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Procedures for assessing thaumasite sulfate attack and adjacent ground conditions at buried concrete structures

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Abstract

In 1998 Halcrow were appointed by the Highways Agency to investigate the thaumasite form of sulfate attack at the buried concrete foundations of structures on major highways in Gloucestershire, UK. Detailed investigations were completed at 28 structures and the results used to apply a risk assessment procedure to a further ninety structures. Standard procedures for sampling, testing and classifying soil, groundwater and concrete were devised to ensure that rigorous statistical analyses of the data could be applied. The procedures were also designed to meet the then current UK guidance notes, BRE. Digest 363 [Building Research Establishment, Sulphate and acid resistance of concrete in the ground, BRE Digest 363, CRC Press, Boca Raton, 1996] and the Thaumasite Expert Group Report [Thaumasite Expert Group, The thaumasite form of sulfate attack: Risks, diagnosis, remedial works and guidance on new construction, DETR, 1999] and are compatible with the subsequent BRE Special Digest 1 [Building Research Establishment. Concrete in aggressive ground, Part 1: assessing the aggressive chemical environment, BRE Special Digest 1, CRC, Boca Raton, 2001]. Recommendations are made for applying many of the procedures that have been developed to future site investigations to enable consistency, compatibility and easier data transfer for future research on the thaumasite form of sulfate attack.

Keywords: Thaumasite; Sulfate; Site investigation; Database; Procedures

1. Introduction

In March 1998 the Highways Agency appointed Halcrow to undertake an extensive investigation with the objective of determining the mechanism, extent and consequences of thaumasite formation (TF) and the thaumasite form of sulfate attack (TSA) at highway structures on the M5 Motorway and on other trunk roads in Gloucestershire, UK. In the course of the study, methods of identifying, monitoring and predicting TF and TSA were to be evaluated. The project initially concentrated on three structures undergoing bridge repair works. By February 1999, when site works had been completed, a total of 28 structures had been investigated by Halcrow, working to a staged program and to several different levels of investigation.

At an early stage in the project it was identified that the occurrence of thaumasite was likely to be related to the presence of Lower Lias clay backfill adjacent to buried concrete foundations. The Lower Lias clay is recognised by the UK construction industry as being a potential sulfate bearing strata. However, based on evidence from the three initial structures investigated, it was observed that the occurrence of thaumasite was variable within and between structures, and that thaumasite growth is complex and dependent on a number of variables. Such variables may include concrete type, backfill type (at the micro-scale), groundwater chemistry and level, foundation design, and seasonal variation (e.g. water level, temperature and road salt use). Therefore, site description, classification, sampling, testing and monitoring procedures were established to determine which variables were most likely to be relevant to the presence, growth or identification of thaumasite at buried concrete foundations. In view of the large amount of data likely to be generated by the investigation, an extensive database system was developed.

The results and conclusions of the project are potentially sensitive to the methods of obtaining and using

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the data. The project also adopted some unusual and non-standard sampling and testing methods. Therefore all of the procedures adopted were fully documented to allow a peer review of the work and for any future analysis of the data. This paper provides a summary of the key procedures used that may be of benefit to future investigations and research into TSA.

2. Site selection

In Gloucestershire the Highways Agency owns approximately 80 structures along the M5 corridor and a further 67 trunk road bridges. The structures selected for investigation needed to include the main structure types in the area, those structures most likely to be at risk of failure if TSA were present, and those structures where the presence of TSA would impact on forthcoming repair work contracts. Therefore, the first stage of the selection process consisted of a risk assessment. A 'mechanism risk' was identified for those structures founded in the Lower Lias clay and where backfill around the foundations was likely to have been derived from the Lower Lias clay. A 'structure risk' was identified for those structures that had a structural form or contained particular details that would make the consequences of concrete deterioration more critical. A review was undertaken of the principal inspection and more recent general inspection reports for the motorway and trunk road structures throughout Gloucestershire to identify any reported problems that could be attributed to the deterioration of concrete. This study also identified those structures that were potentially sensitive to TSA and should be re-examined.

