Teplá trachyte weathering phenomena and physical properties of a rare volcanogenic building stone

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Abstract: One of the few deposits of trachyte suitable for dimension stones is situated in the Western Czech Republic, 6km east of the town of Teplá. The buildings of the famous monastery of Teplá are the best example of the use of Teplá trachyte over more than 800 years.

Teplá trachyte is being exploited in a single quarry on the slopes of the nearby Spicák hill. The trachyte is known to have been quarried from the 12th century onwards. The Teplá trachyte is still an important, very good and stable dimension stone which has been used as intersection material in historical buildings like the cathedral of Xanten and in various towns in the Netherlands. Modern facades like the university hospital in Pilzen consist of trachytic slabs from Teplá.

Alkaline massive volcanic rocks with a bright appearance are fairly rare in Europe. Trachyte consists mainly of fine grained alkalifeldspar and plagioclase with phenocrysts of sanidine. Accessoric minerals are biotite, titanite and magnetite. The Teplá trachyte is comparable to those of the Euganean Hills (Italy), the Auvergne region (France), the Rhine province and Westerwald (Germany). Very characteristic features are the thick black manganese-oxide dendrites. The volcanism of the Teplá trachyte occurred some 12.5 million years ago in the context of the faulting along the Ohre (Eger) rift in the western part of the Bohemian Massif.

The decay of trachyte dimension stones originates mainly in the disintegration of the rock caused by the alteration of the feldspars into the clay minerals kaolinite, illite and vermiculite. This leads to typical damage such as flaking, scaling, alveolar weathering, clearing out of sanidines and manganese-oxide dendrites and different discoloration effects.

Based on the chemical and mineralogical composition and the physical properties of the trachyte an adequate consolidation concept using a TEOS modular system was developed.

Résumé: Un des rares gisements de Trachyte approprié à la construction de pierres de grande dimension, est situé dans l'Ouest de la République Tchèque, à 6km à l'Est de la ville de Tepla. Les bâtisses du célèbre monastère de Tepla sont le meilleur exemple de l'utilisation de ce Trachyte sur plus de 800 ans.

Le trachyte de Tepla est exploité dans une seule mine située sur les flancs de la colline voisine de Spicak. Ce dernier est extrait depuis le 12éme siècle. Le trachyte de Tepla est encore aujourd'hui une importante et très bonne pierre de grande dimension. D'une grande solidité, elle est par exemple utilisée en tant que matériel de jointure dans des constructions historiques comme la cathédrale de Xanten de même que dans différentes villes des Pays Bas. Des façades modernes telles que celle de l'hôpital universitaire de Plzen sont également constituées de dalles de trachyte de Tepla.

Les roches alcalines volcaniques massives et d'apparence brillante sont assez rares en Europe. Le trachyte est constitué prioritairement de feldspath alcalins fins et granuleux et de plagioclase avec des phénocristaux de sanidine. D'autres composants accessoires sont la biotite, la titanite (sphène) et la magnétite. Le trachyte de Tepla est comparable à ceux des monts Euganéens (Italie), de la région auvergnate (France), de la province rhénane ainsi que du Westerwald (Allemagne). Des éléments très caractéristiques sont des dendrites d'oxyde de manganèse noires, d'une épaisseur pouvant aller jusqu'à plusieurs mm. Le volcanisme du trachyte de Tepla est apparu il y a quelques 12.5 Millions d'années lors de la création de failles tout le long de la crevasse de Ohre, appelée également Ohre rift, située dans la partie ouest du massif de Bohème.

L'amoindrissement de pierres de trachytes de grande dimension est dû en grande partie à la désintégration de la roche par l'altération des feldspaths en minéraux argileux tels que la kaolinite, l'illite et la vermiculite. Cela entraîne des dommages caractéristiques, comme le feuilletage et l'écaillement, l'érosion alvéolaire, le dégagement des sanidines et des dendrites d'oxyde de manganèse de même que différents effets de décoloration.

Un concept adéquat de consolidation utilisant un système modulaire TEOS a été développé. Celui-ci se base sur la composition chimique et minéralogique ainsi que sur les propriétés physiques du trachyte.

Keywords: classification, compressive strength, igneous rock, mapping, porosity, weathering.

INTRODUCTION

The Premonstratensian Teplá monastery (see Figure 1) was founded in the 12th century by the Bohemian nobleman Hroznata in Western Bohemia, which belongs today to the district of Karlovy Vary. It is considered to be one of the most famous architectural monuments in the north-western part of the Czech Republic. The oldest parts of the building complex, for example the church, can be dated back to the year of the foundation, 1193.

