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The laboratory investigation of concrete affected by TSA in the UK

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Abstract

Procedures that have been successfully employed by Geomaterials Research Services Ltd. in the determination of the distribution of the thaumasite form of sulfate attack (TSA) in concrete samples taken from bridge and other motorway structures throughout the UK are described. Electron microprobe analysis has been used to provide confirmation of the presence of thaumasite and to investigate the distribution of sulfate compounds including gypsum and ettringite in cement paste at the surfaces of concrete affected by sulfate attack. Electron microprobe analysis has the advantage that it is capable of detecting very small quantities of thaumasite. Electron microprobe analysis used in conjunction with petrographic analysis is regarded as the most effective tool for the diagnosis of TSA and other forms of sulfate attack.

The analysis of numerous cores taken from bridge foundations throughout the UK shows that the development of TSA is often accompanied by the formation of calcium carbonate in cement paste. High levels of chloride in the cement paste of TSA damaged concrete suggest the importance of run-off moisture as a contributory factor in the development of TSA.

Keywords: Sulfate attack; Thaumasite; Petrography; Concrete deterioration

1. Introduction

Since 1998, more than two hundred concrete core samples taken from a substantial number of motorway bridge foundations and related structures from many locations throughout the UK have been examined. Petrographic and electron microprobe analysis carried out on concrete samples removed from a 29-year-old M5 motorway bridge foundation in 1998 showed up some of the most severe thaumasite-related concrete deterioration of any structures we have so far examined in the UK. In the concrete samples examined from the surface of this buried structure, some 40–50 mm of concrete had been softened to such an extent that the concrete could be scraped away using hand tools. This paper describes some of the techniques employed in the analysis of the samples and also provides an overview of some of the results obtained.

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2. Laboratory testing

2.1. Sampling

It is often the case with concrete damaged by thaumasite form of sulfate attack (TSA) that the transition from sound concrete to very substantially deteriorated concrete that has undergone TSA is very sharp and there is a risk that in taking core samples from such concrete, loss of the deteriorated concrete could result. It is therefore necessary to take particular care in the taking of core samples from concrete suspected of being damaged by TSA or other forms of sulfate attack. In particular, it is often desirable to remove by hand any surface material for laboratory analysis. It is of course also essential that careful observations are made of the concrete surface prior to the removal of core samples.

2.2. Preparation of samples for analysis

Special precautions are also required in the laboratory preparation of deteriorated concrete for thin section and electron microprobe analysis. The techniques employed at Geomaterials commence with the careful drying at room temperature of the surface concrete prior

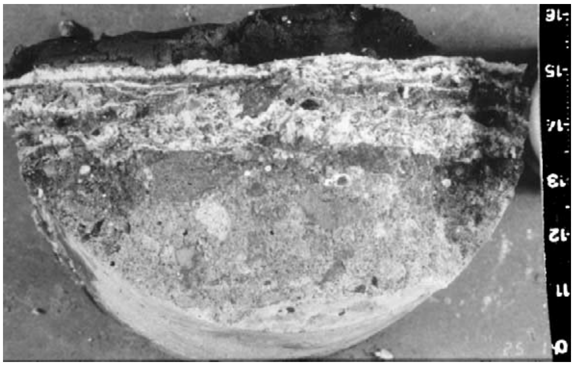

Fig. 1. Thaumasite damaged concrete core (scale bar is divided into centimeters and millimeters).

to the vacuum-impregnation of the surface concrete with a low temperature curing and low viscosity epoxy resin. Only after the samples have been impregnated can the preparation of thin sections and polished surfaces begin. Where conventional wet chemical analysis for sulfate or chloride is required on the same core as petrographic analysis, the samples are split longitudinally using a hydraulic rock splitter setting aside one half of the core for chemical analysis. The typical appearance of some of the more severely damaged samples examined is illustrated in Fig. 1.

2.3. Methods of analysis

Petrographic analysis is probably the most versatile and cost effective technique in the analysis of concrete suspected of being damaged as a result of sulfate attack. Some of the types of information that can be gained from the routine petrographic analysis of concrete are summarised in Table 1.

Using thin sections it is possible to map out the large-scale distribution of deterioration and also to investigate in detail features such as microcrack development and changes in porosity. Four stages are commonly seen in the development of TSA, these stages have been classified into 'Zones' of deterioration [1,3] and are described in Table 2. Fig. 2 illustrates the typical appearance of Zone 3 TSA as seen in thin section. Fig. 3 shows a much lower magnification view and illustrates the large-scale distribution of thaumasite-related cracking in dolomitic limestone coarse aggregate and in the surrounding paste near the surface of a concrete core exhibiting Zone 3 and Zone 4 TSA.

