

**Thaumasite Expert Group Report:
Review after three years experience**

Prepared by

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

March 2002

FOREWORD

Minister

When I presented the One-Year Review of the Report of the Thaumasite Expert Group (TEG) to the Minister then responsible, Nick Raynsford, it was agreed that I would review again the Report's recommendations with BRE in summer 2001. The current report, which was completed in March 2002, is the result of the review after three years' experience of use of the Report's recommendations.

The review has taken account of information from the TEG and other key stakeholders, and the report has been prepared by BRE and me in consultation with the TEG.

The general impression is similar to that reported in the first review: it has been well received by the construction industry and is viewed as being well balanced. The first review identified that there were a few problems in interpreting the intentions of the guidance given in the TEG Report in some situations. These problems have been resolved through the publication of BRE Special Digest 1, and through discussions with relevant industry bodies.

We are of the view that the findings of the original Report are still robust and continue to minimise the risk of the thaumasite form of sulfate attack in new construction.

The new data available at the time of the second review did not permit relaxation of the TEG Report's recommendations other than those incorporated in BRE Special Digest 1.

At March 2002, there had been about 30 new cases of the thaumasite form of sulfate attack identified since the first review. Two of these cases occurred in buried concrete containing siliceous aggregates, reinforcing the view that concrete containing little or no carbonate can be affected if an external carbonate source is available. However, the current understanding of this issue is insufficient to justify an amendment to the current guidance.

We have recommended that the key findings of the review should be published in the journal 'Concrete'. We also recommend that a further review of all relevant guidance documentation should take place in late 2003.

Finally, I should like to acknowledge the valuable contribution to the review made by members of the TEG and BRE Staff.

A handwritten signature in black ink, appearing to read 'Les Clark', with a stylized, cursive script.

Professor Leslie Clark, OBE, FREng
Chairman of the Thaumasite Expert Group

EXECUTIVE SUMMARY

Introduction

Following the identification of the thaumasite form of sulfate attack (TSA) on the concrete foundations to a number of bridges on the M5 motorway in 1998, the then Minister for Construction established the Thaumasite Expert Group (TEG) under the chairmanship of Les Clark, Professor of Structural Engineering, University of Birmingham. It was asked to report on the nature and threat of this phenomenon and to provide interim guidance on its avoidance.

The Report ¹ of the TEG was received by the then Minister for Construction, Nick Raynsford, in December 1998 and published by DETR in January 1999. At the Minister's request, the Report was followed up in spring 2000 by a One-Year Review ² of the Report's factual statements and guidance in the light of new developments on TSA.

A second review of the Thaumasite Expert Group Report has now been undertaken. This review has been carried out after some three years experience of the advice in the Report. The Review has been informed by contributions received from members of the Group and responses from industry since the publication of the One-Year Review.

Scope of review

This Review has been conducted under the following headings:

- New guidance produced by others as a follow up to the TEG Report;
- Dissemination of new guidance;
- Current impacts and awareness of TSA;
- Problems in the practical interpretation and implementation of the TEG Report guidance;
- New cases of TSA in the UK;
- New features of TSA;
- New UK research on occurrence and mitigation of TSA;
- Guidance documents in preparation at March 2002.

Current impacts and awareness

Our overall impression is similar to that reported in the first review; 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 stakeholder sectors.

¹ 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.

² Thaumasite Expert Group One-Year Review. Concrete. June 2000, Volume 34, No 6, pp 51 – 53.

The publication of new BRE guidance and the amendment of BS 5328 has meant that now the industry is turning to these new documents for guidance rather than to the TEG Report. However, these new documents implement the guidance that was originally in the TEG Report. 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 and/or implementing the intentions of the guidance given in the TEG Report in some situations. These problems have been addressed through revision of the guidance on specification of concrete in aggressive ground given in BRE Digest 363, BS 5328 and BS 882, and through discussions with the relevant industry bodies. In particular, problems were encountered by the manufacturers of pre-cast concrete construction products, including those for precast concrete pipes and tunnel linings, in complying with the TEG Recommendations. These have been resolved by the inclusion in the new BRE Special Digest (SD1)³ of specific design guidance for these products.

New field cases of TSA

About 50 new cases of TSA have been identified since the publication of the TEG Report and 30 since the publication of the first review in 2000. The majority of these were in the foundations of bridges founded on sulfate-bearing Lower Lias Clay (alternatively known as the Charmouth Mudstone Formation), found as a result of Highways Agency (HA) investigations of highway sub-structures in Gloucestershire, Somerset and Wiltshire. The total number of highway cases in this region is now about 50. The remaining cases have occurred in a wide range of structures, buildings and environmental conditions. Most of these new cases have taken place in conditions that were anticipated in the TEG Report. The few exceptions are discussed under Section 8 of this review. The TSA field cases discovered since the publication of the first review in 2000 are itemised as follows:

- 16 new HA cases from the Gloucestershire/Wiltshire area
- 1 new HA cases from County Durham
- 6 new cases associated with sulfate-bearing brickwork
- 2 cases of internal sand/cement render contaminated with gypsum
- 1 set of harbour steps in S. Wales exposed to seawater
- 2 new cases of heave in ground floor slabs resting on sulfate-bearing fill
- 1 case in a concrete kerb forming part of a drainage adit in S. Wales

Two new field cases of TSA occurred in buried concrete containing siliceous aggregates, reinforcing the view that concretes containing little or no carbonate can be affected by TSA if an external source of carbonate ions is available, for example from groundwater. Currently the guidance for specification of concrete for use in sulfate-bearing ground presumes that restriction of the carbonate content of aggregate is an effective measure for combating TSA. This measure will plainly be less effective when other sources of carbonate are available for the thaumasite reaction. Currently the understanding of the problem is insufficient to underpin amendment of guidance. This awaits the outcome of

³ BRE Special Digest 1: Concrete in aggressive ground: Parts 1 to 4. CRC, London, 2001.

further research on the relative contribution that sources of carbonate other than aggregate make to the occurrence of TSA.

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 DTI, HA, EPSRC and industry bodies. Some initial findings have become available and are reported in this review. Several major laboratory and field investigations will not be concluded until 2003.

Of the numerous research requirements identified by the report of the TEG, only three items would currently appear not to be receiving attention, namely:

- Diagnostic techniques for buried structures obviating the need for excavation.
- Tests on waterproofing admixtures.
- Effects of TSA on chloride binding of Portland cement concrete

Other research requirements that have emerged from this review are

- The need for a field trial of concrete mixes currently recommended for use in sulfate-bearing ground by BRE SD1, BS 5328 and BS8500.
- The need for a selection of presently available repair techniques to be subjected to accelerated exposure trial under laboratory conditions. This is in order to provide timely interim guidance on effectiveness of repair materials for TSA-affected concrete.

Guidance or interpretative documents completed March 2002

Key items of new published guidance include:

- New BRE Special Digest 'Concrete in aggressive ground'. Parts 1 to 4.
- Amendments to BS 882. Specification of aggregates from natural sources for concrete.
- Amendments to BS 5328: Concrete: Parts 1 to 3.
- BS 8500: Parts 1 to 4: 2001. Concrete – complementary British Standard to BS EN 206-1.

These are generally in line with the guidance given in the TEG Report, but 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.

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1. INTRODUCTION

Following the identification of the thaumasite form of sulfate attack (TSA) on the concrete foundations to a number of bridges on the M5 motorway in 1998, the then Minister for Construction established the Thaumasite Expert Group (TEG) under the chairmanship of Les Clark, Professor of Structural Engineering, University of Birmingham. It was asked to report on the nature and threat of this phenomenon and to provide interim guidance on its avoidance.

When the TEG Chairman presented the Group's Report ⁽¹⁾ to the Minister in December 1998, it was agreed that a review of the Report's recommendations would be carried out one year after the publication of the Report. The findings of this Review were received by the Minister in spring 2000 and published on the DETR web site in April 2000 ⁽²⁾. A summary was published in the magazine Concrete in June 2000. ⁽³⁾

A recommendation of the one-year review was that a second review of the TEG Report's recommendations be instigated in autumn 2001 to take account of further developments in respect of TSA and, in particular, of the findings of laboratory and field trials being carried out on the resistance to TSA of specific concrete mixes.

For this second review, members of the TEG and other key stakeholders were requested to provide any relevant new information. The various documents, which informed the Review, are summarised in Section 2 and full details given in Annex 1.

In this second review, the Thaumasite Expert Group Report (TEG Report) is considered under the following headings:

- New guidance produced by others as a follow up to the TEG Report (Section 3);
- Dissemination of new guidance (Section 4);
- Current impacts and awareness of TSA (Section 5);
- Problems in the practical interpretation and implementation of the TEG Report guidance (Section 6);
- New cases of TSA in the UK (Section 7);
- New features of TSA (Section 8);
- New UK research on occurrence and mitigation of TSA (Section 9);
- Guidance documents in preparation at March 2002 (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 second Review and the recommended actions are summarised in Section 11.