Different phases of construction were necessitated by many fires, rebuilding, extension and subsequent renovation and restoration. After a devastating fire in the year 1659, major parts of the monastery were reconstructed by the famous Bavarian-Bohemian Baroque architect Christoph Dientzenhofer. The Teplá monastery was not affected by secularisation as were most of other Central European monasteries, and was therefore continuously renovated and extended (Lehrberger & Gillhuber 2004). In the years 1930/1931, many building stones which had been damaged by fire or weathering were replaced in the facade of the church. Only a minor part of the original material is now preserved. Vast amounts of damage to the complex were caused by the troops of the Czechoslovakian army in the years from 1950 to 1990. Only the church and the library were protected as cultural monuments. Since the monastery was given back to the Premonstratensian in the year 1990, a series of restoration activities have been undertaken.

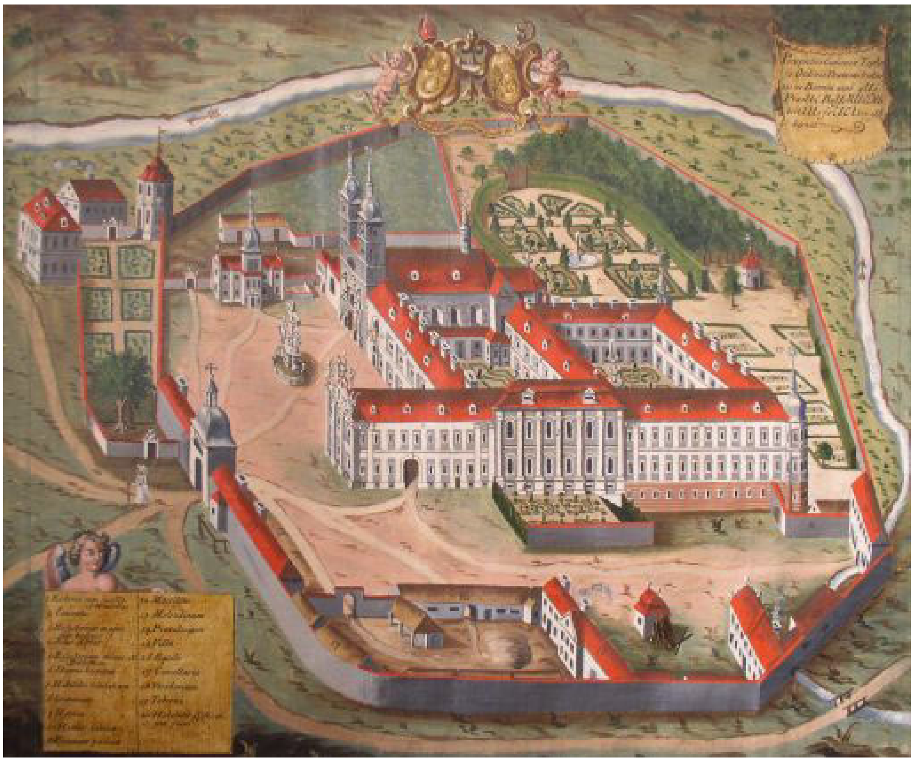

Figure 1. Coloured engraving of the monastery Teplá dated to the year 1735 (in the ownership of the monastery).

DEPOSITS OF TRACHYTE

Deposits in Central and Southern Europe

In the following compilation (Table 1), which only includes true petrographic trachytes, the emphasis lies on trachytic deposits which could be usable for the dimension stone industry.

Table 1. Deposits of trachyte in Central and Southern Europe with name and age.

Deposits in Germany	**Name**	**Age**	**Deposits in Italy**	**Name**	**Age**
Siebengebirge, Rhine province	Drachenfelstrachyt, Figure 2	Miocene	mine of Zovon di Vò, Euganean Hills near Padua	Trachite Zovonite "Grigia Antiacida"	Oligocene
Reimerath (Mayen), Rhineland-Palatinate	Reimerath-Trachyt	Eocene	mine of Zovon di Vò, Euganean Hills near Padua	Trachite Zovonite "Calda Variegata", Figure 3	Oligocene
Selters, Westerwald	Selters-Trachyt	Oligocene			

Figure 2. Drachenfels trachyte, Germany with phenocrysts of sanidine (size of sanidine: 4cm).

Figure 3. Trachite Zovonite "Calda Variegata", Italy. Brownish variety of Trachite Zovonite "Grigia Antiacida" with its typical brown striae of limonite. The phenocrysts consists mainly of feldspar (full-scale).