Two of the most common reaction products that are found in concrete that has undergone sulfate attack are ettringite and thaumasite. These two minerals cannot

Table 2
Stages in the development of TSA [3,4]

Zone 1	Needles of thaumasite and occasional crystals of ettringite within voids
Zone 2	Thin cracks infilled with thaumasite
Zone 3	Wide cracks infilled with thaumasite and haloes of thaumasite around coarse and fine aggregates
Zone 4	Cement paste replaced by thaumasite

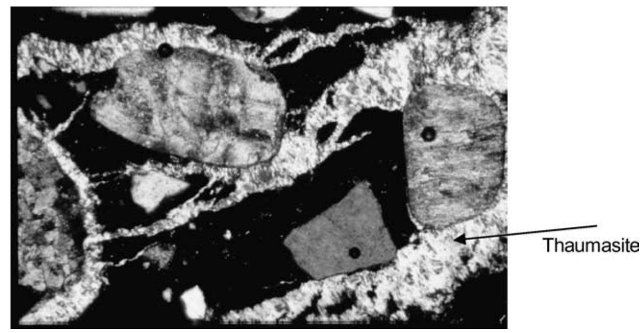

Fig. 2. Zone 3 TSA in thin section (width of view 1.5 mm), crossed polars.

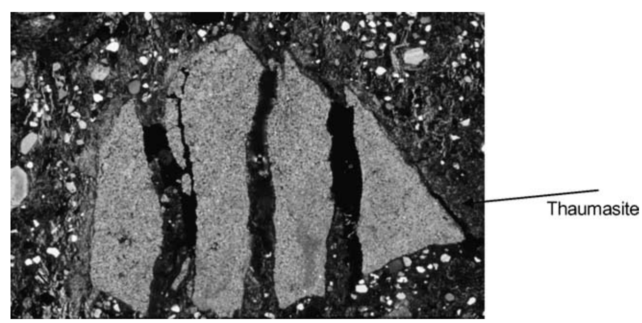

Fig. 3. Thaumasite-related cracking in a dolomitic limestone particle (width of view 22 mm), crossed polars.

Table 1
Summary of the types of information provided by petrographic analysis

1. Determination of the maximum depth of deterioration
2. Classification of the severity of thaumasite-related deterioration based on Fig. 5.1 of the Report of the Thaumasite Expert Group [1]
3. Determination of the composition of the concrete including water/cement ratio and cement content
4. Identification of aggregate type and classification of the 'Carbonate Range' of the combined coarse and fine aggregates based on Table 9.1a of the Report of the Thaumasite Expert Group [1]
5. Identification of other forms of deterioration such as ASR or leaching
6. Determination of the general condition of the concrete at depth
7. Estimation of compressive strength of the concrete from petrographically determined composition and void content

Table 3
Comparison of the chemical compositions of ettringite and thaumasite [4]

	Ettringite	Thaumasite
SiO_2	0.0	19.4
Al_2O_3	15.0	0.0
CaO	49.5	54.5
SO_3	35.5	26.1

Note: Compositions are normalised to 100% and exclude CO_2 and H_2O.

always be unambiguously distinguished from the analysis of thin sections alone and it is for this reason that petrographic analysis should be supplemented with either electron microprobe or X-ray diffraction analysis. In the examination of concrete damaged by TSA, extensive use has been made at Geomaterials of the electron microprobe which has been used to readily provide unambiguous identification of thaumasite and also to map out variations in the chemical composition of cement paste. Table 3 illustrates the characteristic chemical compositions of ettringite and thaumasite.

Chemical analysis using the electron microprobe shows that ettringite and thaumasite can be unambiguously distinguished on the basis of their chemical composition. The principal differences in the compositions of the two phases being in aluminium and silicon content. Both ettringite and thaumasite can also be distinguished by X-ray diffraction. However, the products of sulfate attack have to be present in sufficient quantities for some of the material to be collected crushed and analysed separately or, alternatively, a portion of the surface concrete has to be crushed with the risk of diluting the compounds of interest to such an extent that they cannot be detected. It is for these reasons that electron microprobe analysis is considered preferable to X-ray diffraction for the investigation of sulfate attack in concrete.

3. Overview of results

3.1. Cement type

Conventional measures taken to avoid the development of sulfate attack in concrete placed in sulfate-bearing ground conditions include the usage of sulfate resisting portland cement (SRPC) [1,2]. The analysis of all samples to date strongly suggests that SRPC is no better than ordinary portland cement (OPC) in reducing the likelihood of the development of TSA (Fig. 4).

3.2. Aggregate type

The formation of thaumasite requires a source of CO_2 and the liberation of CO_2 from the breakdown of aggregate containing calcium carbonate in concrete is regarded as a potential source of CO_2 in the development of TSA. The calcium carbonate contents of combined coarse and fine aggregate have been classified in to Ranges A, B and C based on the calcium carbonate content of the fine aggregate and on the total calcium carbonate content of the combined coarse and fine aggregates [1,2]. In this classification, Range C has the lowest calcium carbonate content and Range A has the highest calcium carbonate content. The majority of samples examined to date where TSA has been found have had a 'Range A', or less commonly a 'Range B' aggregate. However a number of exceptions have been seen in foundation concrete where TSA has developed in concrete with a 'Range C' aggregate. Thaumasite has occasionally been found in concretes containing flint gravel with no calcium carbonate in the coarse or fine aggregates in foundation structures within the London Clay. Severe TSA has been seen in samples from one structure that had a 'Range C' aggregate. In many of the cases of TSA in concrete containing little or no limestone aggregate, there has been evidence for calcium carbonate formation in the paste. In these cases, the source of the CO_2 for the formation of thaumasite would appear to be CO_2 dissolved in groundwater.