2. DOCUMENTATION SUBMITTED TO THIS REVIEW

Documents submitted for consideration in the Review are listed in Annex 1. They comprise:

- Letters from members of the TEG presenting an update of 'stakeholder' views as at autumn 2001.
- Reports of field investigations on Highways Agency structures investigated for TSA.
- Reports of research on aspects of concrete and the ground relevant to TSA prepared in April 2000 – March 2002.
- New interpretation and guidance documents published during April 2000 – March 2002.
- Draft new documents proposed for publication in 2002.

3. NEW GUIDANCE PRODUCED BY OTHERS AS A FOLLOW UP TO THE TEG REPORT

The following guidance documents have been published in the period April 2000 to March 2002:

(i) **BRE Special Digest 1 (SD1): Concrete in aggressive ground.**

SD1 ⁽⁴⁾ comprises the new BRE guidance for concrete in aggressive ground. This replaces Digest 363 which was first published in 1991 and subsequently revised in 1995 to include preliminary guidance on TSA.

In respect of TSA, the guidance in SD1 is founded on that given in the TEG Report ⁽¹⁾, but the detailed provisions have evolved following extensive consultation with construction stakeholders.

Key new features of SD1 as compared to the TEG Report are:

- introduction of Aggressive Chemical Environment for Concrete (ACEC) class to clarify the modifications to initial ground sulfate classification that take account of factors such as acidity, groundwater mobility and type of site;
- the introduction of the term Design Chemical (DC) Class for the concrete qualities needed to combat sulfate attack;
- the introduction of the DC classes for acidic conditions which place no restriction on the type of cement to be used;
- the dropping of the requirement for any Additional Protective Measures (APM) for Class 2 sulfate conditions and/or when groundwater is Static;
- the provision of further APM as alternatives to 'design drainage';
- the dropping of the use of Range B and/or Range C aggregates as an APM;
- the introduction of 'starred' DC classes which permit a reduction in the number of APM when Range B and/or Range C aggregates are used;
- an interface with emerging European Standards for cement and concrete.

SD1 has been published in four parts, owing to its greater length and complexity as compared with D363:

Part 1: Assessing the aggressive chemical environment deals with assessing the chemical aggressiveness of the ground. It shows how to derive the ACEC class of a site by determining soluble sulfate and magnesium, potential sulfate (from oxidation of any pyrite), the pH and mobility of groundwater. It also takes into account whether the site is natural ground or brownfield.

Part 2: Specifying concrete and additional protective measures deals with specification of concrete for given aggressive ground conditions. Starting from the ACEC class of a site, together with the proposed use and section thickness of the concrete, a range of concrete qualities are recommended (14 DC Classes), higher specifications requiring use of one or more APM. The DC classes are specified in terms of Aggregate

Carbonate Range, cement group, minimum cement content and maximum free water/cement ratio.

Part 3: Design guides for Common applications

Three series of Design guides for specifying concrete are included:

- Series 1 for non-domestic buildings;
- Series 2 for low-rise domestic buildings;
- Series 3 for transport structures.

Each Design guide leads the user directly from the ACEC class to the appropriate DC class and to the relevant number of APM. Each guide is limited to a particular type of concrete construction and hydrostatic and carbonation conditions. In addition to recommending the appropriate DC class and APM, the Design guides carry specific design notes based on expert experience.

Part 4, Design guides for specific precast products

This Part covers :

- Pipeline systems;
- Precast linings for tunnels and shafts;
- Precast box culverts;
- Precast concrete masonry blocks.

The products are grouped into a separate part of SD1 as their manufacture, combined with tight quality control and surface carbonation before use, are considered to give them greater resistance to chemical attack. The guidance, therefore, differs from that for in-situ concrete. As the products are made to be suitable for use in mobile groundwater conditions, they need only to be specified to meet particular sulfate and acidity conditions, rather than comply with ground assessments in terms of ACEC class.

(ii) Amendments to BS 5328: Guide to specifying concrete

BS 5328: 1997: Concrete, comprising four Parts, is currently the Standard used for most below-ground concrete in the UK. Amendments have been prepared to align it with BRE SD1. These comprise Amendment 2 to Part 1, Amendment 3 to Part 2 and Amendment 5 to Part 3 ⁽⁵⁾. Since BS 5328 is scheduled to be withdrawn in December 2003, when BS 8500 takes precedence, the Amendments are limited to giving the requirements to meet the specified Design Chemical class and are applicable only to 'Designed' and 'Designated' concrete mixes ('Prescribed' and 'Standard' mixes remain unchanged). Guidance on selecting the DC Class and the number of APM is not given. For these the reader is referred to BRE SD1

The Amendments were sent for public comment in October 2001 and it is anticipated that revised versions of BS 5328 incorporating the Amendments will be published in mid 2002.

(iii) Amendment No 1:2000 to BS 882. Specification of aggregates from natural sources for concrete

An amendment to BS 882 was published in 2002 ⁽⁶⁾ to require the aggregate producer to provide information on the carbonate content of the aggregate, expressed as the equivalent calcium carbonate content, in accordance with SD1.

(iv) BS 8500: 2002. Concrete – complementary British Standard to BS EN 206-1

BS 8500 standard was published in February 2002 ⁽⁷⁾. It comprises the following 2 parts:

- Part 1: Method of specifying and guidance for the specifier;
- Part 2: Specification for constituent materials and concrete.

This standard gives more information than that given in BS 5328, but it is still necessary for the user to be familiar with BRE SD1. As this is a concrete standard, no information on classifying the site is provided. The starting point is information on the ACEC Class from the site survey. It is anticipated that experienced users will be able to take the site information provided and use Part 1 of BS 8500 to select the Design Chemical class or designated concrete and the number of Additional Protective Measures for many in-situ applications. Less experienced users will need to check their conclusions using the Design guides in BRE SD1: Part 3. Unlike SD1, BS 8500 does not provide guidance on selecting the DC class and number of APM for precast concrete products.

When a Design Chemical class is specified, the producer has to comply with the comprehensive specifications given in Part 2 of BS 8500. These define the constituent materials and limiting values that are permitted and, in the case of designated concrete, the characteristic strength. The limiting values are identical to the recommendations in BRE SD1.

(v) BCA Guide. Specifying Concrete to BS-EN 206-1 / BS 8500 : Concrete resistant to chemical attack

This guide ⁽⁸⁾ is one of a series of publications on concrete produced to support the introduction of BS 8500. It was drafted by a BCA-led consortium part funded by a DTI Pil project. It gives concise guidance on the specification of concrete when sulfate and acid ground conditions will be encountered. It gives recommendations similar to SD1. However, requirements for concrete in ground containing waste materials or in structures exposed to chemicals are not covered.

(vi) CIRIA publication C569: Concrete technology for cast in-situ foundations

CIRIA report C569⁽¹⁰⁾ focuses on the concrete technology issues relating to common buried foundation types including piles, diaphragm walls and pad, strip and raft foundations. This report provides guidance on the analysis and construction parameters to be considered in the selection of in-situ concrete for foundation applications. The report includes a detailed discussion of the problem of sulfate attack on concrete, including TSA. A case history is given of TSA to one of the M5 bridges, the information being drawn from the TEG Report. Comprehensive guidance, based on SD1, is given for the specification of concrete for sulfate/sulfide-bearing ground.

4. DISSEMINATION OF NEW GUIDANCE

Since the publication of the One-Year Review, the guidance on concrete in respect of TSA initiated by the Report of the TEG has been incorporated into new and revised documents as listed in Section 3. Publication of these derived documents has been backed by an intensive national dissemination exercise, led by BRE and anchor-funded by the DTI, to familiarise users with the problem of TSA and the latest guidance to combat it:

- Numerous news items and papers have been published in the construction press, journals and on the BRE internet web site.
- Meetings, seminars and workshops to present and explain the new guidance to professionals have been held in 25 locations across the UK. The events have been organised by local groups of the Concrete Society, Institution of Civil Engineers, Institution of Structural Engineers and other professional bodies representing engineers and material specialists. Events have included evening, half-day and full-day presentations and workshops, the latter enabling delegates to apply the new guidance to tutorial exercises. Overall, these events have been attended by more than 1000 construction professionals, including representatives of most leading construction firms and stakeholder organisations.

5. CURRENT IMPACTS AND AWARENESS OF TSA

Our overall impression is similar to that reported in the One-Year Review: that the TEG Report has been well received by the key stakeholders in the construction world 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.

