

# **Thaumasite Expert Group One-Year Review**

**Prepared by**

**Professor L A Clark and BRE  
in consultation with  
The Thaumasite Expert Group**



## EXECUTIVE SUMMARY

### Introduction

A One-Year Review of the Thaumaside Expert Group Report <sup>1</sup> published in January 1999 has been undertaken. The Review has been informed by contributions received from members of the Group and responses from industry since the publication of the Report.

### Scope of review

The Review has been conducted under the following headings:

- Dissemination of guidance presented in the TEG Report;
- New guidance or interpretative documents produced by other bodies as a follow up to the TEG Report;
- Current impacts and awareness of the thaumasite form of sulfate attack (TSA);
- Situations which have arisen where there have been problems in the practical interpretation and implementation of the guidance given in the TEG Report;
- New field cases of TSA;
- New features of TSA;
- New research on occurrence and mitigation of TSA;
- Guidance documents presently in preparation.

### Current impacts and awareness

The general impression is that the TEG Report has been well received by the construction industry and is viewed as well balanced. Overall its recommendations and guidance are considered safe and robust. The publication of the TEG Report has not had a significant adverse impact on the various industry sectors.

Despite an intensive implementation campaign, not all sectors of the construction industry are seemingly aware of the occurrence of TSA and of the appropriate mitigating measures.

### Some problems in the practical interpretation and implementation of the guidance

There have been a few problems in interpreting the intentions of the guidance given in the TEG Report in some situations. These problems are being addressed through revisions to BRE Digest 363, BS 5328 and BS 882, and through discussions with the relevant industry bodies. In particular:

- There have been problems in some sectors, including precast concrete pipes and tunnel linings, with the recommendation to 'Design drainage' as an Additional Protective Measure. This has been resolved by a clarification of terminology and by the provision of alternative options for Additional Protective Measures.

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<sup>1</sup> Department of Environment, Transport and the Regions (1999). The thaumasite form of sulfate attack: Risks, diagnosis, remedial works and guidance on new construction. Report of the Thaumaside Expert Group. DETR, January 1999.

- It is considered that the Report's very conservative procedure for assessing the Sulfate Class of sulfide-bearing ground can now be relaxed somewhat in respect of pyritic clays.

### **New field cases of TSA**

About 20 new cases of TSA have been identified since the publication of the TEG Report. Most of these were brought to light as a result of Highways Agency (HA) investigations of highway sub-structures founded on sulfate-bearing Lower Lias Clay in Gloucestershire/Avon. However, in one case, a bridge sub-structure in County Durham, burnt colliery spoil used as road sub-base material was identified as the sulfate source. All of the new cases have taken place in conditions that were anticipated in the TEG Report.

### **Research on occurrence and mitigation of TSA**

Recommendations for future research given in the TEG Report are being largely met by a wide-range of current and proposed projects initiated by the Building Research Establishment (BRE), the universities and industry. Principal sponsors are DETR, HA, EPSRC and industry bodies. Some initial findings have become available and have been taken account of in this review. Several major laboratory and field investigations will be not be concluded until 2002-2003.

### **Guidance or interpretative documents in preparation January 2000**

Key items of guidance presently being prepared for publication include:

- a new BRE Digest: Concrete and concrete products in aggressive ground (a successor to the present BRE Digest 363);
- a revision of BS 5328: Part 1: Guide to specifying concrete;
- a revision of BS 882: Specification of aggregates from natural sources for concrete.

These will generally be in line with the guidance given in the TEG Report, but will also incorporate amendments arising from industry consultations and new research.

### **Future actions**

It is recommended that a paper should be published in the journal "Concrete" giving the key findings of the Review.

It is also recommended that there should be a further review in summer 2001 when key results will be available from a DETR sponsored three-year field trial of specimens of candidate concrete mixes, buried in Sulfate Class 3 conditions.



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## CONTENTS

	Page
1. INTRODUCTION	1
2. DOCUMENTATION SUBMITTED TO ONE-YEAR REVIEW	1
3. DISSEMINATION OF GUIDANCE PRESENTED IN THE TEG REPORT	2
4. NEW GUIDANCE OR INTERPRETATIVE DOCUMENTS PRODUCED BY OTHER BODIES AS A FOLLOW UP TO THE TEG REPORT	3
5. CURRENT IMPACTS AND AWARENESS OF TSA	3
6. PROBLEMS IN THE PRACTICAL INTERPRETATION AND IMPLEMENTATION OF THE TEG REPORT GUIDANCE	4
6.1 Establishing the carbonate content of aggregate	4
6.2 Enhanced sulfate concentration in backfill	4
6.3 Water regime	4
6.4 Chemical stability of groundwater	5
6.5 Design of drainage as an Additional Protective Measure	5
6.6 The role of sulfuric acid attack	5
6.7 Use of additional protective measures for Sulfate Class 2 conditions	6
6.8 The specification of concrete for precast concrete products	6
6.9 Specification of concrete when using ggbs cements	6
6.10 Determination of sulfate content of existing concrete	7
6.11 Appraisal of sulfate content by groundwater	7
6.12 Appraisal of potential sulfate arising from oxidation of pyrite	7
7. NEW FIELD CASES OF TSA	8
8. NEW FEATURES OF TSA	9
9. NEW RESEARCH ON OCCURRENCE AND MITIGATION OF TSA	10
9.1 Research data made available in 1999	10
9.1.1 Laboratory performance at four years of PC, SRPC and ggbs/PC concrete immersed at 5°C and 20°C in four sulfate solutions	10
9.1.2 Laboratory performance at one-year of concrete immersed at 5°C in sulfate solution: parallel to Shipston-on-Stour field trial	10
9.1.3 Field investigation of TSA occurrence in highway structures	11
9.1.4 Field investigation of performance of concrete pipes	12
9.1.5 Sulfate specification for structural backfills	13
9.1.6 Assessment of Sulfate Class of pyritic clay	13
9.2 New research initiatives - results not yet available	14
9.3 Topics not yet addressed by current research proposals	16
10. GUIDANCE OR INTERPRETATIVE DOCUMENTS IN PREPARATION JANUARY 2000	16
11. CONCLUSIONS & RECOMMENDATIONS	17
12. REFERENCES	19
TABLE 1	21
GLOSSARY OF ACRONYMS	24

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# Thaumasite Expert Group One-Year Review

## 1. INTRODUCTION

When the Chairman of the Thaumasite Expert Group (TEG) presented the Group's Report <sup>1</sup> to the Minister in November 1998, it was agreed that he would review the Report's recommendations one year after the publication of the Report (i.e. in January 2000). The current report is the result of the One-Year Review.

Each member of the Group was requested in November 1999 to provide information for the Review. In addition letters which had been addressed to the TEG since publication of the Report in January 1999 were included in the Review. The various documents which informed the Review are summarised in Section 2 and full details given in Section 12.

In the current report, the Thaumasite Expert Group Report (TEG Report) is considered under the following headings:

- Dissemination of guidance presented in the TEG Report (Section 3);
- New guidance or interpretative documents produced by other bodies as a follow up to the TEG Report (Section 4);
- Current impacts and awareness of the thaumasite form of sulfate attack (TSA) (Section 5);
- Situations which have arisen where there have been problems in the practical interpretation and implementation of the guidance given in the TEG Report (Section 6);
- New field cases of TSA (Section 7);
- New features of TSA (Section 8);
- New research on occurrence and mitigation of TSA (Section 9);
- Guidance documents presently in preparation (Section 10);

In each case the need for revisions to the guidance given in the TEG Report has been considered.

Finally, the conclusions of the Review and the recommended actions are summarised in Section 11.

## 2. DOCUMENTATION SUBMITTED TO ONE-YEAR REVIEW

Documents submitted for consideration in the Review are listed in the References in Section 12. They comprise:

- Letters to the TEG from industry containing comment or posing questions <sup>(1-4)</sup>.