A phased investigation was then planned consisting of:

- *Phase 1*. Structures where bridge repair/strengthening works were underway or imminent for the 1998/1999 program of works. Eleven structures were investigated.
- *Phase 2*. Structures sensitive to TSA or of variable design and ground condition. This included: structures that would provide data from a variety of structure types (including under-bridges and culverts); structures that were considered to be potentially sensitive to thaumasite; and structures that had a good spatial distribution around the Gloucester area. Fifteen structures were investigated.
- *Phase 3*. Structures where bridge repair/strengthening works were underway or imminent for the (1999/2000 program of works. Two structures were investigated.

The types of structures investigated are shown in Table 1.

3. Soil sampling

All samples of backfill or natural ground taken from around foundations are collectively termed 'soil' samples. The methods that have been used to recover soil samples are:

- Total excavation of the fill above foundation footings.
- Trial pits to expose part of the foundation.
- Window sampling through fill and beneath/behind the void caused by concrete coring through foundations.
- Contiguous dynamic sampling (similar to dynamic probe).
- Dry percussive boring with rotary coring in mudstone and through concrete foundations into underlying soil.

Each sampling method is summarised in Table 2. A summary of the soil sampling method employed at each type of structure is provided in Table 3. The main points of the soil sampling procedure are:

- for efficiency wherever possible, soil sampling procedures were combined with concrete sampling and bridge repair works;
- in order to minimise disruption to services and highway or motorway traffic flow and because of difficult access and limited working space, 2-man portable dynamic sampling rigs and tracked combined rotary-percussion rigs were used;
- site works were designed as much as possible to be on the downstream side of traffic flow of the structure to reduce the risk to site staff from oncoming traffic;
- to minimise disturbance to the soil and groundwater, the introduction of drilling fluids to the ground was largely prevented by using a percussive boring system with an air flush and occasionally a mist flush;
- all samples from dynamic probing, percussive boring and rotary coring were recovered in semi-rigid clear plastic liner and immediately sealed on site to minimise oxidation or other disturbance from exposure to the atmosphere;
- The percussive rig could be angled to drill between vertical and horizontal so that at counterfort abutments, the concrete face, backfill behind the face, the concrete of the footing and the founding strata below the footing could be sampled in the same 45° or 60 inclined borehole.

4. Groundwater sampling and monitoring

At an early stage in the project it was recognised that TF and TSA probably required wet conditions in the

Table 1
Summary of structures investigated

Structure name and number	Phase	Type[a]	Structure details[b]	Main reasons for investigation
Ashchurch Interchange North and South bridges (M5_70.00, M5_70.10)	1	O/B	Columns, spread footings	Ongoing works
Tredington—Ashchurch Road Bridge (M5_72.50)	1	O/B	Columns, spread footings	Ongoing works
B4008 Slip Road Bridge and Road Bridge (M5_97.00, M5_97.20)	1	O/B	Columns, spread footings	Imminent works
Grove Lane Overbridge (M5_101.50)	1	O/B	Columns, spread footings	Ongoing works
Lansdown Road Bridge (A40_158.20)	1	U/B	Brick faced mass concrete abutment	Imminent works, structure type/age
Golden Valley Interchange Centre Bridge (A40_161.60)	1	O/B	Columns, cast in situ piles	Ongoing works
Golden Valley Interchange east and west bridges (A40_161.50, A40_161.80)	1	O/B	RC 'A' Frame, spread footing	Ongoing works
Walham Viaduct (A40_171.40)	1	U/B	Columns, cast in situ piles	Ongoing works
Hatherley Brook Culvert (M5_81.00)	2	C	RC box	Structure type
Cheltenham—Gloucester road bridge (M5_81.20)	2	U/B	Cantilever abutments	Cracking observed
Golden Valley Interchange North and South Bridges (M5_82.30. M5_82.60)	2	O/B	Hinged columns, strip footing	Freyssinet hinge
Uphill Court Footbridge (M5_85.60)	2	O/B	Raking portal frame legs, inclined spread footings	Slender legs
Barnwood Bypass Bridge (M5_86.80)	2	U/B	Counterfort abutments	Movement observed
Gloucester—Painswick road bridge (M5_90.30)	2	U/B	Counterfort abutments	Possible movement, slender counterfort
Grove Court Footbridge (M5_90.90)	2	O/B	Raking portal frame legs, inclined spread footings	Slender legs
Hatherley Brook Culvert (A40_159.90)	2	C	RC box culvert	Structure type
Arle court underpass (A40_160.00)	2	U/B	RC retaining wall	Cracking observed
Church-down Footbridge (A40_163.80)	2	O/B	Columns, spread footings	Slender columns
Horsebere Brook Culvert (A40_166.90)	2	C	RC box culvert	Structure type/age
Over bridge (A40_171.80)	2	O/B	Columns, cast in situ piles	Abutment movement, forthcoming works
Highnam Bridge (A48_0.50)	2	U/B	Brick arch, brick footings	Forthcoming works
Horesebere Culvert (A417_.83.90)	2	C	RC box culvert	Seepage and cracking, structure type
Pipe Bridge near Naas Lane (M5_95.00)	3	O/B	Columns, spread footings	Slender columns
Clingre Pipe Bridge (M5_110.10)	3	O/B	Columns, spread footings	Slender columns