The publication of new BRE guidance (SD1) ⁽⁴⁾ and the amendment of BS 5328 ⁽⁵⁾ has meant that now the industry is turning to these new documents for guidance rather than to the TEG Report. However, these new documents implement the guidance that was originally in the TEG Report.

In respect of existing buried concrete construction, the greatest impact to date and also greatest awareness of the TSA problem to date lies with the Highways Agency (HA). The HA is undertaking a strategic assessment of structures in its care to check for this form of chemical attack. This has taken the form of a desk study of risk factors and a field investigation of those structures assessed as at highest risk of TSA. The experience of the HA has shown that where the risk factors identified in the TEG Report are all present, the prevalence of TSA is high. Where necessary, remedial measures involving concrete repair and protection have been undertaken. This initiative gives assurance that the serviceability and safety of structures in HA care will be maintained.

The TEG is, however, concerned that, as far as it is aware, no other owners of existing structures with buried concrete elements have undertaken a similar assessment. The TEG Report advised that there was minimal danger of sudden collapse of structures, provided that structures were adequately monitored and assessed. The experience of the HA indicates that there could be a large number of structures with some degree of attack to buried concrete. It is therefore important that owners of key structures do assess the risks and take necessary measures.

In respect of new build, the various new publications (Section 3), together with the widespread dissemination activities (Section 4) have attempted to ensure that construction professionals in the UK are well informed about the problem of TSA and steps that should be taken to avoid it in new construction. Feedback indicates that producers of ready-mixed concrete and precast concrete products, together with most of the major engineering and construction firms are aware of and are using the new guidance in respect of TSA. Familiarity and use of the new guidance in smaller concerns, and in particular the domestic housing sector is, however, still currently low.

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

6.1 Action on issues that were identified in the One-Year Review

A number of significant issues were identified in the One-Year Review including:

- (i) the need for additional procedures for establishing the carbonate content of aggregate;
- (ii) the need for clarification of groundwater mobility;
- (iii) the need to recommend tests on groundwater rather than soil for sulfate assessment;
- (iv) the need to take into account the possible role of attack on concrete from sulfuric acid generated by oxidation of pyrite;
- (v) the need for further options for Additional Protective Measure (APM), in addition to drainage;
- (vi) the scope for relaxing the procedure leading to sulfate class based on Potential Sulfate;
- (vii) the relaxation of the need for APM in Class 2 Sulfate conditions.

By and large these issues have been addressed in the recently issued guidance in BRE SD1, BS 5328 and BS 8500 (see Section 3). Guidance has not been modified in respect of item (iv) pending the outcome of on-going research.

6.2 Other issues addressed during drafting of BRE SD1 and BS 5328

The following issues were raised during extensive consultation with industry sectors on BRE SD1 and the amendments to BS 5328:

- (i) Problems were encountered by the manufacturers of some pre-cast concrete construction products in complying with the TEG Recommendations. Such products, included precast concrete pipeline systems, segmental linings for tunnels and shafts, and pre-cast culverts. These problems have been resolved by the inclusion of specific design guidance for these products as Part 4 SD1.
- (ii) The need to avoid possible double counting towards sulfate resistance, which can occur when the use of Range B or C aggregates is allowed to count directly as an additional protective measure. This issue has been resolved by removing 'Use of Range B or C aggregates' as an APM and instead specifying these in

'starred' DC Classes, the use of which allows DC-Class to be reduced by 1 for Range B and by 2 for Range C.

- (iii) The need for separate provision for concrete to resist acid attack, such that resistance to the acid is provided by cement content independent of cement type. This has been facilitated in SD1 by the introduction of 'z' designated Design Chemical classes for concrete.
- (iv) The need to clarify the role of drainage as an APM, and to be sparing with the recommendation of this measure, as there are numerous construction scenarios in which implementation is impractical. SD1 has tackled this requirement by better explanation of drainage and redefinition of the APM as 'Addressing site drainage'. Also, by not prioritising the use of drainage - except in the case of concrete that would otherwise be subject to significant hydrostatic pressure.
- (v) Extensive comment was received during the drafting of SD1 about the perceived complexity of its guidance for concrete in sulfate-bearing ground now that extra factors such as allowance for oxidation of pyrite, Aggregate Carbonate Range, Structural Performance Level and Additional Protective Measures have been added to the traditional considerations. This concern has been addressed by the inclusion in SD1 of numerous flow diagrams to guide the user through the procedures for ground assessment and concrete specification, and by addition of Design guides for common types of concrete construction which recommend concrete quality and APM in one step.

6.3 New issues raised by correspondents

New issues raised by correspondents (see Annex 1 for list) are:

- (i) “The requirement for up to three Additional Protective Measures (APM) has caused problems in implementation. The TSA problem arose, in part, because the groundwater aggressivity, particularly in ‘disturbed’ Lower Lias Clay, was incorrectly assessed. This is unlikely to be the case in future, and as a consequence I believe the requirements for APM are probably too onerous. Could consideration be given to reducing the number of APM by one?”

Response

We are aware of difficulty of providing as many as three APM for some construction situations. SD1 has gone a considerable way in reducing the number of APM required in given situations. When there is better information on the performance of the concrete mixes recommended to resist TSA, the requirements for APM will be reviewed.

- (ii) “In the context of repair of concrete affected by TSA, the TEG Report should have stated that soil conditions have been found to be very variable around sites where TSA has been found. Therefore, on such sites the repair should assume at least DS-4 conditions regardless of lower results which may have been found from current soils testing, unless measures are taken to isolate the foundation from local groundwater.”

Response

We endorse this view and advocate inclusion of this advice in any future guidance on the repair of concrete affected by TSA.

- (iii) (c) “In respect of repair of concrete affected by TSA, materials such as polymer modified cementitious mortars, and alternative cementitious materials such as BRECEM and calcium aluminate, are likely to exhibit enhanced durability and may have significantly lower permeability than concretes listed in Table 9.1 of the TEG Report. In some cases where the depth of TSA has been limited to less than 20 mm, the most appropriate repair method may be to remove the affected concrete and to replace with such a repair material instead of casting new concrete. However, the equivalence of such materials to the recommended mixes and any requirement to apply APM in conjunction with these is not stated in the TEG Report or subsequent derived guidance.

Acceptance criteria are urgently required for the properties of repair materials and coatings which will allow testing accreditation against various classes of aggressive ground conditions. As an interim measure, the use of specialist proprietary repair mortars and requirement for any associated APM should be at the discretion of the designer, who should take into account the severity of the environment, the performance level of the structure and the properties of the repair material.”

Response

The TEG Report (Appendix C, Item 8 of Future research topics) recognised the need for research on the effectiveness of repair materials and associated APM to provide a basis for future guidance on the repair of TSA-affected concrete. A Highways Agency funded field project devised in response to this requirement is described in Section 9.2.2 of this Report. The findings of this study will not, however, be available for some years.

We note the need to provide timely interim guidance and therefore recommend that, in addition to field trials of repairs and coatings, a selection of presently available repair techniques be subjected to accelerated exposure trial under laboratory conditions to determine resistance to renewed TSA. Pending the outcome of such research, we endorse the above view of the correspondent that, until further information on performance is available, the use of specialist proprietary repair mortars and requirement for any associated APM should be at the discretion of the designer.

7. NEW CASES OF TSA IN THE UK

7.1 General

About 50 new cases of TSA have been identified in cementitious components of buildings and structures in the UK since the publication of the TEG Report and 30 since the publication of the first review in 2000. The majority of these were in the foundations of bridges founded on sulfate-bearing Lower Lias Clay², found as a result of Highways Agency (HA) investigations of highway sub-structures in Gloucestershire, Somerset and Wiltshire. The remainder have occurred in a wide range of structures, buildings and environmental conditions. Most of these new cases have taken place in conditions that were anticipated in the TEG Report.

Additionally there have been a number of cases reported where concrete has 'thaumasite formation' (TF) present. The TEG Report defined this as 'thaumasite formed within existing pores and cracks in the concrete where there is no softening of the matrix'. It may be a precursor of TSA.

7.2 New cases of TSA in HA Area 2 (M5 and M4 in Gloucestershire, Somerset and Wiltshire)

In HA Area 2 (south western England), currently being managed by W S Atkins, the HA have a phased strategy for identifying and remediating cases of TSA in highway structures, and in particular in bridge foundations and sub-structures. Phase 1 comprised an initial desk study, carried out on 733 highway structures including some 400 bridges in the Area. Each structure was allocated a 'priority factor' depending on its Structural Performance Level, the expected ground conditions, the slenderness of the buried concrete members etc. Two hundred of the bridge structures with the highest priority factor were then selected for a Phase 2 study involving window sampling to obtain adjacent soil and groundwater samples for chemical analysis. The subsequent results were used in conjunction with knowledge of the backfill and groundwater mobility to produce a more accurate 'risk rating' for each structure.