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<sup>1</sup> Department of Environment, Transport and the Regions (1999). The thaumasite form of sulfate attack: Risks, diagnosis, remedial works and guidance on new construction. Report of the Thaumasite Expert Group. DETR, January 1999.

- Letters from members of the TEG presenting an update of 'stakeholder' views as at December 1999 <sup>(5-11)</sup>.
- Reports of research on aspects of concrete and the ground relevant to TSA prepared in 1999 <sup>(13-19)</sup>.
- New interpretation and guidance documents published during 1999 <sup>(20-23)</sup>.
- Draft new documents including BSI documents and BRE Digest proposed for publication in 2000 <sup>(24-29)</sup>.

### 3. DISSEMINATION OF GUIDANCE PRESENTED IN THE TEG REPORT

The publication of the TEG Report in January 1999 was followed up by an application campaign through publications, presentations and workshops. The publications included papers in the principal journals of the Concrete Society <sup>(20)</sup>, the Institution of Structural Engineers <sup>(21)</sup>, the British Geotechnical Society <sup>(22)</sup>. Workshops and presentations participated in by various members of the TEG included:

- February 1999, one-day technical seminar with workshops 'The thaumasite form of sulfate attack: theory and practice', at BRE, Garston.
- March 1999, one-day seminar convened by Gloucester and Wiltshire branch of Concrete Society 'Thaumasite attack on buried concrete in Gloucestershire', at Cirencester.
- March 1999, one-day conference 'Thaumasite: Expert views' at Aston University.
- March 1999, presentation at Technical Briefing, Centre for Concrete Information (Concquest).
- March 1999, One-day seminar 'Concrete deterioration and protection', at Centre for Cement and Concrete, University of Sheffield.
- April 1999, presentation on TSA at two half-day seminars 'Innovation in concrete construction' at BRE Cardington.
- May 1999 presentation on TSA at evening meeting of the Concrete Society, London Club, Institution of Structural Engineers.
- June 1999, one-day seminar convened by North West Region branch of Concrete Society 'The thaumasite form of sulfate attack: theory and practice at Warrington.
- June 1999, presentation on TSA at Concrete Day, Bristol.
- July 1999, presentation on TSA at 7<sup>th</sup> Euroseminar on Microscopy, Delft, Netherlands.
- September 1999, presentation on TSA at evening meeting of the West Midlands Branch of the Concrete Society.
- October 1999, Presentation on TSA at evening meeting of the Institution of Civil Engineers, Hereford & Worcester Group, County Hall, Worcester.
- November 1999, presentation on TSA at evening meeting of Concrete Society, Chilterns Club, University of Hertfordshire.
- November 1999, presentation on TSA at evening meeting of the Concrete Society, Gloucestershire & Wiltshire Club, Swindon.



#### **4. NEW GUIDANCE OR INTERPRETATIVE DOCUMENTS PRODUCED BY OTHER BODIES AS A FOLLOW UP TO THE TEG REPORT**

The following guidance document has been published in 1999:

- A guide on application of the recommendations of the TEG Report to new construction has been published by the Quarry Products Association (QPA) <sup>(23)</sup>

#### **5. CURRENT IMPACTS AND AWARENESS OF TSA**

The general impression is that the TEG Report has been well received by the industry as a well-balanced presentation of TSA and its implications. Furthermore, the TEG Report's recommendations and guidance do not appear to have had a significant adverse impact on the various industry sectors considered below.

- Materials suppliers
- Construction industry
- Construction Clients
- Domestic housing market

Information from the TEG member representing the Quarry Products Association (QPA), who is from the aggregates industry, and discussions with another senior QPA representative from the ready mix concrete industry, indicates that the QPA have some concerns associated with the practicalities of complying with the aggregate carbonate limits and problems associated with the high minimum cement contents recommended in the TEG Report. QPA have addressed these issues in their guide to the TEG Report <sup>(23)</sup>. They consider that further research on the minimum cement contents may be appropriate. (This is being addressed by DETR funded PII - see Table 1, item 2).

The TEG membership covered all sectors of the construction industry, and with the exception of one issue, no adverse impact on the industry as a result of the TEG Report's recommendations and guidance has been reported. The exception is that problems of implementing the guidance on additional protective measures and on designed drainage have been encountered by some sectors of the industry. The problems have arisen as a result of misinterpretations of the TEG's intentions, and have been addressed in the draft revision to BRE Digest 363. In addition discussions have been held with the Tunnel Lining Manufacturers Association (TLMA) and the Concrete Pipe Association (CPA). These discussions have informed the CPA's Guide <sup>(24)</sup>.

Both public and private sector client bodies were represented on the TEG. They report no adverse impact of the TEG Report. However, the Highways Agency (HA) has updated its specification and guidance for structural concrete <sup>(16)</sup> and has experienced problems relating to the TEG Report's guidance on designed drainage. As mentioned above, the latter point has been addressed in the draft revision to BRE Digest 363 and in discussions with TLMA and CPA.

Information from the TEG member representing the Royal Institution of Chartered Surveyors (RICS) and Council of Mortgage Lenders (CML) indicates that there has been no adverse reaction in the domestic house market sector to the TSA problem.

The following comments <sup>(5)</sup> have been received about the industry knowledge and understanding of the TSA problem:

- Not all sectors of the construction industry are yet aware of the occurrence of TSA and of mitigating measures;
- There would appear to be a perception in the construction industry that TSA is a problem only in Gloucestershire and Avon;
- There would appear to be a perception in the construction industry that the recommended concrete specifications are overly conservative and that the carbonate ranges produce restrictions on some commercial producers.

## 6. PROBLEMS IN THE PRACTICAL INTERPRETATION AND IMPLEMENTATION OF THE TEG REPORT GUIDANCE

A number of significant issues have been identified in comments and queries received by the TEG. These are dealt with in the Sections 6.1 to 6.12.

### 6.1 Establishing the carbonate content of aggregate

Correspondents: Stats Consultancy - Dr I Sims <sup>(2)</sup>

Quarry Products Association - C R Curtis <sup>(6)</sup>

Sandberg Consulting Engineers - Dr W F Price <sup>(11)</sup>

Issue: Petrographical examination of aggregates, carried out in accordance with British Standard procedures, is an appropriate method of determining the carbonate content. This should be recommended as an alternative to indirect chemical analysis based on measurement of CO<sub>2</sub> evolved when aggregate is treated with acid, as given in TEG Report Chapter 9, Table 9.1a.

Proposed response: To incorporate the alternative petrographic procedure in the revisions of BRE Digest 363 <sup>(25)</sup>, BS 5328 <sup>(26)</sup> and BS 882 <sup>(27)</sup>.

### 6.2 Enhanced sulfate concentration in backfill

Correspondent: Amec Civil Engineering - R L Edwards <sup>(1)</sup>

Issue: TEG Report, Section 6.1 only mentioned 'clay backfill' in respect of backfill materials that are liable to enhancement of sulfate levels. Mention should also be made of shales and mudrocks. The discussion on 'taking of soil samples' should likewise cater for shales and mudrocks.

Proposed response: Include mention of pyritic shales and mudrocks in the revision of Digest 363 <sup>(25)</sup>.

### 6.3 Water regime

Correspondent: Amec Civil Engineering - R L Edwards <sup>(1)</sup>

Issue: References to groundwater conditions in the TEG Report are not clear and consistent. Reference to 'wet ground' is not helpful as all clay is wet in that it contains water.

Proposed response: Include clarification of groundwater regime with respect to chemical attack in revision of Digest 363 <sup>(25)</sup>.

#### **6.4 Chemical stability of groundwater**

Correspondent: Amec Civil Engineering - R L Edwards <sup>(1)</sup>

Issue: TEG Report, Section 6.4.4 did not inform the reader that the chemistry of groundwater may be unstable after sampling, and that acidity may increase with time.