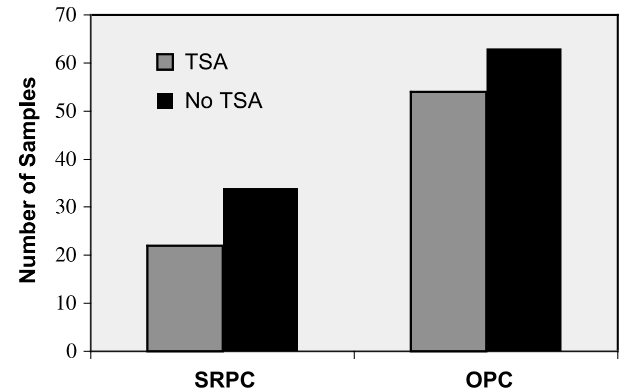

Fig. 4. Cement type and the development of TSA in samples from 22 structures.

3.3. Sulfate/chloride relationship

In many of the foundation concrete samples examined, the development of TSA is often accompanied by high levels of chloride in the cement paste (Fig. 5). An obvious source for the chloride in the motorway foundation structures examined is de-iceing salts and the presence of chlorides in the concrete samples strongly suggests that run-off moisture from motorway road surfaces is reaching buried concrete in bridge foundations. In some cases, where TSA has been found, the clay in contact with the damaged concrete has been found to contain the remnants of partially dissolved crystals of selenite (gypsum), and it is considered probable that the

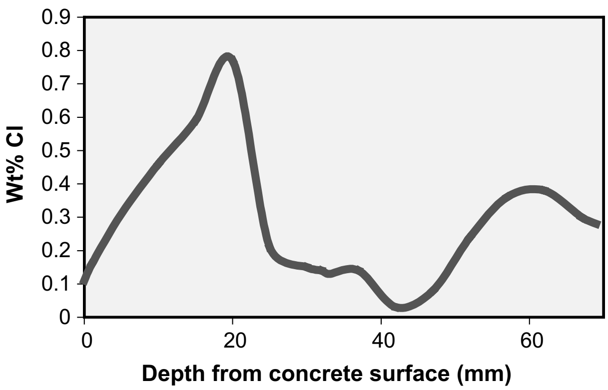

Fig. 5. Variation in chloride content with depth from the surface of concrete with TSA (chloride determined by microprobe analysis).

presence of chloride ions in moisture surrounding the concrete foundations may be a contributory factor in the development of TSA at certain localities because of the high solubility of gypsum in water containing chloride ions.

3.4. Influence of ground conditions on TSA development

In many of the structures examined, the concrete samples have been obtained from base structures where the base rests on undisturbed pyrite-bearing clay and the vertical sides and higher parts of the bases are in contact with clay back-fill. Almost without exception, in structures where TSA has been found, it is the concrete in contact with the clay back-fill that shows the development of TSA whereas the concrete in contact with undisturbed clay shows no evidence of TSA. This strongly suggests that the reworking of the clay is of key importance in the development of TSA. The oxidation of pyrite within clay as a result of exposure to the atmosphere during excavation and back-filling is generally regarded as the primary explanation for the much higher degree of TSA seen in concrete in contact with reworked pyrite-bearing clay compared to undisturbed pyrite-bearing clay. However, in some cases unaltered pyrite has been found in clay in contact with concrete that has undergone severe TSA and it is considered probable that the increase in permeability caused by the excavation and back-filling of clay surrounding foundation concrete is at least as important as pyrite oxidation in the development of TSA in foundation concrete in contact with clay back-fill.

4. Conclusions

- Special precautions are required in the sampling and handling of concrete damaged by TSA. In particular it is essential that any weakened surface concrete is not lost.
- Petrographic analysis used in conjunction with electron microprobe analysis is regarded as the most effective tool for the diagnosis of TSA and other forms of sulfate attack.
- Concrete made with SRPC cement has been found to be equally susceptible to TSA as concrete made with OPC.
- In the majority of the samples examined where TSA has developed, the aggregate has contained abundant calcium carbonate. However the development of TSA in foundation concrete is not restricted to concrete containing limestone aggregate, and the role of dissolved carbon dioxide in groundwater appears to be important in these cases.
- High levels of chloride are often encountered in TSA damaged concrete from motorway bridge foundations suggesting that run-off from road surfaces may be an important factor in the development of TSA.

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