HA and WS Atkins have used these risk ratings as the starting point for a Phase 3, 20 year rolling assessment programme, for intrusively investigating the bridge structures rated as at highest risk in Area 2. The findings of 25 investigations carried out since April 2000 have been received for the review. Of these, 16 of these were found affected by

² The geological term 'Lower Lias Clay' is used here as it is well known to construction professionals. However, the stratum has been renamed 'Charmouth Mudstone Formation' in recent British Geological Survey literature.

TSA. In four additional cases, just TF was present. The cases identified have ranged in severity from slight to severe. One case near to Junction 11a of the M5 is possibly the most severe HA case to date, with softening of concrete to 60 mm depth. Only an exploratory investigation has been undertaken so far but a more detailed study is planned.

Important observations which have emerged from the Area 2 investigations to date are:

- All TSA-affected concrete elements have contained Range A limestone aggregates.
- The cement used in the affected concrete elements has most often been identified as PC, but in some cases SRPC was used.
- Bituminous waterproofing applied to some of the buried concrete exposed may have prevented the onset of TSA, although more evidence is needed before this can be positively confirmed.
- There has been no obvious signs of TSA in precast concrete pipes uncovered in the vicinity of TSA-affected buried structural concrete.

Some of the M4 overbridges have post-tensioned concrete elements which run below carriageway level to 'tie' the bridge abutments. Such elements need to be added to the critical elements list of the TEG Report as minor TSA was found in one such bridge on the M4 near Swindon.

7.3 New cases of TSA in HA Area 18 (County Durham)

Halcrow Group are carrying out a phased investigation of structures in Area 18 (north eastern England) for the HA. Up to autumn 2001 they had carried out intrusive investigation of six bridges. The presence of thaumasite in the buried structural concrete has been identified in two of these. At the first site, on the A66(M), (needles of thaumasite within voids, was found to a depth of 3.5 mm. The concrete was assessed as Class 1 to BRE Digest 363 and contained a Range A limestone aggregate. Possible sources of the sulfate were made ground comprising dark brown clay with occasional fragments of red shale (burnt colliery spoil), and in-situ clay (Till?) containing fragments of coal. Chemical analysis of the former gave a maximum Sulfate Class of 2 from a water/soil extract. Both materials had a significant oxidisable sulfides content with a maximum of 1.61 SO₄ indicating pyrite to be present.

At a second site, on the A1(M) TSA was identified, in two piers constructed with different concretes. The east pier had a maximum depth of TSA of 6 mm with no surface softening. This concrete was assessed as Class 1 to Digest 363, having a PC content of 390 kg/m³ and a water/cement ratio of 0.56. The aggregate was Range A, comprising limestone coarse and siliceous fine aggregate. The west pier had TSA penetration to a depth of 22 mm including a 3 mm softened zone (Zone 4). This is surprising, since the concrete contained Range C aggregate, with siliceous gravel coarse and fine fractions. It was assessed as Class 1 to BRE Digest 363, having a Portland cement (PC) content of 330-380 kg/m³ and a water/cement ratio of 0.58.

The source of the sulfates was possibly made ground containing occasional to abundant fragments of shale (unburnt colliery spoil). This had a current maximum Sulfate Class of 1 from 2:1 water/soil extract tests. It did however contain a significant amount of Oxidisable Sulfide (1.7 g/l SO₄) indicating pyrite to be present.

7.4 New cases in sulfate-bearing brickwork

Since the publication of the first review of the TEG Report, BRE has found a further six cases of TSA in sulfate-bearing brickwork structures, some less than two years old. Four of these were rendered external brickwork to buildings, one was a free-standing unrendered garden wall and the sixth was the unrendered columns and benches in an old underground factory. All of the cases were located in the South of England. There appears to be a steady trickle of reported cases of TSA in brickwork and it would appear that the prevention of such problems is not being currently addressed by some practitioners. Current UK guidance recommends that common sulfate-bearing bricks should not be used in exposed wet conditions. Hence, many architects and builders apply render coats in order to keep such brickwork dry. If, through poor detailing or workmanship, the rendering is not sufficiently watertight, then a TSA problem may arise. Once water penetrates through to the brickwork, all the ingredients are present for TSA, which often proceeds at a relatively rapid rate at the render/brickwork interface and in mortar joints. We therefore recommend that guidance on the rendering of brickwork be revised to inform of a potential TSA problem and emphasise the need for good construction practice and workmanship.

7.5 New cases in internal rendered walls contaminated with gypsum

Two new cases of TSA have been identified by BRE within internal sand/cement rendered walls of two UK properties, again in the South of England. In both cases the walls had become damp, one through inadequate waterproofing of bathroom tiles and the other through a lack of a damp proof membrane. As the cement paste in both of the renders was contaminated with gypsum plaster, it was hardly surprising that TSA occurred at the back of the each render, near the intersection with underlying brickwork. What was surprising was that the temperature of both properties would have normally been around 20°C or above, which is a temperature range not normally associated with rapid TSA development.

7.6 New case in harbour steps exposed to seawater

TSA has been found by BRE and W S Atkins to be the cause of severe, rapid deterioration of the bedding mortar in recently constructed harbour wall steps in South Wales. Sulfates from seawater had penetrated the mortar, which suffered severe cracking and spalling within two years of construction. Apart from TSA, a further end product of deterioration was identified in the form of large, non-interlocking crystals of

calcite (termed popcorn calcite) in the areas of the mortar previously occupied by cement paste. A parallel investigation of the structural concrete foundations to the steps has also shown early stages of TSA.

7.7 New cases of floor slab heave

TSA has been diagnosed by BRE to be the cause of damage to floor slabs in two domestic buildings in the Bristol area. These buildings were constructed in the 1950s with concrete floor slabs cast on hardcore comprising brick rubble (from demolished buildings) without a separating damp-proof membrane. TSA had caused expansion of the slab and softening of the underside, resulting in cracking and uplift of the concrete. In both cases the concrete had carbonate aggregate. The source of the sulfate was the demolition rubble.

7.8 New case in a drainage adit

Halcrow Group has found minor TSA in a drainage adit in South Wales, which was constructed in 1985/86 as part of a landfill stabilisation measure. The TSA had caused softening, expansion and discolouration to 10 mm depth in a reinforced concrete invert made from site-batched concrete. Petrographic examination of the affected concrete indicated a cement content of 450 kg/m³, a water/cement ratio of 0.49 to 0.55 and an estimated in situ cube strength of 35 N/mm²: a specification that would be expected to meet Class 2 sulfate conditions to BRE Digest 363, 1996. The coarse and fine aggregates consisted of crushed particles of bituminous limestone and the cement type was sulfate-resisting Portland cement. The source of sulfates was groundwater which was locally infiltrating into the adit.

8. NEW FEATURES OF TSA THAT HAVE EMERGED SINCE APRIL 2000

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

(i) **Different types of sulfate-bearing ground have contributed to TSA.**

Three further sources of sulfate in the ground have been identified leading to TSA:

- Kimmeridge Clay
- Rheatic Mudstone
- Railway ash

The first two strata were identified in Table 3.1 of TEG Report as a potential sources of sulfate. The latter material is presumed to be a combustion product mainly derived from coal (a known source of sulfate).

Additionally TSA has been found in mortar exposed to **sea water**. Note, however, that at this time there is no reason for concern about structural concrete exposed to sea water, since as noted in the Report of the TEG, 'measures such as the use of high quality concrete and the provision of extra cover to reinforcement, both commonly used to counteract other causes of attack of sea water on concrete, such as corrosion of steel reinforcement from chlorides, will at the same time make concrete more resistant to TSA'.

(ii) **Occurrence of TSA in concrete having siliceous aggregates**

Two new field cases have been reported which support the possibility mentioned in the TEG Report (Chapter 2.4.3) that concretes containing little or no carbonate could be affected by TSA if an external source of carbonate ions was available. One TSA case, in HA Area 18 (reported in Section 7.2) was in PC concrete made with Range C aggregate comprising low-carbonate siliceous gravel. The other field occurrence was at the Shipston on Stour field trial, in three year old specimens of PC concrete made with siliceous coarse and fine aggregate (see Section 9.1.2). In both cases the carbonate source is likely to have been groundwater.

Other features from site investigations worthy of note are:

(i) **Effectiveness of coatings**

W S Atkins have concluded that bituminous waterproofing applied to some of the buried concrete exposed to sulfates in HA Area 2 may have prevented the onset of TSA.