Proposed response: Include recommendation in the revision of Digest 363 <sup>(25)</sup> for on-site testing for pH and minimal delay before off-site chemical testing.

#### **6.5 Design of Drainage as an Additional Protective Measure**

Correspondents: Amec Civil Engineering - R L Edwards <sup>(1)</sup>

National House-Building Council - J C Haynes <sup>(8)</sup>

Issue: It is often not practicable to 'Design drainage' as an Additional Protective Measure as recommended in Table 9.3 of the TEG Report.

Proposed response: In the revision of Digest 363 <sup>(25)</sup>, modify terminology to refer to 'Address site drainage'; include full explanation of what is meant by 'Address site drainage'; also, for all situations requiring an Additional Protective Measure, offer enhanced concrete quality as an alternative.

#### **6.6 The role of sulfuric acid attack**

Correspondents: Mott MacDonald - Dr N A Henderson and Dr D S Leek <sup>(3)</sup>

British Cement Association - Dr D Hobbs <sup>(7)</sup>.

Rugby Cement - Mr A Harrison <sup>(12)</sup>.

Issue: Has the role of sulfuric acid attack been understated in the TEG Report? In particular has sufficient consideration been given to the possibility of particularly aggressive sulfate and acid conditions which may have existed directly after construction due to oxidation of previously undisturbed pyritic clays? The consequences of underestimating the role of sulfuric acid attack could be that:

- The recommendation of the TEG Report that the quantity of carbonate-bearing aggregates should be limited for higher sulfate conditions could be inappropriate. The use of limestone aggregates is standard practice in order to limit the effects of acid attack. Also restrictions in the use of limestone aggregates could lead to reductions in service life of concrete placed in disturbed sulfide-rich ground and reworked clay where acid generation and attack may be the primary form of degradation.
- The assumption of the TEG Report that limestone aggregate concrete performs less well than siliceous aggregate concretes could be wrong.

Proposed response: No change to be made to recommended aggregate and concrete specifications at present pending the outcome of further research (see Table 1, Items 4 & 10).

Justification: The majority of evidence to date does not indicate that acid conditions were ever significantly developed on the sites where TSA has been observed. Extensive studies by BRE <sup>(14)</sup> and Halcrow <sup>(16)</sup> of sites where there has been pyritic clay backfill have not

detected any evidence of present acidic ground conditions in either the undisturbed natural ground or backfill. In Lower Lias Clay cases, a relative abundance of calcite (calcium carbonate) has invariably been found, the presence of which would readily neutralise any sulfuric acid generated as a result of oxidation of pyrite, forming gypsum (calcium sulfate). Furthermore, there is an absence of other sulfate-bearing minerals, such as jarosite and alunite, which are aluminium and potassium bearing sulfates that are elsewhere<sup>(33, 34)</sup> characteristic of the weathering of pyritic shales in acid conditions. This indicates that the abundance of calcium carbonate has prevented the acid attack on the clay minerals and consequent leaching of exchangeable cations, and has thus limited the activities of aluminium and potassium in solution. Also, in a recently investigated case of TSA in County Durham<sup>(14)</sup>, the source of sulfate was burnt colliery shale, which published data<sup>(32)</sup> indicates is not likely to have given rise to significant acidic ground conditions at any time. Yet the characteristics of the TSA in that case were near identical to the M5 cases reported in the TEG Report.

The concept that ground conditions in disturbed pyritic clays may have been more aggressive in respect of sulfate content and/or acidity for a time directly after construction and that this had a major role in the occurrence of TSA is presently only a hypothesis. Further laboratory and field research to be carried out by BRE and University of Sheffield during the next three years should clarify the impact of the early post-construction ground chemistry. Meanwhile, it would seem appropriate to align recommendations to the majority of evidence to date.

### **6.7 Use of Additional Protective Measures for Sulfate Class 2 conditions**

Correspondent: British Cement Association - Dr D Hobbs<sup>(7)</sup>.

Issue: For Sulfate Class 2 conditions, should the recommendations in respect of Additional Protective Measures be the same for Range A aggregates as they are for Ranges B and C aggregates?

Proposed response: No change to be made to recommended concrete specification, but additional options for Additional Protective Measures, including enhanced concrete quality, are to be recommended in the revision of Digest 363<sup>(25)</sup>.

### **6.8 The specification of concrete for precast concrete products**

Correspondent: British Cement Association - Dr D Hobbs<sup>(7)</sup>.

Issue: It is not clear from Table 9.1c of the TEG Report that, as intended by the TEG, precast products can be designed for one class lower than the actual ground classification.

Proposed response: The interpretation of Table 9.1c has been clarified in correspondence with the TLMA and the CPA. The revised Digest 363<sup>(25)</sup> will give unambiguous recommendations in respect of specifications for precast concrete products.

### **6.9 Specification of concrete when using ggbs cements**

Correspondent: Cementitious Slag Manufacturers Association - Dr D Higgins<sup>(4)</sup>.

Issue: Four-year laboratory trials<sup>(13)</sup> indicate that concretes made with 70% ggbs/ 30% PC (C<sub>3</sub>A level 7.2% by mass of PC) and normal-quality carbonate aggregates have performed well and show no deterioration due to TSA. Additionally the presence of carbonate in the mix

improved the resistance of the ggbs/PC mixes to conventional sulfate attack. This apparently demonstrates that concretes made with slag cements have increased sulfate resistance when carbonate is present in aggregates. Currently the Table 9.1 of TEG Report recommends higher cement contents and lower free water/cement ratios when slag cements (Group 2b) are used with carbonate aggregates than when they are used with non-carbonate aggregates. Should the opposite apply?

Proposed response: No change to be made to recommended concrete specification at present.

Justification: Although the performance of slag-containing concretes with the better quality carbonate aggregates was good in 4-year laboratory trials<sup>(13)</sup>, this was not the case with the poorer quality carbonate aggregates where the performance at both 5°C and 20 °C was poorer than with flint aggregates. Any relaxation in the requirements for slag cements would also result in less onerous requirements than for SRPC, which would not be justifiable in terms of the data at 20 °C, or in terms of the data with the lower grade carbonate aggregates at 5 °C. It should also be noted that the TEG had the 3½ -year results (which were practically identical to the 4-year results) available to it when it formulated its Report recommendations.

#### **6.10 Determination of sulfate content of existing concrete**

Correspondent: Halcrow Group - Mr D Slater<sup>(10)</sup>.

Issue: The reference in TEG Report to SO<sub>4</sub> in relation to sulfates in existing concrete needs further explanation. Guidance should be given that the results (in terms of SO<sub>3</sub>) obtained by the recommended BS1881 procedure need to be multiplied by a factor of 1.2 before comparing with the threshold values for sulfate attack in concrete of 5% SO<sub>4</sub>.

Proposed response:

Incorporate extra guidance in any future publications on appraisal of sulfate attack to existing concrete.

#### **6.11 Appraisal of sulfate content by groundwater**

Correspondent: Halcrow Group - Mr D Slater<sup>(10)</sup>.

Issue: Investigations of highway structures in Gloucestershire affected by TSA<sup>(16)</sup> have shown that the severity of attack correlates well with the sulfate Class determined by tests on groundwater, but poorly with sulfate Class determined by tests on soil (2:1 water/soil extract and potential sulfate). Greater emphasis should therefore be given to groundwater sampling and testing.

Proposed response: Sulfate classification based on results of sulfate analysis of groundwater will be clearly stated to be the preferred procedure in the revision of Digest 363<sup>(25)</sup>.

#### **6.12 Appraisal of potential sulfate arising from oxidation of pyrite**

Correspondent: Halcrow Group - Mr D Slater<sup>(10)</sup>.