Deposits in the Czech Republic

Geological setting

The Teplá monastery is situated almost on the border between the metamorphic Teplá complex and the metamafic to ultramafic Marianské Lázne complex (Lehrberger & Gillhuber 2004). The weak alkaline trachytic volcanism in this area occurred during the Miocene between 15.9 and 11.4 Ma (Ulrych *et al.* 2002). There are three deposits of trachyte in this area: Spicák hill (12.5 Ma), Prachomety hill (11.9 Ma) and Trebounský hill (12.1 Ma). The volcanism occurred in the context of the faulting along the so-called Ohre rift (Egergraben) in the western part of the Bohemian Massif.

Quarry and usage

The active quarry at Spicák hill was originally owned by the monastery, 3km to the west. The trachyte at this site occurs in a dome-shaped formation as is typical for a subvolcanic intrusion (Figure 4). The quarry has been active since the construction of the Teplá monastery in the year 1193. Teplá trachyte is an important, stable and very good quality and dimension stone. Famous historical buildings where it has been used (mainly as intersection material) include the cathedral of Xanten (Figure 5) and many buildings in the Netherlands. The Teplá trachyte is also widespread in the Netherlands. Trachytic slabs are used in the facade of modern buildings like the university hospital of Pilzen.

Figure 4. Panoramic view of the large, active Spicák quarry east of Teplá monastery. The quarry is run by a Czech-German joint venture company.

Figure 5. Cloister and part of the Cathedral of Xanten, Germany.

TRACHYTE

Petrography

The so called Stenská-trachyte or Tepla-trachyte (Müller 1997) which is quarried at the Spicak is one of the acidic neovolcanic stones of the Bohemian Massif with a strong alkaline character: alkalitrachyte. The colour varies from light grey to yellowish-beige, alternating in the quarry with greenish colours (Figure 7). The groundmass is dense to fine-grained. Typical for this trachyte are brownish striae and black manganese-oxide and hydroxide dendrites (Figure 6, 7 & 8). The genesis of these phenomena is related to secondary precipitation from hydrothermal circulation.

The trachyte consists mainly of fine-grained alkalifeldspar and plagioclase with insets of sanidines up to a size of 12mm. Smaller quantities of biotite, Mn-oxides and Fe-oxides were found. Accessories are titanite, apatite, magnetite, goethite and hematite.

Figure 6. Slab of a typical yellowish-beige trachyte from the quarry (full-scale).

Figure 7. Trachytic block with brownish striae, black manganese-oxide and hydroxide dendrites and greenish colour (size: approx. 20cm).

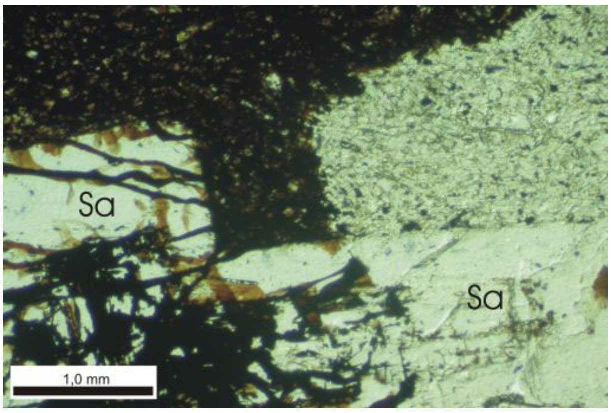

Figure 8. Sanidine-phenocrystes in a dense alkalifeldspar groundmass. Mn-oxides diffused along the micro-cracks and cleavage faces of the sanidine crystals.

Trachytic dimension stones

The best example of the use of trachyte in more than 800 years is the monastery of Teplá. 95% (1723 stones) of the western facade of the church has been built using trachyte (Figure 9). Dimension stones of conglomerate (5%) were used for the base of the church and for replacements.

Classification scheme and weathering forms

A classification scheme of weathering forms was developed for trachytic dimension stones on the western facade of the church. This scheme is based on the established classification scheme of Fitzner *et al*. (1995). Due to different periods of restoration a lack of original material from 1193 in the wall of the church is obvious. That is one of the reasons why different weathering forms occur side by side in the facade. Another reason for variation is inhomogeneity in the rock itself (see Figures 6 & 7).