(ii) **No TSA was (visually) observed by W S Atkins in precast concrete pipes which were located closely adjacent to concrete affected by TSA.**

9. NEW UK RESEARCH ON OCCURRENCE AND MITIGATION OF TSA

9.1 Research data made available April 2000 – March 2002

The TEG Report listed in its Appendix C the research currently being carried out on aspects of the TSA problem and the requirements for further research. These are itemised in Annex 2 of this Review together with the current status. In response to needs identified, a concerted programme of research is currently underway in the UK. Research is being carried out by BRE, by five universities and by industry. The key findings will be presented at a Conference to be held at BRE in June 2002 [⌘] to which more than 60 papers have been submitted, including many from overseas.

The principal UK research studies for which findings have become available since publication of the One-Year Review are:

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

This is research at BRE (Dr N J Crammond), sponsored by the DTI 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 C₃A content of 7.2% by mass, a SRPC and a combination of PC blended with one or other of two slags (ggbs). 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 at six-years are: ⁽¹¹⁾

- (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. However, it also occurred in some flint aggregate concretes and to a lesser extent at the higher temperature of 20°C.
- (ii) It has proven difficult to differentiate between conventional sulfate attack and TSA purely by visual assessment. Thaumasite was the main sulfate-bearing reaction product detected in the fifty deteriorated samples examined using X-ray Diffraction and petrographic microscopy. However, this does not necessarily mean that TSA was the only mode of deterioration, just that it was the most pervasive.
- (iii) BRECEM was the most sulfate resistant cement type examined in this study.
- (iv) Concretes made with 70% ggbs/30% PC and normal quality carbonate aggregates performed extremely well and showed no evidence of TSA in any of the solutions. The presence of carbonate aggregate in the mix appeared to substantially improve the sulfate resistance of 70% ggbs concretes.

[⌘] First International Conference on Thaumasite in Cementitious Materials. BRE, 19-21 June 2002.

- (v) However, 70%ggbs/30%PC concretes made with all-flint aggregate did not perform as well as their PC equivalents at 20°C; nor did they perform quite as well as similar concretes studied previously at BRE.
- (vi) There was no discernible difference between the performances of SRPC concretes containing normal quality carbonate aggregates and those made with PC at 5°C.
- (vii) Overall, the worst performers were concretes made with PC, as would be expected.
- (viii) After six years, all of the concretes containing the low quality carbonate aggregates stored at 5°C have fallen apart in the strongest magnesium sulfate solution irrespective of cement type. The quality of these concretes was much inferior to those containing normal concreting aggregates and their use as structural-grade buried concrete would be debatable.
- (ix) The degree of TSA increased with the sulfate concentration of the test solution and with time.
- (x) 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 (contact face effect).
- (xi) The protection afforded to PC and SRPC concrete specimens through air-curing has gradually diminished over the years. It is uncertain how much of this is due to the contact face effect. The air-cured 70%ggbs concretes are still in perfect condition.
- (xii) A new reaction mechanism has been observed in which large non-interlocking calcite crystals precipitate in the area of the degraded concretes formerly occupied by cement paste hydrates. This has been termed 'popcorn' calcite' precipitation and appears to be related to TSA.

9.1.2 Shipston on Stour field trial of specific concrete mixes exposed to sulfate-bearing groundwater

This is research at BRE (Dr N J Crammond), sponsored by a DTI Framework programme. In 1998, 196 test specimens, with a range of concrete compositions of varying quality using different binders and aggregates were buried on a trial site at Shipston on Stour, Central England. The ground comprised Lower Lias Clay with wet, Sulfate Class 3 ground conditions at a reasonable working depth (2.5 m) for test specimens. The test specimens were buried in two trenches with half to be excavated for assessment in June 2001 after three years, and the other half to be excavated for assessment after ten years. A selected number of specimens were also exposed in the laboratory at 5°C to a sulfate solution that simulated the Shipston groundwater.

The field trial concrete mixes were designed to provide combinations of aggregates and binders previously shown to have given rise to deterioration due to TSA (under laboratory conditions) and combinations, which had proved resistant. Most of the trial concretes took the form of specimen cubes 250 x 250 x 250 mm in size (both precast and cast in situ), but a number of precast concrete masonry blocks were also included. Ten types of cement have been included in the trial: SRPC, two PCs, PLC, PC/30% pfa,

two ggbs/PCs, PCs containing metakaolin and microsilica and BRECEM. Four types of aggregate have been included in the trial: Magnesian limestone, Carboniferous limestone, Jurassic limestone and siliceous aggregate. The main group of mixes all had a nominal binder content of 320 kg/m³ and a water/binder ratio of about 0.55. There was also an 'outlier' group of mixes with a binder content of 290 kg/m³ and a water/binder ratio of about 0.75. These mixes are therefore generally lower in binder content and higher in water/binder ratio than the mixes currently recommended in SD1 for Sulfate Class conditions.

Excavation of the three-year specimens in June 2001 confirmed that a time scale of three years exposure to Class 3 sulfates on site has been sufficient to differentiate between TSA-resistant concrete mixes and those which are susceptible. The surfaces of many of the test specimens were found covered with a white-coloured reaction product identified by X-ray Diffraction (XRD) as thaumasite. The visual results correlate well with those of the parallel laboratory study, except for concretes containing pfa and 40% ggbs. A more detailed analytical programme is now underway at BRE using XRD, scanning electron microscopy and petrography. It will not be possible to draw definitive conclusions on the 3-year findings until this work is completed.

The key findings on the specimens excavated after three years, available from an interim report ⁽¹²⁾, are as follows:

(i) ***Ground and temperature conditions at specimen location***

Groundwater conditions at the 2.5 m specimen depth are Mobile, with sulfate concentrations in the lower-half of Sulfate Class 3, and a neutral pH of about 7.5, ie ACEC Class AC-3 conditions.

Ground temperatures have varied seasonally between about 9°C and 13°C at the 2.5 m depth of the concrete specimens. This is within the temperature range which encourages the occurrence of TSA in susceptible concrete.

(ii) ***Possible external carbonate source***

The sulfate ions in groundwater are associated primarily with calcium (Ca⁺⁺), magnesium (Mg⁺⁺) and sodium (Na⁺) cations. The groundwater is near-saturated with respect to gypsum (CaSO₄.2H₂O). There is an anionic imbalance in the groundwater analyses in the form of surplus cations. This may be due to the presence of carbonate or bicarbonate ions. If so, this may be the explanation for the fact that PC concretes containing siliceous aggregates have not performed well, see (iii), the carbonate ions necessary for TSA having come from the groundwater.

(iii) ***Condition of specimens after three years exposure to Class 3 conditions***

- The precast concrete masonry blocks containing either siliceous aggregate or pfa were in good condition, but those containing Jurassic Oolitic limestone aggregate were coated with thaumasite.

- The precast concrete cubes had performed much better than their cast-in-situ counterparts.
- The poorer quality outlier concrete mixes showed more evidence of surface deterioration compared with their equivalent main mixes.
- The cast-in-situ cube side faces in contact with undisturbed/in-situ clay appeared to have been attacked to a greater extent compared with the side faces exposed to backfill clay. (This is probably due to dilution of sulfate-bearing Lower Lias Clay backfill with superficial clay having little or no sulfate).
- All cast-in-situ concrete cubes made with either PC or PLC have shown significant signs of surface attack irrespective of aggregate type. The degree of attack was less in the concretes containing siliceous aggregate but was still substantial. This finding had not been observed during the previous BRE sulfate field trial excavations at Northwick Park in London. The main difference between the groundwater chemistry at the two sites is probably related to the type and quantity of carbonate ions in solution.
- The SRPC cast-in-situ concretes containing siliceous aggregate had performed satisfactorily whereas those made with carbonate aggregates have shown significant signs of attack.
- All concretes made with blended cements containing pfa, ggbs (including BRECEM), microsilica and metakaolin performed more or less satisfactorily irrespective of aggregate type.

9.1.3 The design of structural concrete to resist the thaumasite form of sulfate attack.

This is a three year Pil research project, commenced at BRE (I R Holton and Dr N J Crammond) in June 1999, supported by DETR (now DTI), QPA, BCA, CSMA and UKQAA.

The objectives are to develop the key specifications for new works to prevent premature deterioration in concretes due to TSA, and to provide better quantified advice for the assessment of the future life of existing structures.

A laboratory-based investigation is being carried out to establish the resistance of different binders (including PC, ggbs/PC, PFA/PC and SRPC) to TSA, the susceptibility of different types of limestone and the acceptable threshold of carbonate in aggregate sources, including sands and gravels.

An initial assessment after 1 years exposure was carried out in summer 2001. The findings will be subjected to verification in 2002 and 2003, after 2 and 3 years exposure.

The key project findings, available from an interim report ⁽¹³⁾, are as follows:

(i) Performance of the different binders

The performance of the different binders against the recommendations of the TEG were variable.