Issue: The TEG Report recommended derivation of 'potential sulfate' using, as a starting point, the determination of the total sulfur content measured by combustion in a high temperature oxygen flame. This can be misleading if some sulfur exists in organic form or in relatively insoluble sulfates such as barite (BaSO<sub>4</sub>). The use should therefore be considered of a 'direct' test for pyrite, and in particular of the acidified chromium reduction method<sup>(16)</sup>.

Proposed response: The determination of the total sulfur content measured by combustion in a high temperature oxygen flame will be recommended in the revision of Digest 363<sup>(25)</sup> as the routine procedure for determination of potential sulfate. Accompanying text will explain the limitations of the method in respect of organic matter and barite. The acidified chromium reduction method will be considered for mention in the Digest as an optionally useful additional diagnostic technique for confirming the presence of pyrite.

Justification: The acidified chromium reduction method is not regarded as an appropriate method for routine determination of potential sulfate (applicable to sulfide-bearing ground) due to complexity and cost of the test procedure. It is important to keep the cost of individual tests to a minimum so that the testing of a sufficient number of samples, to take account of the variability of sulfides in the ground, can be encouraged. In this respect, the high temperature combustion method is considered more straightforward and affordable.

## 7. NEW FIELD CASES OF TSA

About 20 new cases of TSA have been identified since publication of the TEG Report. These include:

- 17 more cases in highway bridge sub-structures founded on the Lower Lias Clay in Gloucestershire/Avon<sup>(5,10)</sup>. These were all brought to light as a result of HA investigations for TSA. The cases have all occurred in ground conditions similar to those reported in the 1998 cases. The total number of cases in Gloucestershire/Avon is now 27<sup>(5)</sup>.
- One case in a 32-year old highway bridge sub-structure on the A1(M) in County Durham<sup>(5,14)</sup>. This was a fortuitous discovery of TSA during bridge strengthening operations. The affected concrete contained an all-in limestone aggregate and would appear to have been designed to be resistant to Class 2 conditions according to current Digest 363 recommendations, having a cement content of 15.5% (probably Portland cement), and a water/cement ratio of about 0.4-0.5. The pattern of TSA degradation was very similar to that seen in the Gloucestershire/Avon highway structures. The maximum depth of attack was some 40 mm. The source of sulfate was concluded to be burnt colliery spoil (red shale) used as backfill around the concrete foundations and as sub-base/capping layer material in the adjacent carriageway construction. The measured soluble sulfate contents in the red shale were relatively low, about 0.22 g/litre SO<sub>4</sub> (Class 1) for solid material and 1.08 g/litre SO<sub>4</sub> (Class 2) for contained water. However, sulfate concentrations may well have been reduced by groundwater leaching in the 30 years or so since construction. Ground water had probably ponded within a sump formed by the original construction excavation.
- One case in part of a trenchfill foundation to a domestic garage founded on Lower Lias Clay in Gloucestershire<sup>(14)</sup>. The affected concrete contained carbonate Range A aggregate, the coarse fraction being composed primarily of crushed dolomite. The quality of the concrete was modest with a moderate cement content and water-cement ratio of greater than 0.55. The pattern and depth of TSA degradation was

broadly similar to that seen in the Gloucestershire/Avon highway structures. The source of sulfate was gypsum in adjacent weathered Lower Lias Clay. Mobile water was available from an adjacent fractured drainpipe.

- One case in the Rugby area of oversite concrete above hardcore comprising brick-rubble and plaster demolition debris <sup>(18)</sup>.
- One case in a concrete aeration tank in water treatment works in Denmark <sup>(19)</sup>.

Precautionary investigations for TSA occurrence in highways structures are presently still underway and it is expected that yet more structures affected by TSA will be identified <sup>(5)</sup>. These may well include further cases involving burnt colliery spoil, as the evidence suggests that there may have been very extensive past use of this material in road construction in the former coalfield areas.

## 8. NEW FEATURES OF TSA

Only two new significant features have emerged from inspection of the new cases of TSA reported in Section 7. These are:

- **Different type of sulfate-bearing ground has caused TSA.**

The motorway bridge sub-structure in County Durham had a different type of sulfate-bearing ground as compared to previous cases of TSA in bridge sub-structures <sup>(14)</sup>. The material used as backfill around affected pad footings and pier collars, and as sub-base/capping layer material in adjacent carriageway construction, was burnt colliery spoil (red shale), as against Lower Lias Clay. This material had, however, been previously identified in the TEG Report as a possibly hazardous sulfate source.

- **TSA occurred in Class 2 sulfate conditions.**

Investigation of the undisturbed ground immediately adjacent to the TSA-affected foundation to the domestic garage founded on Lower Lias Clay in Gloucestershire <sup>(14)</sup> showed apparent Class 2 ground conditions. This classification was based on results of the standard 2:1 water/soil extract test, since no ground water was available for analysis. All previous cases of TSA have been attributed to sulfate conditions of Class 3 or greater, albeit sometimes using tests based on samples of groundwater. The disparity may lie in the fact that the upper limit to Class 2 is rather high (2.3 g/l) if the standard 2:1 water/soil extract test is used. This compared with an upper limit of only 1.4 g/l for a classification based on results of tests on groundwater samples. The maximum solubility of calcium sulfate (gypsum) in water at 20°C is only 1.4 g/l. So even though a soil sample may contain copious amounts of gypsum (in the garage foundation case up to 10% of the dry mass was found), the result of the 2:1 water/soil extract test will not produce a Class 3 result unless substantial amounts of more-soluble sulfates, such as magnesium sulfate are also present.

## **9. NEW RESEARCH ON OCCURRENCE AND MITIGATION OF TSA**

### **9.1 Research data made available in 1999**

New results have become available from research that was in progress at the time of publication of the TEG Report. The principal items are:

#### **9.1.1 Laboratory performance at four-years of PC, SRPC and ggbs/PC concrete immersed at 5°C and 20°C in four sulfate solutions**

This is an interim report of research at BRE, sponsored by the DETR and Cementitious Slag Makers Association (CSMA). The objective of the study is to investigate how cement type, aggregate type and curing affect the susceptibility of concrete to TSA. The cements tested were a PC with a relatively low C<sub>3</sub>A content of 7.2% by mass, a SRPC and a combination of the PC blended with one or other of two slags. Various carbonate aggregates have been used in addition to a non-carbonate control aggregate. The mixes were designed to have a free-water/cement ratio of 0.5. The sulfate solutions comprise three different strengths of magnesium sulfate and one strong sodium sulfate.

The key findings<sup>(13)</sup> are:

- (i) Deterioration, consistent with TSA, occurred on many of the concretes that had been made with carbonate aggregate and stored in sulfate solutions at 5°C.
- (ii) At four years, with PC and SRPC mixes, a small amount of TSA was observed, even in the weakest solution, which corresponds to the top of Sulfate Class 2 in BRE Digest 363.
- (iii) The degree of TSA increased with the sulfate concentration of the test solution and with time.
- (iv) Despite their very good resistance to conventional attack in concentrated sulfate solutions, the SRPC specimens appeared to have no better resistance to TSA, than the corresponding PC concretes.
- (v) Concretes made with 70% ggbs/ 30% PC, and normal quality carbonate aggregates (crushed Carboniferous limestone coarse aggregate and Jurassic limestone fine aggregate) performed extremely well and showed no evidence of TSA in any of the solutions.
- (vi) Concretes made with 70% ggbs/ 30% PC, and poor quality carbonate aggregates (Magnesian Limestone coarse and fine aggregate, and Inferior Oolite coarse and fine aggregate) did not perform well at either 5°C or 20°C. The exact degradation mechanism responsible is not fully understood at present.
- (vii) The presence of carbonate in the mix, substantially improved the resistance of the ggbs/PC mixes to conventional sulfate attack.
- (viii) An initial air-cure proved beneficial against both the conventional and TSA.
- (ix) Surfaces, which had been fully exposed to water during the initial water-cure, appeared somewhat less susceptible to TSA than those which had cured in contact with another surface.