In Figure 10 the variation in weathering is illustrated graphically. The predominant colour is green which represents the decay form 'relief'. Relief means a change in the morphology of the stone surface due to partial or selective weathering. The white coloured and black dotted blocks do not show any signs of weathering. The original surface shows point chisel marks which derive from the restoration period 1930/1931. Other important weathering forms are various degrees of flaking (yellow, orange and red colours). These decay forms only appear in the uppermost millimetres to centimetres of the stone surface. They are mainly caused by the treatment of the stone cutters. The adjusted feldspars were cleaved by the mechanical stress (Figure 12; Gillhuber 2005). After the flakes and scales are removed a relatively stable surface of trachyte appears.

Other weathering forms which could be seen on the dimension stones are:

- Alveolar weathering: rare weathering form on trachytes.
- Clearing out of sanidine, Mn-oxides and hydroxides: loss of the matrix due to granular disintegration into sand or flaking.
- Frame formed weathering as a combination of flaking and scaling: form is caused by an improper use of non-flexible cement mortar.
- Notching: precipitation fronts of circulating dissolutions and hydrothermal alteration fronts with greenish colour in the trachyte (see Figure 7) vulnerable to weathering.
- Brownish discolouring: observed on newly intersections.

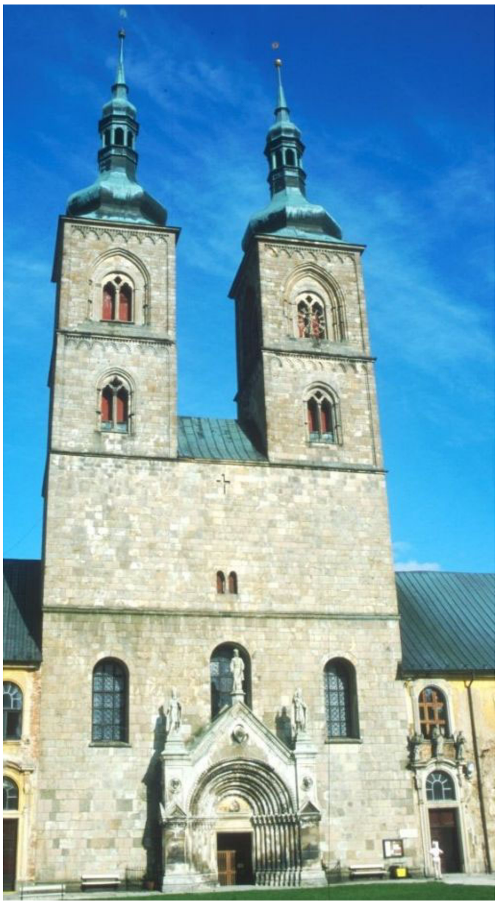

Figure 9. Nearly the whole western facade of the monastery Teplá is built of trachyte.

The next step after mapping the decay types is to classify them depending on the time which is necessary to restore the blocks and the urgency (Figure 11). Restoration measures are not necessary for the white blocks. The colours can be compared to traffic lights. Red means 'dangerous'. These are the blocks with the worst decay excluding intersections, which would be presented in violet colour. Approximately 2/3rds of the mapped blocks are almost unweathered and can be restored by easy and quick measures.

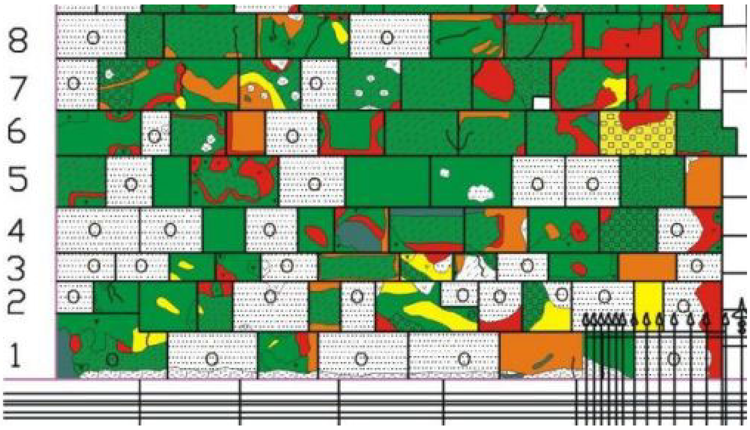

Figure 10. Mapping of weathering forms on the lower part of the western facade of the monastery church (cp. Figure 9). Simplified explanation of the colours: green (relief), yellow (flaking), orange (flaking due to scaling), red (scale), grass-green (soiling), white with black dots (technique of workmanship with a point chisel), black line (fissures).

