are both frost resistant under a high moisture load; some layers of 'classic' Römer tuff are also frost resistant under an extreme moisture load.
- A relatively large length / width ratio, in combination with the partially sticking out of a tuffstone element, may possibly cause formation of cracks. For such applications, the tuffstone may be less suitable.

In order to obtain better understanding of damage and the (remaining) service life, it is important to get answers to the following questions:

- How is the hard crust with craquelé formed on some kinds of tuffstone ?
- Is the hypothesis regarding hygric-thermal expansion as cause of crack formation in elements with a relatively large length/width ration correct ?
- What is the relationship between porosity and pore structure of tuffstone and its resistance to freeze-thaw or salt damage ?
- What parameters are suitable for the assessment of the quality of tuffstone ?

Answering these questions would considerably help to conserve tuffstone heritage, that sometimes proves to have a quite acceptable durability (Fig. 17, 18).

Fig. 17. Sculptures in Römer tuff dating back to about 1200 in the Kompfporte, Andernach (picture T.G. Nijland, 2009).

Fig. 18. Ettringen tuffstone sculptures at the façade of Schiedamse Vest 89, Rotterdam, renovated by architect J. Wils in 1942 (pictures T.G. Nijland, 2010).

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