- The 70% slag (ggbs) mixes were performing well in all sulfate classes.
- The 30% ash (pfa) mixes were performing well under Class 2 conditions but were showing some deterioration in more aggressive conditions.
- The SRPC mixes were showing poor performance with the high carbonate aggregates and variable performance with the low carbonate aggregates.
- In contrast the Portland cement binders with high carbonate aggregates were performing well in the Class 2 solutions (the most aggressive conditions at which they are recommended) but were showing some attack in these conditions with the low carbonate aggregates.
- Some mixes outside the TEG recommendations were also performing well at one year; in particular the 45% pfa and 50 % ggbs mixes.

(ii) Performance in respect of carbonate content of the aggregate

Overall, there is no apparent correlation to date between the amount of attack and the carbonate content of the aggregate.

9.1.4 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 in a Report to the HA ⁽¹⁴⁾. The findings of investigations of ground, groundwater and concrete were collated in a database which ultimately totalled 23,000 soil and 5,000 concrete records. Correlations made between occurrence and severity of TSA and the chemical and physical characteristics of soil and groundwater have enabled postulated mechanisms of TSA to be validated. The key findings are:

- 25 concrete structures were examined in the Lower Lias Clay, most being about 30 years old and located in Lower Lias Clay backfill. Of these, 19 had some degree of sulfate attack, either TSA or TF.
- None of the structures were weakened by TSA to the extent that they had an imminent safety risk. However, it was considered that there was a potential for many structures to be damaged to a degree which impaired safety within their service life of 120 years.
- The future rate of progression of TSA penetration was estimated at 4 to 6 mm per decade.
- The most usual impairment would be loss of bond strength and corrosion to reinforcement following softening of concrete around reinforcement.
- The extent of TSA damage zones correlate with the maximum and minimum groundwater levels. No attack was found above the maximum water level: full attack was found below minimum water level and partial attack was usually found between maximum and minimum ground water levels.

- Storage tests on Lower Lias Clay indicate rapid oxidation of pyrite (iron sulfide) to sulfates under suitable conditions: in addition to access to air, moisture is an essential controlling factor.
- Sulfate levels in groundwater extracted from backfill show strong correlation with the amount of TSA found in structures.
- Groundwater in Lower Lias Clay backfill and undisturbed ground generally classified the same or one class higher than soil at the same site.
- Bituminous coatings found on concrete at 11 sites provided partial protection from sulfate attack, to a degree dependent on the quality of the coating, and other factors.

9.1.5 Sulfate specification for structural backfills

Research has been carried out for the HA by the Transport Research Laboratory (TRL) (Dr M Reid) and University of Sheffield (Dr J C Cripps) in connection with corrosion of galvanised steel buried structures in sulfides-bearing ground. The research has identified appropriate tests methods for determining sulfur compounds in structural backfills ⁽¹⁵⁾.

There has been collaboration with BRE to ensure that procedures and terminology are compatible with those being recommended by BRE SD1 for ground assessment in respect of concrete.

9.1.6 Assessment of Sulfate Class of pyritic clay

This is research at BRE (T I Longworth), sponsored by a DTI Framework programme, on the assessment of Sulfate Class of the ground. There are two key aspects to the research:

(i) *To reconcile sulfate classifications based alternatively on groundwater and soil.*

In many strata, including the Lower Lias Clay, the Sulfate Class derived from analysis of 2:1 water/soil extracts has proved to be lower (often by one Class) than the Sulfate Class derived from analysis of groundwater.

(ii) *To improve procedures for sulfate classification of ground containing pyrite*

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.

Developments in the period April 2001-March 2002 have been:

- (i) Comparison of sulfate tests soil and groundwater from sites on strata other than Lower Lias Clay. One finding has been that for London Clay the disparity may be less due to the greater presence magnesium cations which support sulfate in the 2:1 water/soil extracts.

- (ii) Decision made in preparation of BRE SD1 to stay with previously used limits to sulfate class based on 2:1 water/soil extracts until comparable results for soil and groundwater are known for a wide range of ground types. But to recommend strongly that groundwater samples be taken whenever practically possible.
- (iii) Decision made in preparation of BRE SD1 to modify the procedure for assessment of the Sulfate Class of pyrite-bearing ground based on Total Potential Sulfate to allow 'capping' to two classes above the corresponding result based on 2:1 water/soil extracts.
- (iv) New test procedures for chemical determination of sulfur species included in BRE SD1 to harmonise with new procedures recommended by TRL Report 447⁽¹⁵⁾.

9.1.7 Oxidation field trials on pyritic Lower Lias Clay

This is research at BRE (T I Longworth), sponsored by a DTI Framework programme. The context of this study is that investigations carried out by BRE and others in 1998 concluded that unexpectedly high levels of sulfate arising from oxidation of pyritic Lower Lias Clay have made a major contribution to the occurrence of TSA on highway structures on the M5 in Gloucestershire and Somerset. The TEG Report⁽¹⁾ identified the need for research on oxidation of sulfide-bearing clays, and in particular the determination of time scales for production of sulfuric acid (if any) and sulfates.

The research, which commenced in June 2000, comprises a field trial on a Lower Lias Clay site at Moreton Valence in Gloucestershire. The methodology is: firstly, to determine the chemistry and hydrology of the undisturbed ground and groundwater on the trial site and in particular of the weathered and unweathered Lower Lias Clay; secondly, to determine the chemical changes which take place in initially unweathered Lower Lias Clay when excavated and exposed (in two stockpiles) to atmospheric elements; and thirdly, to determine the chemical changes which take place in Lower Lias Clay when backfilled around concrete, below water level

The key project findings to date, available from an interim report⁽¹⁶⁾, are as follows:

- A significant degree of oxidation occurred in 5 months tests on the two stockpiles of Lower Lias Clay. Oxidation was greater in a stockpile subject to cool wet conditions than in a stockpile subject to warm dry conditions.
- There was no development of significant acidic conditions in the stockpiled Lower Lias Clay, despite the general understanding that the oxidation of pyrite results in sulfuric acid (H_2SO_4) as a by-product. It is probable that there is immediate neutralisation of any such acidic product due to reaction with the abundant calcium carbonate (CaCO_3) contained within the Lower Lias Clay.

Studies are continuing on a residual stockpile of Lower Lias Clay and similar material placed as backfill into two trenches containing concrete specimens.

9.1.8 Research on composition, formation and stability of thaumasite in concretes.

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

The objectives are:

- (i) To identify equilibrium phase compositions and establish the solubility curve for thaumasite.
- (ii) To use derived solubility product to generate solubility surfaces for multi-phase systems relevant to assessing the stability of thaumasite in contact with natural groundwaters.
- (iii) To study thaumasite-ettringite solid solution characteristics.

The work has focused on the mechanism of thaumasite formation from solution. It has involved the acquisition and modelling of composition and solubility data obtained under various environmental conditions, so that conditions to inhibit crystallisation can be identified. Towards the end of the project, the work was progressing as well as could be expected given that thaumasite is a complicated molecule containing three separate cationic groups with one being present in a very unusual form. Longer-term experiments were set up during the first year and the project has been extended into 2002 so that the results can be interpreted.

The results so far reported are as follows:

- (i) Three sets of solid solutions between thaumasite and ettringite-based end products have been systematically prepared in the laboratory. The mixed crystals were examined using X-ray Diffraction and this identified a miscibility gap in the solid solution series between thaumasite and ettringite. The same mixed crystals were analysed using Scanning Electron Microscopy microanalysis, in order to establish the chemical composition of individual crystals, but in this case, a miscibility gap was not detected. However, this was probably because the preparations had not yet reached equilibrium and when they do, it is anticipated that a miscibility gap will emerge.
- (ii) The work carried out has confirmed that the availability of a source of soluble alumina during the laboratory preparation of thaumasite can greatly encourage its formation and its yield.
- (iii) The determination of a solubility product for thaumasite is a painstaking procedure as it involves careful handling of ingredients and preparations in order to avoid contamination in conjunction with repeated dispersion and filtration of the solid products formed. The amount of solubility data on thaumasite is gradually building up and a reliable solubility product at 5°C, 15°C and 30°C should be forthcoming by the end of the extended project.

9.1.9 The resistance of metakaolin (MK) - Portland cement (PC) blends to TSA

Research started in October 1999 at the School of Built Environment (now the School of Technology), University of Glamorgan, under the direction of Prof. S. Wild. The work is sponsored by Imerys (formally English China Clays International), and EPSRC, under an EPSRC CASE award (for Ivan Smallwood). It is scheduled for completion in Sept 2002.