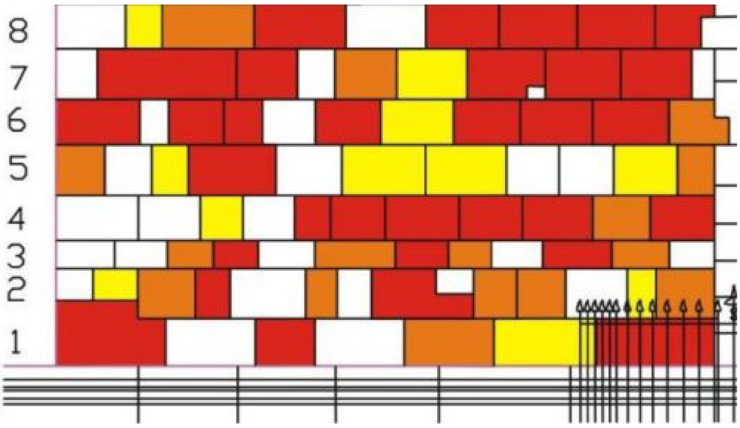

Figure 11. Decay classification, based on Figure 10. The different colours of the blocks present different kinds of restoration measures. They are dependent on the factor of time. Explanation of the colours: white (no procedure necessary), yellow (no to minimum action required), orange (middle action for flaking and granular disintegration into sand over stable grounds), red (partial washed surfaces).

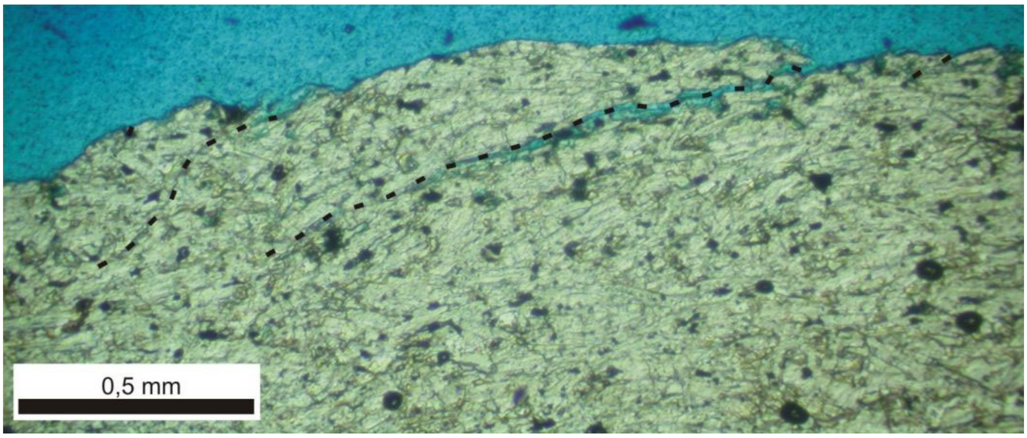

Figure 12. Thin section of trachyte embedded in colour resin under vacuum. After chiseller like treatment micro-cracks can be seen on the surface of the trachyte which are parallel to the fluidal feldspar orientation. The weathering process of scaling and flaking is accelerated by the infiltration of solutions.

An interesting form of decay was found on the southern facade of the church. The trachytic blocks show an intense red colour which was caused by fire (Figure 13). After a detailed examination of the facade showed cavernous scaling sometimes several centimetres thick. This scaling derived from thermal stress in the stone which was caused by the heat of the fire. Samples for scanning electron microscopy (SEM) were taken to confirm this assumption. The area near the surface of the trachyte blocks shows intense heating features such as molten feldspars. Combined with this phenomenon are melt globules (Figure 14) originating from the melting of silicate minerals in the trachyte. A major difference to fly ash pellets are the development of sinter necks and sinter crusts.

It can be deduced from this research that the trachyte dimension stones on the southern facade derive from the 17th century because the whole church was on fire in the year 1659. The observed fire damage was caused by another conflagration in the year 1677.

Selected physical properties

UCS

Compressive strength tests were carried out on cylindrical samples with L:D=2:1. The test and the analysis of the results was carried out with a computer controlled compressive machine "TONINORM" and datalogger Spider 8, following the reference of Mutschler 2004. The uniaxial strength of around 86.4 MPa for two different rock types of the Spicák quarry (a yellow and grey trachyte) is classified as 'high' according to ISRM 1978. All samples show a brittle failure.

Figure 13: Southern facade of the church with reddened trachyte dimension stones.