#### **9.1.2 Laboratory performance at one-year of concrete immersed at 5°C in sulfate solution: parallel to Shipston-on-Stour field trial.**

DETR-sponsored laboratory tests at BRE on concrete cube specimens are running in parallel with field tests on concrete cubes exposed to Class 3 sulfate conditions at Shipston-



on-Stour. Seven types of cements have been included in the trial: SRPC, two PCs, PLC, PC/30% pfa, and two ggbs/PCs. Three types of aggregates have been included in the trial: Magnesian limestone, Carboniferous limestone and siliceous aggregate. The free-water/cement ratio of the concretes averaged 0.55. The sulfate solution was made up to simulate the actual groundwater chemistry observed at the Shipston site. Some of the cube samples were air and water-cured following well established procedures. Additionally, a proportion of the specimens were cured under sealed conditions for 27 days by wrapping them in cling film and placing them in a polythene bag.

The key findings <sup>(15)</sup> are:

- (i) Sealed-curing of the concrete cubes has made them more reactive, with the resultant mode of attack proving to be very similar to the 'contact face' effect found in previous laboratory trials.
- (ii) Concrete mixes containing siliceous aggregate (typically with less than 6% calcium carbonate) and Portland cement, used as 'controls' for the investigation, have not performed as well as expected. Sealed-cured control cubes have been just as badly affected by a TSA-related degradation as have their limestone counterparts. This may be evidence to support previous observations reported in the TEG Report (Section 2.4.3) that a TSA-related form of deterioration can occur in PC concretes in the field, which contain little or no carbonate-bearing aggregate.
- (iii) Concrete mixes in which ggbs forms 70% of the binder (the other 30% being PC) have shown no signs of sulfate attack after one year, despite the fact that the PC contained 10% C<sub>3</sub>A.
- (iv) Concrete mixes, with both siliceous and limestone aggregates, in which pfa forms 30% of the binder (the other 70% being PC) have shown poor resistance to sulfate attack over the first year.

It should be noted that the first results from the parallel field tests will be available in summer 2001.

### 9.1.3 Field investigation of TSA occurrence in highway structures.

Some further results of the in-depth study of 30-year-old highway structures affected by TSA in Gloucestershire, carried out for the HA by the Halcrow Group, have been made available <sup>(16)</sup>. The key findings to date are:

- (i) The concrete used in the structures surveyed was predominantly that appropriate to Class I as presently defined in BRE Digest 363. This is generally on account of the cement type being Portland cement and the water/cement ratio exceeding the limit of 0.50 for Class 2.
- (ii) In all cases, the aggregates used in the structures contained carbonates within Range A of Table 9.1a of TEGR. Also, in all except 6 structures from a total of 25 where data are available, the aggregates contained dolomitic limestone.
- (iii) Piezometric observations have shown that occurrence of TSA over the entire surface of the concrete generally correlates with that surface being below minimum groundwater level. Occurrence of TSA in patches on the surface of the concrete generally correlates with that surface being below maximum groundwater level.

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- (iv) The severity of TSA correlates best with a sulfate Class based on the results of tests on groundwater. The correlation with a sulfate Class based on the results of 2:1 water/soil extract tests is significantly poorer.
  - (v) Often, when both types of sulfate test are available for the same location, the tests on groundwater give a higher sulfate Class than do the 2:1 water/soil extract tests. Statistical correlation shows that for made-ground the Class is either the same or one Class higher from groundwater results. Likewise, for natural ground, the Class is either the same or up to two Classes higher than that based on 2:1 water/soil extract tests. Both these correlations again indicate (cf. Section 8) that in typical sulfate-rich clay soils the 2:1 water/soil extract tests inherently tend to lead to a lower sulfate Class than do tests on groundwater.
  - (vi) Sulfate Class for undisturbed pyritic ground, based on the 'potential sulfate' calculated from the measured total sulfur content is generally very much higher than the sulfate Class based on 2:1 water/soil extract tests and/or groundwater tests. A jump from Class 1, based on 2:1 water/soil extract to Class 5 based on the potential sulfate is common. In contrast, material which has been oxidised due to disturbance by the original construction activities most commonly has a sulfate Class increase of only one or two (eg 1 to 3) as compared to counterpart undisturbed pyritic ground <sup>2</sup>.
  - (vii) Coatings (including traces in coatings) were found on 11 highway structures including: one bridge with severe attack (Barnwood Bypass Bridge), four bridges with moderate attack, two bridges with slight attack, and four culverts with no attack. The variability in the severity of attack found in the concrete behind the coatings may primarily reflect a variability in the quality of the coatings.
  - (viii) The groundwater was found to be predominantly alkaline with few results of pH below 7 and none below 6.5.

#### 9.1.4 Field investigation of performance of concrete pipes

A field investigation is currently in hand of the long-term performance of concrete pipes in sulfate-bearing ground. The investigation is being carried out by the CPA with assistance from BRE. To date two pipes have been inspected <sup>(14)</sup>:

- (i) Pipe installed in Lower Lias Clay fill at Cheltenham  
The pipe showed no sign of being affected by TSA despite being buried for some 23 years in sulfate-bearing fill derived from Lower Lias Clay. This is, however, not particularly surprising, since the investigation showed that factors such as composition of concrete, sulfate class and presence and mobility of ground water were not critically adverse in this particular case. The key factors are considered to be: Sulfate Class of the fill of only Class 1 /Class 2; ground well drained and not subject to copious and mobile water; pipe of high quality concrete made with SRPC and relatively low in carbonates (~15% of aggregates, equivalent to Range B as defined in the TEG Report).

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<sup>2</sup> It should, however, be noted that most of the construction activities which resulted in ground disturbance and the presently enhanced sulfate levels took place some three decades ago. A view is held by some parties that ground conditions directly after construction were more aggressive than presently found. Research is continuing to clarify this (see Table 1, Item 10).

(ii) Pipe installed in alluvium over Blue Lias Clay at Tewkesbury.

The pipe showed no sign of being affected by TSA. This was to be expected since the investigation showed that factors such as composition of concrete, sulfate class and presence and mobility of ground water were in no way adverse for this concrete pipe.

**9.1.5 Sulfate specification for structural backfills**

Research is being carried out for the HA by the Transport Research Laboratory (TRL) and University of Sheffield on corrosion of galvanised steel buried structures. The corrosion is attributed to the presence of sulfates and sulfides in the ground. Part of the research, reported in May 1999 <sup>(17)</sup>, aims to identify appropriate tests methods for determining sulfur compounds in structural backfills. A four-stage procedure is provisionally proposed for the identification and quantification of sulfate and sulfides:

- (i) Determination of water-soluble sulfates (modification of BS 1377: Part 3).
- (ii) Determination of acid volatile sulfur species, using hydrochloric acid (HCl) digestion to quantify the presence of reactive sulfates (gypsum) and monosulfides (pyrrhotite) species.
- (iii) Determination of disulfide (pyrite) by chromium reduction.
- (iv) Determination of total sulfur by microwave digestion or Eschka fusion. This is very useful to check the results for the sulfur species mentioned above. The sum of the other three determinations should not exceed the total sulfur content.

Further research is in progress to determine the robustness and reproducibility of the suggested procedures, and to assess the effects of storage under different conditions on the sulfur compounds.

**9.1.6 Assessment of Sulfate Class of pyritic clay**

Research is being carried out at BRE on the assessment of Sulfate Class of the ground and in particular of pyritic clay. In respect of the latter, it is known that if previously undisturbed pyritic clays are exposed to air and water during construction, then the pyrite will oxidise leading to formation of sulfates. The TEG Report recommended that assessment of the Sulfate Class of pyrite-bearing ground be made by first determining the 'potential sulfate' from the measured sulfur content, and then using a correlation with Sulfate Class based on former BRE Digest 250:1981. The procedure was acknowledged to be conservative, but was recommended in the absence of a safe alternative method.