The objectives are:

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

A laboratory-based investigation is in progress using concrete prisms made up at two water/binder ratios (0.40 and 0.46) and with partial replacement of Portland cement with MK (7, 14, and 21%) and also with ggbs (80%). The aggregate used is a dolomitic limestone (CaO content 30%, MgO content 20%). The prisms are exposed to two sulfatic environments comprising; (i) 5% sodium sulfate solution; and (ii) a high sulfate, high sulfide-bearing clay (Lower Oxford Clay); and also to water, all at 5°C. The Lower Oxford Clay has a Total Potential Sulfate content of 6.12% (0.97% sulfate and 2.45% sulfide) and the sulfide readily oxidises to sulfate in an alkaline environment. Currently specimens have been exposed to the different environments at 5°C for nearly a year and some specimens are now showing substantial distress.

The key findings are:

- (i) For those cubes exposed to water, physically there is no loss of external integrity, though significantly there is evidence of deleterious reaction(s) manifest by the presence of a 'gel' on cube surfaces. The development of this 'gel' (which is an alkali carbonate gel consisting principally of Ca and K cations with small levels of Al, Si and Na and negligible Mg) is substantial in the 25 mm cube size PC concrete control samples and the 7%MK/93% PC samples, particularly for concrete with water to binder ratio (w:b) of 0.40, where extrusion is a function of a smaller pore volume.
- (ii) The form of degradation of the concrete exposed to sulfate solution at 5°C is very different from that exposed to sulfatic clay at 5°C. In the former case, material resulting from chemical reaction continually spalls away from the outer surfaces leaving them continuously exposed to the aggressive solution. In the latter case the vulnerable surface regions transform into a white pulpy 'mush'. Clearly diffusion rates and concentration gradients of aggressive species at the concrete – exposure-medium interface are going to be very different in the two different exposure environments and the former may not be appropriate for investigating reaction mechanisms under field conditions.
- (iii) The preliminary evidence does confirm that both MK and ggbs inhibit TSA in the short term (up to one year) and may therefore have potential application for

preventing TSA in concrete. In addition the observation of extrusion of gel, which was particularly extreme for the concrete with w:b ratio 0.40 and with 0% and 7% MK, suggests that alkali carbonate reaction may be associated with the TSA in the particular system under investigation. It is anticipated that detailed analytical work currently being undertaken will answer some of these questions.

9.1.10 Thaumasite formation by combined acid and sulfate attack on concrete

Research started in 2000 at the Department 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. It is scheduled for completion in 2003.

The objectives are:

- (i) To investigate the chemical and physical processes associated with pyrites oxidation in clays and the resulting aggressivity of groundwater to concrete.
- (ii) To establish whether the TEG proposal which allows for enhanced sulfate levels resulting from oxidation of all the sulfates in the ground is correct.
- (iii) To demonstrate and explain the chemical and physical processes occurring in concrete exposed to groundwater in disturbed and undisturbed pyrite-containing clays.
- (iv) To understand and explain the chemical and physical interactions at the clay/concrete interface.
- (v) 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.
- (vi) To investigate the effectiveness of bituminous coatings on minimising TSA.
- (vii) To propose prescriptive specifications for concrete at risk of TSA and acid exposure classes in BS 5328 and BRE Digest 363.
- (viii) To disseminate the recommendations of the project to the construction industry and BSI Committees.

The work to date has examined the laboratory deterioration of candidate concretes immersed in a range of sulfate solutions that are equivalent to the Sulfate Classes of BRE SD1. The cement combinations chosen for investigation include PC, PLC, SRPC, PC/ggbs, PC/pfa. Visual and petrographic methods have been used to determine why and when thaumasite forms in a range of concretes made with common binders and oolitic limestone aggregates.

The work will also investigate the chemical changes during laboratory simulated excavation and backfill cycles to provide the information necessary to make informed specification of concrete in those conditions and to recommend aggressivity-testing procedures for pyritic clays.

9.1.11 A study of thaumasite and related phases in cements and concretes

Research was started at the University of Staffordshire in October 1999, sponsored by EPSRC, and supervised by Dr A R W Jackson, Dr C D Adam and Dr J Wright. The work is scheduled for completion in July 2003.

The objectives are:

- (i) 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.
- (ii) 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.

9.1.12 A study of reinforcement/concrete bond strength in TSA-affected concrete

Research has been carried out at the University of Birmingham (Prof L A Clark and Dr N J S Gorst) for W S Atkins on behalf of the HA on the bond strength of plain round reinforcement in both TSA-affected and unaffected concrete elements from the Tredington-Ashchurch Bridge. Reinforcement pull out tests were performed on six columns sections extracted from the structure. The column sections comprised four TSA-affected structural elements and two unaffected control specimens.

An experimental programme was undertaken to measure the following properties:

- bond strength of each reinforcement bar in all test specimens by pullout tests,
- depth of softened zone in TSA-affected test specimens by hand held drilling, and
- estimated in-situ cube strength in all test specimens by compressive tests on extracted cores.

The test results showed that TSA reduced the mean bond coefficient by 24% for corner bars and 10% for other bars, representing an average reduction in mean bond coefficient of 15% for all bars. A further consequence of TSA was increased scatter in the measured bond coefficients, particularly in the case of corner bars.

The experimental work also revealed that the bond between reinforcement and concrete is affected by nett cover, where nett cover is defined as cover less the depth of any softened zone. Consequently, as TSA proceeds and the depth of softened zone increases so bond is reduced.

The TEGR implies a characteristic bond coefficient of 0.39 for plain round reinforcement bars irrespective of bar location and nett cover, whilst the experimental data clearly show that bond is affected by bar location and nett cover. Although the recommended value of

0.39 for the characteristic bond coefficient is generally conservative for non-corner plain bars, it overestimates the bond strength when the nett cover is less than about 0.5 times the bar diameter. Hence, caution should be exercised for such small covers. In the case of corner plain round bars it is advised that, in the absence of further data, only 50% of the bond strength recommended in the TEGR should be taken.

9.2 New research initiatives commenced in April 2000 – March 2002 for which results not yet available

9.2.1 Field trial of performance of concrete pipes

A field investigation is currently in hand of the long-term performance of concrete pipeline systems in sulfate-bearing ground. The investigation is being carried out under the DTI Pil scheme by a Partnership comprising BRE (I R Holton), the CPA and the producers of constituent materials for pipeline systems. Pipe sections have been fabricated using a variety of materials and mixes and buried in the sulfate-bearing clay at the Moreton Valence exposure site. The choice of materials and mixes will allow assessment of the recommendations in the BRE SD1 design guides for pipeline systems and also will assess the performance of mixes that currently fall outside those guides. Two identical sets of pipes are under test; one to be retrieved in 2004 after three years duration and the other in 2011 after 10 years ground exposure. Core samples from a third identical set are under undergoing accelerated laboratory testing in 5°C sulfate solutions.

9.2.2 Field trial of repaired/protected concrete

A field investigation is currently underway by BRE (I R Holton) for the HA of the long-term performance of repair and protection techniques for concrete affected by TSA in sulfate-bearing ground. Sections of TSA-affected concrete removed from the Tredington-Ashchurch M5 bridge were repaired and protected at BRE in collaboration with industry by a selection of commercially available techniques. These concrete sections were then placed in trial trenches cut into Lower Lias Clay at the Moreton Valence trial site and backfilled with Lower Lias Clay which had been exposed in surface stockpiles for 5 months to facilitate oxidation which would increase sulfate contents. The Concrete sections will be exposed to sulfate-bearing soil and groundwater for up to 10 years.

9.3 Topics not yet addressed by current research proposals

The "Future research topics" suggested in Appendix C of the TEG Report are restated here in Annex 2 together with the current position on each of these topics, including the projects referred to in Sections 9.1 and 9.2. It would seem that the only topics for which research is either not underway or currently proposed are:

5. Diagnostic techniques for buried structures obviating the need for excavation.
7. Tests on waterproofing admixtures.
10. Effects of TSA on chloride binding of Portland cement concrete

In addition to these, two other topics research requirements that have emerged from this review are:

- (i) The need for a field trial of concrete mixes currently recommended for use in sulfate-bearing ground by BRE SD1, BS 5328 and BS 8500. Reasons for the research are:
 - Currently accelerated exposure testing of these mixes is only being carried out in laboratory sulfate solutions (Section 9.1.3). While the results of this testing will be indicative of concrete durability, it will not provide the high level of confidence requested by the construction community for long-term field performance of the mixes.
This is because inconsistencies have been repeatedly found when laboratory studies are compared to field trials, and only the latter are considered definitive.
 - The field trial underway at Shipston on Stour, which was implemented before publication of the TEG Report and SD1, does not include mixes as recommended by the new guidance (see Section 9.1.2).
- (ii) In order to provide timely interim guidance on effectiveness of repair materials for TSA-affected concrete it is recommend that, in addition to field trials of repairs and coatings, a selection of presently available repair techniques be subjected to accelerated exposure trial under laboratory conditions (see Section 6.3).