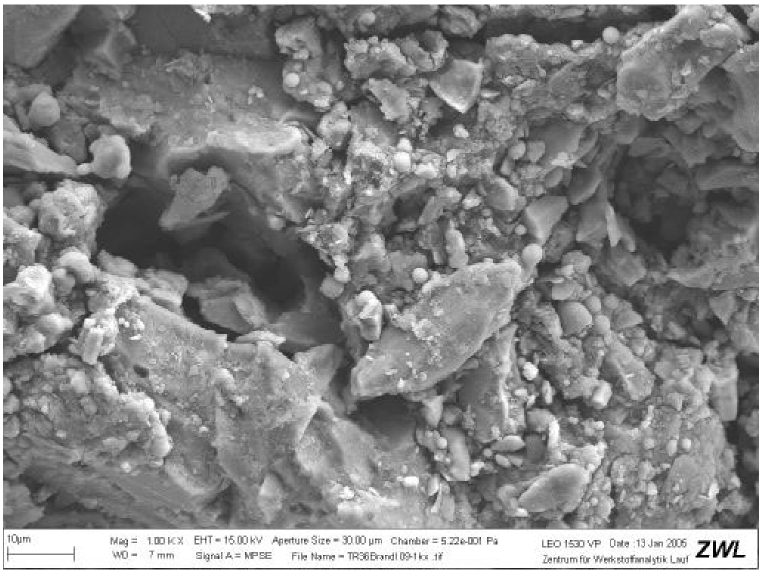

Figure 14: SEM-Picture. The sample was taken from the southern facade of the church and shows melt globules on the inner side of the scale. They derive from the melting of the silicates during the burning of the church.

Cyclic salt crystallization test with sodium sulphate

Salt weathering tests were performed according to the DIN EN 12370 (1999). The cylindrical samples (L:D=2:1; length: 100mm/50mm) were left in a 14% sodium sulphate-10-hydrate solution for 2 hours. Afterwards they were dried for at least 16 hours in an oven at 105°C. After cooling the samples were stored in a water bath for 24 hours and dried in the oven till a constant mass was reached. The change of mass was determined after a cooling phase of at least 2 hours.

Specimens from different blocks of the quarry were prepared for the crystallisation test. Care was taken to choose homogeneously looking blocks. An average of five samples were taken out after each cycle. Before the water bath, a constant increase of the mass could be observed with the exception of block no. 2 which constantly lost weight from the 8th cycle onwards (Figure 15). Another exception was block no.4, which lost weight after the first cycle and then gained weight similarly to the other specimens.