BRE has collaborated with industry during several site investigations on pyrite-bearing clays including Lower Lias Clay, Kimmeridge Clay and London Clay. The studies have confirmed that both the Lower Lias Clay and Kimmeridge Clay are highly pyritic when unweathered, and that the assessment procedure commonly leads to a Sulfate Class of 5. Moreover, in south-central England, such unweathered pyritic clays are commonly encountered at relatively shallow depths, eg 2 m on sites in Tewkesbury and Cheltenham, and therefore need to be taken account of in many construction works. However in practice, a ground assessment of Sulfate Class 5 has led to significant problems in the design and specification of below-ground concrete.

The situation is better in the case of unweathered London Clay. This normally has a smaller amount of pyrite, and the 'potential sulfate' assessment procedure commonly leads to a Sulfate Class of only 3. Also the London Clay is typically more deeply weathered, and pyritic clay is generally not encountered in the topmost 6 -10 m. Only deep construction works will therefore encounter it.

The study has compared the Sulfate Class derived from the 'potential sulfate' procedure on unweathered pyritic clay with the Sulfate Class determined for counterpart reworked clays, and naturally weathered clays. Much data in this respect has been provided by the Halcrow Group from their investigations for the HA of highway structures in Gloucestershire/Avon.

The study has indicated that for the more highly pyritic clays the very conservative procedure in TEG Report can be safely amended for pyritic clays by limiting the increase in Sulfate Class based on the 'potential sulfate' estimation to two Classes above that derived from 2:1 water/soil extract tests. New guidance on sulfate assessment which provides for this limitation has been prepared for inclusion in a new BRE Digest <sup>(25)</sup>, intended to replace Digest 363.

## **9.2 New research initiatives - results not yet available**

### **(i) The design of structural concrete to resist the thaumasite form of sulfate attack.**

This Partners in Innovation (PII) research project commenced at BRE in June 1999, supported by DETR, QPA, BCA, CSMA, UKQAA (UK Quality Ash Association).

Objectives: To develop the key specifications for new works to prevent premature deterioration in concretes through the thaumasite form of sulfate attack, and to provide better quantified advice for the assessment of the future life of existing structures.

Work programme: A laboratory-based investigation will be carried out to establish the resistance of different binders to the reaction, the susceptibility of different types of limestone and the acceptable threshold of carbonate in aggregate sources including sands and gravels.

Scheduled for completion: June 2003.

### **(ii) Research on composition, formation and stability of thaumasite in concretes.**

Research started in 1999 at Aberdeen University, Department of Chemistry sponsored by EPSRC (Dr D E McPhee, Dr S J Barnett), with BRE as a collaborator (Dr N J Crammond).

Objectives: (1) identify equilibrium phase compositions and establish the solubility curve for thaumasite. (2) Use derived solubility product to generate solubility surfaces for multi-phase systems relevant to assessing the stability of thaumasite in contact with natural groundwaters. (3) Study thaumasite-ettringite solid solution characteristics.

Work Programme: This study will establish the mechanism of thaumasite formation from solution. It will involve the acquisition and modelling of composition and solubility data obtained under various environmental conditions, so that conditions to inhibit crystallisation can be identified.

Scheduled for completion: December 2001.

**(iii) The resistance of metakaolin (MK) - Portland cement (PC) blends to thaumasite attack**

Research started in October 1999 at the School for Built Environment, University of Glamorgan, (Prof. S Wild) sponsored by English China Clays International.

Objectives: (1) To identify and monitor the chemical and physical interactions at the interface of concrete with cold wet sulfate-bearing soil. (2) to develop concrete mixes based upon PC-MK binders which are resistant to TSA.

Work programme A laboratory-based investigation will be carried out using concrete prisms made up at various water/binder ratios and with partial replacement of Portland cement with MK (5, 10, 15 and 20%). The prisms will be subjected to two sulfatic environments comprising (i) 5% sodium sulfate solution and (ii) a high sulfate, high sulfide-bearing clay (Lower Oxford Clay).

Scheduled for completion: Sept 2002.

**(iv) Thaumasite formation by combined acid and sulfate attack on concrete**

Research has been approved for a start in 2000 at the Dept of Engineering Materials, University of Sheffield, (Dr E A Byars, Prof. J H Sharp, Dr C J Lynsdale, Dr J C Cripps) sponsored by EPSRC.

Objectives: (1) To investigate the chemical and physical processes associated with pyrites oxidation in clays and the resulting aggressivity of groundwater to concrete. (2) To establish whether the TEG proposal which allows for enhanced sulfate levels resulting from oxidation of all the sulfates in the ground is correct. (3) To demonstrate and explain the chemical and physical processes occurring in concrete exposed to groundwater in disturbed and undisturbed pyrite containing clays. (4) To understand and explain the chemical and physical interactions at the clay/concrete interface. (5) To ascertain the influence of the binder type and water-binder ratio on the rate of TSA for concretes containing either limestone or siliceous aggregates. (6) To investigate the effectiveness of bituminous coatings on minimising TSA. (7) To propose prescriptive specifications for concrete at risk of TSA and acid exposure classes in BS 5328 and BRE Digest 363. (8) To disseminate the recommendations of the project to the construction industry and BSI Committees.

Work Programme: The investigation aims to examine the laboratory deterioration of candidate concretes immersed in a range of sulfate solutions that are equivalent to the Sulfate Classes of BRE Digest 363. The cement combinations chosen for investigation include PC, PLC, SRPC, PC/ggbs, PC/pfa. Visual and petrographic methods will be used to determine why and when thaumasite forms in a range of concretes made with common binders and oolitic limestone aggregates. The chemical changes during laboratory simulated excavation and backfill cycles will also be measured to provide the information necessary to make informed specification of concrete in those conditions and to recommend aggressivity-testing procedures for pyritic clays.

Scheduled for completion: 2003.

**(v) A study of thaumasite and related phases in cements and concretes**

Research started at University of Staffordshire in October 1999 sponsored by EPSRC, supervised by Dr A R W Jackson, Dr C D Adam and Dr J Wright.

Objectives: (1) To refine a technique developed during earlier work at Staffordshire University for the analysis of thaumasite, ettringite and related phases. This technique is based on the full pattern fitting of x-ray powder diffraction data. It has the proven potential to reveal both the exact nature and amount of any thaumasite or ettringite phase present in a given sample of cement or concrete. (2) To use the technique to explore the factors that lead to loss of structural integrity on the formation of thaumasite and related phases in cements and concretes.

Scheduled for completion: October 2002.

### 9.3 Topics not yet addressed by current research proposals

The "Future research topics" suggested in Appendix C of the TEG Report are given in Table 1 together with the current position on each of these topics, including the projects referred to in Sections 9.1 and 9.2. It can be seen that the only topic for which research is either not underway or proposed is waterproofing admixtures.

## 10. GUIDANCE OR INTERPRETATIVE DOCUMENTS IN PREPARATION JANUARY 2000

Three key items of guidance are presently being prepared for publication in 2000:

- (a) A new BRE Digest 'Concrete and concrete products in aggressive ground' <sup>(25)</sup>.  
Sections of this will deal with:
- Background to chemical attack on concrete in the ground;
  - Assessment of the aggressive chemical environment for concrete;
  - Basis for specification of concrete for aggressive ground conditions;
  - Design Guides for specification of concrete for use in different types of construction.

This Digest will replace the present BRE Digest 363 'Sulfate and acid resistance of concrete in the ground'.

- (b) Revision of BS 5328: Part 1: Guide to specifying concrete <sup>(26)</sup>.
- (c) Revision of BS 882: Specification of aggregates from natural sources for concrete <sup>(27)</sup>.

Close collaboration with the Committee responsible for the revision of BS 5328 and BS 882 has ensured that the guidance given in the BRE and BSI documents will be entirely complementary. Only the BRE Digest will cover the investigation and classification of the ground for chemicals aggressive to concrete. The transfer point between the Digest and BS 5328 documents is the guidance table for concrete mix design appropriate to specified aggressive ground conditions.