10. GUIDANCE DOCUMENTS IN PREPARATION AT MARCH 2002

Key items of guidance which are presently being prepared for publication in 2002 are:

- (i) **An amendment to BRE SD1** which switches the cements or combination groups referred to in Table 3 from the existing BS 12, BS 6588, BS 7583 and BS 4246 classifications to the new BS EN 197-1 classification. Presently the above BS Standards co-exist with BS EN 197-1. However, on 1 April 2002 they will be withdrawn by BSI.
- (ii) **Second revision of Highways Agency Manual of Contract Documents.**
Volume 1: Specification for Highway Works, Series 1700 Structural Concrete.
Volume 2: Notes for Guidance on the Specification for Highway Works, Series NG1700 Structural Concrete

Clauses to the Highways Agency Manual of Contract Documents for Highway Works have been updated to encompass the recommendations of SD1.⁽⁹⁾ The amendments start from the point at which the Aggressive Chemical Environment for Concrete (ACEC) Class is determined and guide the reader through to the specification of Design Chemical Class to the concrete producer. Reference is made to the simplification of the process attainable from the Design guides in Parts 3 and 4 of SD1, but these are not reproduced in the Specification. The amendments also incorporate cement designations according to BS EN 197-1. It is expected that these amendments will be implemented in the May 2002 version of the Specification for Highway Works.

- (iii) **A revision of the NHBC Standards** to bring this documentation into line with BS 8500 and SD1. It is anticipated that this will be implemented in December 2003.

11. CONCLUSIONS & RECOMMENDATIONS

- (i) Our overall impression is similar to that reported in the first review; 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.
- (ii) The publication of new BRE guidance and the amendment of BS 5328 has meant that now the industry is turning to these new documents for guidance rather than to the TEG Report. However, these new documents implement the guidance that was originally in the TEG Report. 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.
- (iii) There have been a few problems in interpreting the intentions of the guidance given in the TEG Report and/or implementing it in some situations. These problems have been addressed through revision of the guidance on specification of concrete in aggressive ground given in BRE Digest 363, BS 5328 and BS 882, and through discussions with the relevant industry bodies. In particular, problems were encountered by the manufacturers of pre-cast concrete construction products, including those for precast concrete pipes and tunnel linings, in complying with the TEG Recommendations. These have been resolved by the inclusion in the new BRE Special Digest (SD1) of specific design guidance for these products.
- (iv) About 50 new cases of TSA have been identified since the publication of the TEG Report and 30 since the publication of the first review in 2000. The majority of these were in the foundations of bridges founded on sulfate-bearing Lower Lias Clay (alternatively known as the Charmouth Mudstone Formation), found as a result of Highways Agency (HA) investigations of highway sub-structures in Gloucestershire, Somerset and Wiltshire. The remaining cases have occurred in a wide range of structures, buildings and environmental conditions. Most of these new cases have taken place in conditions that were anticipated in the TEG Report.
- (v) Two new field cases of TSA in buried concrete containing siliceous aggregates, have reinforced the possibility, mentioned in the TEG Report, that concretes containing little or no carbonate can be affected by TSA if an external source of carbonate ions is available, for example from groundwater. In both cases the carbonate source is likely to have been groundwater. This finding is significant since currently the guidance for specification of concrete for use in sulfate-bearing ground presumes that restriction of the carbonate content of aggregate is an effective measure for combating TSA. This measure will plainly be less

effective when other sources of carbonate are available for the thaumasite reaction. Currently the understanding of the problem is insufficient to underpin amendment of guidance. This awaits the outcome of further research on the relative contribution that sources of carbonate other than aggregate make to the occurrence of TSA

- (vi) A substantial body of new guidance has been put in place in 2001-2002 including BRE Special Digest 1 (SD1); Amendments to BS 5328; Amendments to BS 882 and new Standard BS 8500 which is complementary to the new European Standard for concrete BS EN 206-1.
- (vii) A large programme of research is underway on topics related to the occurrence of TSA in concrete. Some early findings have been taken into account during the preparation of BRE SD1 and the corresponding amendments to BS 5328. Future findings will inform intended revision of BRE SD1 in 2003.
- (viii) Of the numerous research requirements specifically identified in Appendix C of the TEG Report, only three items would currently appear not to be receiving attention, namely:
 - Diagnostic techniques for buried structures obviating the need for excavation.
 - Tests on waterproofing admixtures.
 - Effects of TSA on chloride binding of Portland cement concrete
- (ix) Other research requirements that have emerged from this review are (see Section 9.3):
 - The need for a field trial of concrete mixes currently recommended for use in sulfate-bearing ground by BRE SD1, BS 5328 and BS8500.
 - The need for a selection of presently available repair techniques to be subjected to accelerated exposure trial under laboratory conditions. This in order to provide timely interim guidance on effectiveness of repair materials for TSA-affected concrete.

12. ACKNOWLEDGEMENTS

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Part 3: Design guides for common applications.
Part 4: Design guides for specific precast products.
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Amendment 2 to Part 1: Guide to specifying concrete.
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6. Amendment to BS 882. Specification of aggregates from natural sources for concrete.
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ANNEX 1: COMMUNICATIONS RECEIVED DURING REVIEW

1. email from P Robery, Maunsell Ltd, 18 July 2001, 'Review of Thaumaside Expert Group Report'.
2. email from P Waskett, DTI, 23 July 2001, Thaumaside Expert Group Report.
3. Letter from Dr W F Price, Sandberg Consulting Engineers, 1 August 2001, 'Review of Thaumaside Expert Group Report'
4. Letter from Dr D Hobbs, BCA, 2 August 2001, 'Review of Thaumaside Expert Group Report'.
5. Letter and Reports from N Loudon, Highways Agency, 14 August 2001, 'Review of Thaumaside Expert Group Report'.
6. email from J C W Patch, Roger Bullivant, 31 August 2001.
7. email from J C Haynes, NHBC, 5 October 2001, 'Review of Thaumaside Expert Group Report'.
8. Letter and Reports from D Slater, Halcrow Group, August 2001, 'Thaumaside Investigations - Thaumaside Expert Group One-Year Review'.
9. Letters and reports from S Bennett, W S Atkins.

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Future research proposed in TEG REPORT		Research, either underway or proposed
<p>10. Miscellaneous:</p> <ul style="list-style-type: none"> Investigation of the effects of severe wetting on building products containing or subject to sources of sulfates and carbonates; Investigation of buried precast concrete products containing or subject to sources of sulfates and carbonates; Field study collection of data for house foundations; Investigation of foundations in other sulfide-bearing clays in wet conditions; Simulation of Tredington-Ashchurch ground conditions to determine time-scale for the effects and the quantities of sulfuric acid and sulfates produced against time; Effect of TSA on the chloride binding in Portland cement concrete. 	<p>✓</p> <p>✓</p> <p>✓</p> <p>✓</p> <p>✓</p> <p>×</p>	<p>Part of BRE Framework Project on TSA for DTI (Watching brief on field cases).</p> <p>(a) Part of BRE Framework Project on TSA for DTI (i) Watching brief on field cases. (b) Pil funded field and lab trials comprising exposure of specimen pipes to aggressive sulfate conditions.</p> <p>Part of BRE Framework Project on TSA for DTI (i) Watching brief on field cases, (ii) Field exposure trial).</p> <p>Part of BRE Framework Project on TSA for DTI (Watching brief on field cases).</p> <p>(a) Field study is part of BRE Framework Project on TSA for DTI (Oxidation field trial at Moreton Valence). (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>No proposal known.</p>

ANNEX 3: GLOSSARY OF ACRONYMS

ACEC	Aggressive Chemical Environment for Concrete
APM	Additional Protective Measures
BRE	Building Research Establishment
BCA	British Cement Association
BSI	British Standards Institution
CAC	Calcium aluminate cement
CSMA	Cementitious Slag Makers Association
CIRA	Construction Industry Research and Information Association
CPA	Concrete Pipe Association
DC Class	Design Chemical Class
DETR	Department of Environment, Transport and the Regions
DTI	Department of Trade and Industry
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
Pil	Partners in Innovation
PLC	Portland limestone cement
QPA	Quarry Products Association
RICS	Royal Institution of Chartered Surveyors
SD1	BRE Special Digest 1
SRPC	Sulfate-resisting Portland cement
TEG	Thaumasite Expert Group
TF	Thaumasite formation (possible precursor to TSA)
TRL	Transport Research Laboratory
TSA	Thaumasite form of sulfate attack
TLMA	Tunnel Lining Manufacturers Association
UKQAA	UK Quality Ash Association