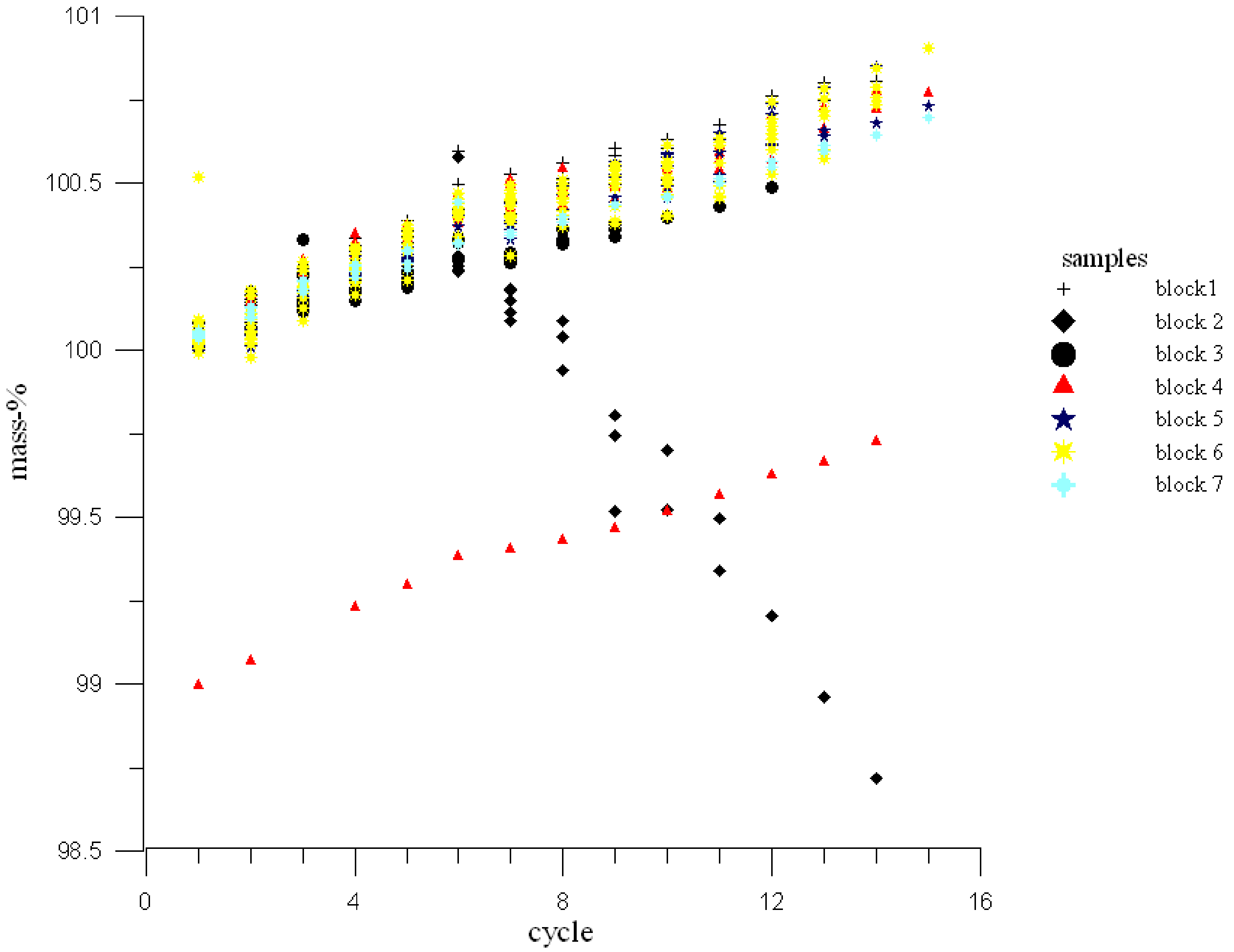

Figure 15. Behaviour of samples from different blocks after the cyclic salt crystallization test with sodium sulphate and before the water bath.

Three different phenomena could be noticed after storing the samples in the water bath for 24 hours (Figure 16). Group 1 started to continuously lose weight after the 7th cycle onward. A granular disintegration into sand of yellowish-whitish feldspars caused the loss of weight (33.0% from the original weight). The second group began to lose around 2.5% of the original weight after the 8th cycle. The deficit of mass originated in the development of cracks parallel to the axis of the specimen and the chipping of a 6mm thick scale on the top of the sample. The third and last group showed a continuous gaining of weight till the 15th cycle. After another cycle they also started to lose a minimum of 0.1% of their original weight due to granular disintegration into sand, caused by weathered yellow feldspar crystals.