As soon as the above are published other bodies have notified their intention to release or update guidance documents, including:

- The National House-Building Council <sup>(8)</sup> will issue a revision of NHBC Standards, Chapter 2.1: Concrete and its reinforcement <sup>(28)</sup>.

- The Highways Agency <sup>(5)</sup> will issue an amendment to Highways Agency Manual of Contract Documents. Volume 1: Specification for Highway Works, Series 1700 Structural Concrete. Volume 2: Notes for Guidance, Series NG1700 Structural Concrete <sup>(29)</sup>.
- The Concrete Pipe Association will make available a revised version of their leaflet 'A guide on application of the recommendations of the TEG Report to concrete pipes' <sup>(24)</sup>.

Additionally CIRIA are presently preparing a new publication 'Concrete technology for cast in situ foundations' <sup>(30)</sup>. This publication includes guidance on assessment of ground conditions and specification of foundation concretes in respect of aggressive ground, and makes extensive reference to the new BRE Digest <sup>(25)</sup> and the revised BS 5328 <sup>(26)</sup>.

The Institution of Structural Engineers has made reference to the TEG Report in its revised Report <sup>(31)</sup> on the subsidence of low-rise buildings, to be published in summer 2000.

## **11. CONCLUSIONS & RECOMMENDATIONS**

**11.1** The general impression is that the TEG Report has been well received by the construction industry and that overall its recommendations and guidance is safe, robust and has not had a significant adverse impact on the various industry sectors.

**11.2** Despite an intensive implementation campaign, there is a perception that not all sectors of the construction industry are aware of the occurrence of TSA and of the appropriate mitigating measures. Furthermore, amongst those who are aware there is a perception that it is only a problem in Gloucestershire and Avon.

**11.3** About 20 new cases of TSA have been identified since the publication of the TEG Report. All of these have taken place in conditions that were anticipated by the TEG Report.

**11.4** The Review has exposed some problems in the practical interpretation and implementation of the TEG Report. These are being addressed in the revision to BRE Digest 363.

**11.5** The TEG was aware that its procedure in the TEG Report for assessing the Sulfate Class of sulfide-bearing soils was very conservative, but was unable to propose a less conservative method at the time. However, there is now evidence that the procedure can be safely amended for pyritic clays.

**11.6** Recent field studies have indicated that analytical tests on groundwater samples from a particular site typically lead to a higher Sulfate Class than do counterpart water-soluble sulfate tests (using 2:1 water/soil extract) on soil from the same location. Also that the severity of known cases of TSA correlates well with the sulfate Class determined by tests on

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groundwater, but poorly with sulfate Class determined by water-soluble sulfate tests on adjacent soil. In response to these findings, sulfate classification based on results of sulfate analysis of groundwater will be recommended as the preferred procedure in the revision of Digest 363. Further research is continuing that may ultimately lead to a downward revision of the lower limit of Sulfate Class 3 for water-soluble sulfate tests using a 2:1 water/soil extract.

**11.7** It is not considered necessary to issue an amendment to the TEG Report, but it is recommended that a paper giving the key findings of the TEG Report One-Year Review, including the points referred to in 11.4 and 11.5 above, should be published in 'Concrete' to coincide with the publication of the successor to Digest 363.

**11.8** It is recommended that a further review should take place in summer 2001, when the three-year field data for the concrete specimens buried in Sulfate Class 3 conditions at the Shipston-on-Stour test site will be available.



## 12. REFERENCES

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3. Letter from Dr N Henderson and Dr D S Leek, Mott MacDonald, 1 April 1999, 'Thaumaside Expert Group Report, 1999'.
4. Letter from D Higgins, CSMA, 22 November 1999, 'Thaumaside Expert Group'.
5. Letter from N Loudon, Highways Agency, 10 November 1999, 'Review of Thaumaside Expert Group Report'.
6. Letter from C R Curtis, QPA, 3 December 1999, 'Review of Thaumaside Expert Group Report'.
7. Letter from Dr D Hobbs, BCA, 6 December 1999, 'Review of Thaumaside Expert Group Report'.
8. Letter from J C Haynes, NHBC, 14 December 1999, 'Thaumaside Expert Group'.
9. Letter from J C W Patch, Roger Bullivant, 14 December 1999, 'Thaumaside Expert Group - One Year Review'.
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11. Letter and report from Dr W F Price, Sandberg Consulting Engineers, 16 November 1999, 'Review of Thaumaside Expert Group Report'.
12. Letter from Mr A Harrison, Rugby Cement, 15 March 1999.

### Research reports

13. BRE Client Report, prepared for DETR and Cementitious Slag Makers Association by N J Crammond and M Halliwell, August 1999, 'Four-year report on avoiding the thaumaside form of sulfate attack'.
14. BRE Client Report No 80007, prepared for DETR by N J Crammond, T I Longworth and R G Sibbick, December 1999, 'Update on field occurrences of TSA, prepared for one-year review of Thaumaside Expert Group'.
15. BRE Client Report No 80006, prepared for DETR by N J Crammond, December 1999, 'Thaumaside field trial at Shipston-on-Stour - One-year results from parallel laboratory study' .
16. Halcrow Group Ltd Report, December 1999, 'Thaumaside Investigation - Evaluation of classification schemes for the assessment of sulfate attack of concrete'.
17. TRL Project Report (unpublished) by MA Czerwko and J M Reid, 'Sulfate specification for structural backfills: Report on Laboratory test methods'. TRL, May 1999.
18. Preliminary research report, BRE.
19. Personal communication about occurrence of TSA in concrete of the stairway of an aeration tank at Marbjerg waterworks, Roskilde, from Cowi Organisation, Lyngby, Denmark.

**New guidance or interpretative documents published in 1999**

20. Paper 'Thaumasite form of sulfate attack' authored by the TEG, published in 'Concrete' February 1999, pp 37-40.
21. Paper 'The structural implications of the thaumasite form of sulfate attack' authored by the TEG, published in 'The Structural Engineer' Vol 77/No 4, 16 February 1999, pp 10-11.
22. Technical Note 'Responding to the thaumasite form of sulfate attack: ground engineering aspects' by T I Longworth, published in 'Ground Engineering' April 1999.
23. QPA Guide prepared by Professor T Harrison, 1999, 'Practical application of the DETR Expert Group Report on the thaumasite form of sulfate attack on buried concrete'.

**Guidance or interpretative documents in preparation January 2000**

24. CPA Guide, 'A guide to the specification of concrete drainage in relation to the thaumasite form of sulfate attack'. Concrete Pipe Association.
25. New BRE Digest 'Concrete and concrete products in aggressive ground. Part 1: Assessing the aggressive chemical environment. Part 2: Recommendations for concrete specification and additional protective measures'.
26. Revision of BS 5328: Part 1: Guide to specifying concrete.
27. Revision of BS 882. Specification of aggregates from natural sources for concrete.
28. Revision of NHBC Standards, Chapter 2.1: Concrete and its reinforcement.
29. Revision of Highways Agency Manual of Contract Documents. Volume 1: Specification for Highway Works, Series 1700 Structural Concrete. Volume 2: Notes for Guidance, Series NG1700 Structural Concrete.
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**Table 1 : Requirements for further research - Summary of progress to January 2000**