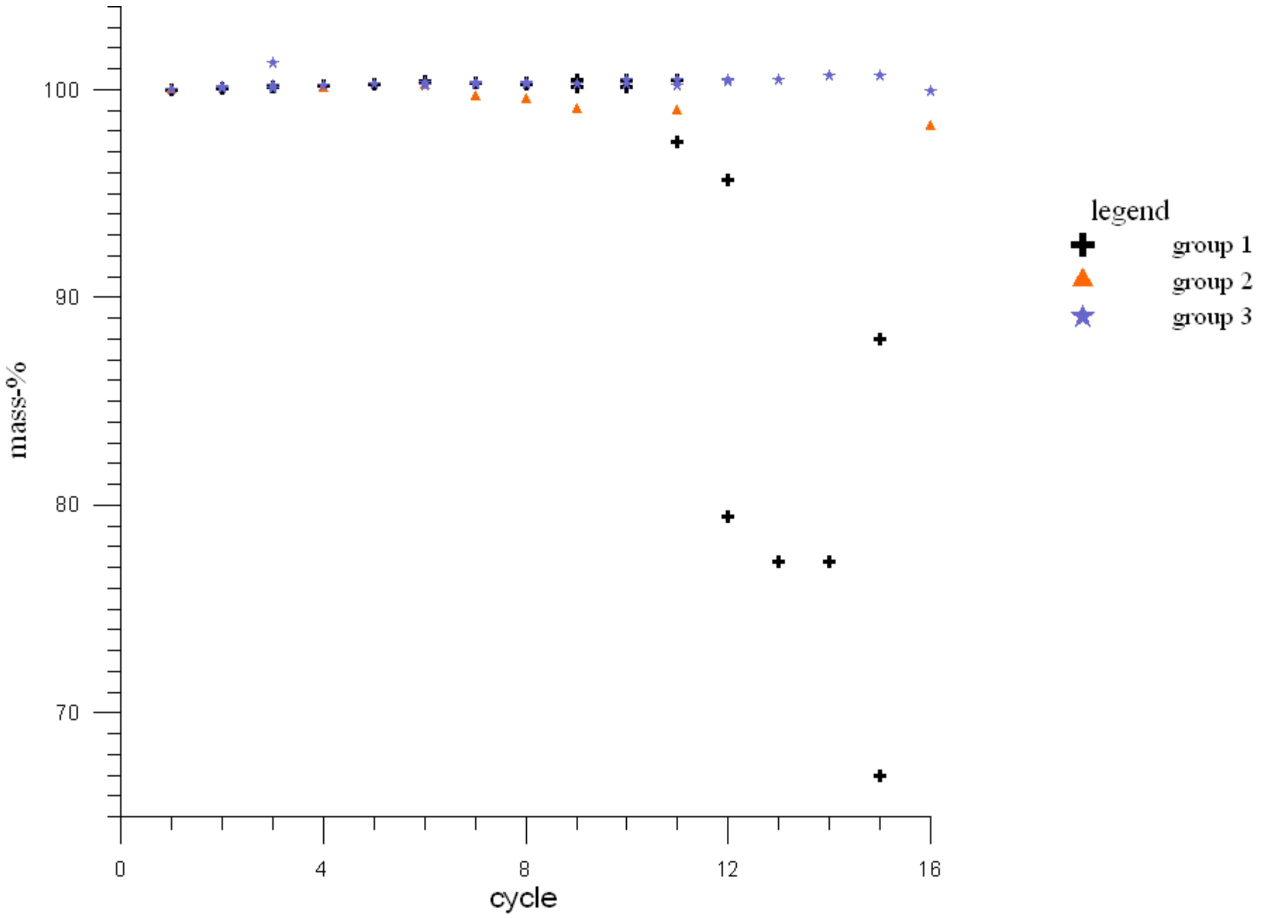

Figure 16. Classification of the samples in regards to their behaviour of gaining, losing or holding mass in three groups. After each cycle, the specimens were stored in a water bath for 24 hours as described in DIN EN 12370 (1999).

Porosity and pore size distribution

The determination of the pore size distribution was performed by means of mercury-porosity on cylindrical specimens. Every capillary radius has its own pressure at which the mercury enters the pores allowing the pore size distribution to be graphed. The measurements showed a total porosity of around 9.4% by volume for the Teplá trachyte (Figure 17).

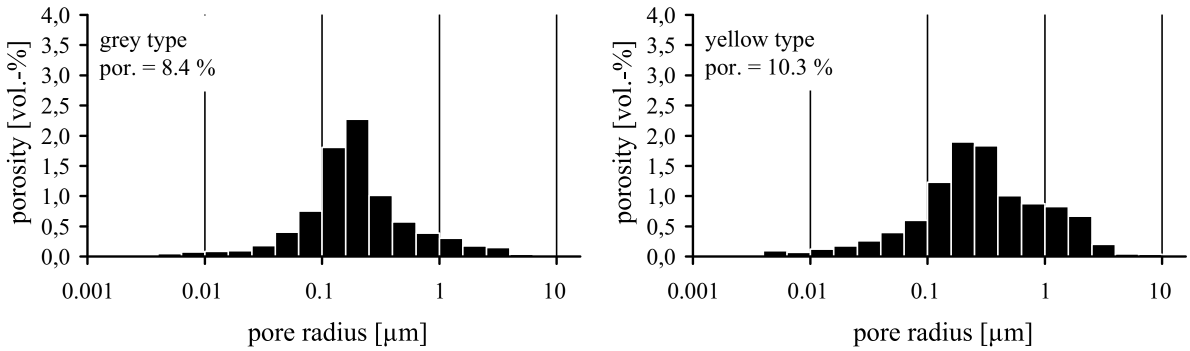

Figure 17. Porosities and pore size distribution of two different types of Teplá trachyte.

CONCLUSION

The trachytic dimension stones were damaged in the region of Teplá through harsh climatic conditions and their vicinity to the brown coal processing industry in the Ohre rift. Although different forms of weathering could be observed on trachytic elements, a decay classification shows that only a minor portion needs an intensive restoration procedure. In laboratory testing, even though a preselection at the quarry excluded the greenish trachytic dimension stone, the other apparently homogenous stones show varying physical properties. Of particular interest are the different behaviours of the samples during the cyclic salt crystallisation test where the damage (loss of weight) could be observed in three different patterns. Further investigation of these phenomena will be carried out.

Very important for the restoration is the porosity. A low porosity of 9.4% on the one hand suggests a low fluid permeability which prevents the infiltration of water into the stone. On the other hand it causes problems for the conservation since the sealant cannot percolate through the stone.

A conservation concept based on the TEOS modular system was developed based on the derived physical properties. Guidance has been given on the different work steps conservation and completion both using a similar adhesive cement. Also working with only short interruption times was shown to be possible.

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