Future research proposed in TEG REPORT		Research, either underway or proposed
1. Thermodynamics and kinetics in relation to the mechanism of thaumasite formation.	✓	Aberdeen University Project ' Research on composition, formation and stability of thaumasite in concretes' funded by EPSRC. BRE is collaborating under Framework Project on TSA for DETR.
2. Avoidance of TSA by establishing resistant concrete mix designs: <ul style="list-style-type: none"> <li>• Assessment of the relative resistance to TSA of various cements including PC, SRPC, cements containing ggbs, pfa, silica fume and metakaolin, CAC and PLC;</li> <li>• Validation of the mixes specified in Table 9.1.</li> </ul>	✓           ✓	(a) Laboratory and field trials of PC, SPRC, ggbs and PFA concretes are part of Part of BRE Framework Project on TSA for DETR. (b) Laboratory research on TSA resistance of PC-metakaolin binders is being carried out by University of Glamorgan sponsored by ECCI.  A specific objective of DETR funded PII research project 'The design of structural concrete to resist the thaumasite form of sulfate attack.' lead contractor BRE, supported by BCA, QPA, CSMA, UKQAA.
3. Carbonate contents of aggregates: <ul style="list-style-type: none"> <li>• Review testing procedures for classifying aggregate carbonate ranges;</li> <li>• Establish more robust limits for Ranges A, B and C by studying a wider selection of carbonate proportions and sources within both coarse and fine aggregates.</li> </ul>	✓     ✓	Review being carried out by Committee for revision of BS 882: Specification for aggregates from natural sources for concrete.  A specific objective of DETR funded PII research project 'The design of structural concrete to resist the thaumasite form of sulfate attack.' lead contractor BRE, supported by QPA, BCA, CSMA, UKQAA.
4. Contribution of the ground to occurrence of TSA: <ul style="list-style-type: none"> <li>• Field collection of data for varying ground conditions, groundwater regimes and soil types, concrete materials and different structure types and elements;</li> <li>• The influence of varying ground conditions, groundwater regimes and soil types on thaumasite formation;</li> <li>• Chemical and physical interactions at the clay/concrete interface;</li> </ul>	✓      ✓    ✓	Part of BRE Framework Project on TSA for DETR (Watching brief on field cases).  Part of BRE Framework Project on TSA for DETR (Watching brief on field cases).  (a) Part of University of Sheffield project 'Thaumasite formation by combined acid and sulfate attack on concrete' funded by EPSRC. (b) Also part of BRE Framework Project on TSA for DETR (Watching brief on field cases).

Future research proposed in TEG REPORT		Research, either underway or proposed
<p>4. Contribution of the ground to occurrence of TSA:</p> <ul style="list-style-type: none"> <li>• Development of a standard laboratory test protocol to take account of sulfide (particularly pyrite) in clay soils which may be oxidised leading to enhanced sulfate levels;</li> <li>• Revised procedure for assessment of sulfate class of ground taking account of new test for oxidation of sulfide-bearing clays. This is needed for revision of Digest 363 and BS 5328: Part 1.</li> </ul>	<p>✓</p> <p>✓</p>	<p>Part of University of Sheffield /TRL project 'Sulfate specification for structural backfills'. Also part of BRE Framework Project on TSA for DETR (Assessment of Sulfate Class).</p> <p style="text-align: center;">" " " "</p>
<p>5. Diagnostic techniques for buried structures obviating the need for excavation.</p>	<p>✓</p>	<p>Halcrow Group are reviewing potential techniques for HA. There are some promising leads, but no technique has been validated to date.</p>
<p>6. Structural effects of TSA;</p> <ul style="list-style-type: none"> <li>• Residual bond tests on reinforced concrete sections affected by TSA;</li> <li>• Investigation of effect of TSA on the skin friction of piles and base friction of foundations.</li> </ul>	<p>✓</p> <p>✓</p>	<p>Proposal being developed by University of Birmingham for Foundation for the Built Environment and/or EPSRC.</p> <p>Preliminary tests to be carried out 2000 under BRE Framework Project on TSA for DETR (Effect of TSA on pile skin friction).</p>
<p>7. Protective measures including the efficiency of coatings on buried concrete:</p> <ul style="list-style-type: none"> <li>• Effectiveness of different coatings including bitumen emulsions against thaumasite formation in the field;</li> <li>• Laboratory tests of simple, single and multiple-layer coatings and sheet membranes on carbonate aggregate concrete within reworked clay backfill and within simulated sulfate-rich water;</li> <li>• Tests of waterproofing admixtures in carbonate aggregate concretes placed within reworked clay backfills and simulated weak sulfuric acid/sulfate conditions.</li> </ul>	<p>✓</p> <p>✓</p> <p>✗</p>	<p>Part of BRE Framework Project on TSA for DETR (Watching brief on field cases).</p> <p>(a) Use of bitumastic coatings to be investigated as part of University of Sheffield project 'Thaumasite formation by combined acid and sulfate attack on concrete' funded by EPSRC.</p> <p>(b) PII Proposal for use of non-bitumastic coatings being prepared by BRE in conjunction with coatings manufactures.</p> <p>No proposal known.</p>
<p>8. Development of assessment procedures and optimisation of effective repair techniques and materials:</p> <ul style="list-style-type: none"> <li>• Tests of various repair materials on TSA-affected concrete with different degrees of TSA/sulfate removal (to check how sensitive the repair bond will be to residual sulfates).</li> </ul>	<p>✓</p>	<p>Halcrow Group are preparing proposal for HA for exposure tests of repairs to concrete elements affected by TSA. Several repair materials will be evaluated.</p>
<p>9. The role of carbonates from sources other than aggregate.</p>	<p>✓</p>	<p>Part of BRE Framework Project on TSA for DETR (Review of existing case studies).</p>

Future research proposed in TEG REPORT		Research, either underway or proposed
<p>10. Miscellaneous:</p> <ul style="list-style-type: none"> <li>• Investigation of the effects of severe wetting on building products containing or subject to sources of sulfates and carbonates;</li> <li>• Investigation of buried precast concrete products containing or subject to sources of sulfates and carbonates;</li> <li>• Field study collection of data for house foundations;</li> <li>• Investigation of foundations in other sulfide-bearing clays in wet conditions;</li> <li>• Simulation of Tredington-Ashchurch conditions to determine time-scale for the effects and the quantities of sulfuric acid and sulfates produced against time;</li> <li>• Effect of TSA on the chloride binding in Portland cement concrete.</li> </ul>	<p>✓</p> <p>✓</p> <p>✓</p> <p>✓</p> <p>✓</p> <p>?</p>	<p>Part of BRE Framework Project on TSA for DETR (Watching brief on field cases).</p> <p>Part of BRE Framework Project on TSA for DETR ( (i) Watching brief on field cases, (ii) Field exposure trial).</p> <p>Part of BRE Framework Project on TSA for DETR ( (i) Watching brief on field cases, (ii) Field exposure trial).</p> <p>Part of BRE Framework Project on TSA for DETR (Watching brief on field cases).</p> <p>(a) Field study is part of BRE Framework Project on TSA for DETR (Watching brief on field cases). (b) Laboratory study is part of University of Sheffield project 'Thaumasite formation by combined acid and sulfate attack on concrete' funded by EPSRC.</p> <p>Proposal on chloride-induced corrosion associated with TSA being explored by Civil Engineering Department of University of Leeds in collaboration with BRE.</p>

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**GLOSSARY OF ACRONYMS**

BRE	Building Research Establishment
BCA	British Cement Association
CSMA	Cementitious Slag Makers Association
CIRA	Construction Industry Research and Information Association
CPA	Concrete Pipe Association
CML	Council of Mortgage Lenders
DETR	Department of Environment, Transport and the Regions
EPSRC	engineering and Physical Sciences Research Council
ggbs	Ground granulated blastfurnace slag
HA	Highways Agency
MK	Metakaolin
NHBC	National House-Building Council
PC	Portland cement
pfa	Pulverized fuel ash
QPA	Quarry Products Association
RICS	Royal Institution of Chartered Surveyors
SRPC	Sulfate-resisting Portland cement
TEG	Thaumasite Expert Group
TRL	Transport Research Laboratory
TSA	Thaumasite form of sulfate attack
TLMA	Tunnel Lining Manufacturers Association
UKQAA.	UK Quality Ash Association