[a] O/B—overbridge, U/B—underbridge, C—culvert.
[b] RC—reinforced concrete.

ground surrounding the concrete. This was subsequently confirmed by the publication of the report of the Thaumasite Expert Group in January 1999 [2]. Therefore, groundwater sampling and monitoring was considered to be essential to the investigation of all the main structures. Groundwater was sampled wherever it was encountered during the site work from seepage into trial pits, excavations, dynamic probe holes and boreholes). For controlled groundwater sampling and medium to long term monitoring (18 months to 3 years), BAT piezometers were installed.

The BAT piezometer system was identified as the most appropriate method for obtaining high quality water samples from piezometer response zones that were located in low permeability ground (either clay fill, clay or mudstone). The system also met a second requirement of allowing the piezometric head to be monitored. The system uses a thermoplastic tip installed in an inert sand filter response zone and connected to a 50 mm diameter high-density polyethylene access tube. The tip is sealed with a rubber disc so that there is no groundwater above the tip in the access tube but the tip is saturated and in contact with the surrounding groundwater conditions. The borehole is sealed using bentonite pellets and a cement plug at the surface. The piezometers were installed inside approximately 0.50 m deep and 0.75 m square concrete manhole chambers with a steel manhole cover placed on top to provide protection from future construction activities.

Access to the tip is achieved by lowering a hypodermic needle down the access tube to penetrate the rubber disc. The rubber disc is self-sealing once the needle is extracted. Different instruments are attached to the hypodermic needle to either collect a sample of the groundwater or to measure the piezometric head. Water samples are collected in an evacuated glass vial that is

Table 2
Summary of geotechnical sampling methods

Sampling method	Sample type	Advantages	Disadvantages
Total excavation of foundation base	'D' disturbed jar samples approx. 1 kg taken by hand 'U' undisturbed U100 samples driven by hand or excavator bucket against concrete 'B' bulk samples, sometimes as intact blocks taken by hand	Detailed sampling at most relevant locations (i.e. in conjunction with concrete sampling and observations) 100% exposure for geological logging	Expensive, slow, possible complex support measures, services diversions and traffic management Long exposure of soil and concrete affecting chemistry and soil classification tests Installation of piezometers in fill not possible
Inspection Pits	None	Cheap and quick exposure of column face Possible identification of fill type beneath capping layer	Insufficient exposure of soil and concrete for adequate interpretation
Trial Pits	As total excavation above	Cheaper and quicker than total exposure Sufficient exposure to sample and identify concrete and soil from one column face and part of base Not all fill disturbed so adjacent piezometer installation possible	May need service diversions/reinstatement and support measures Machine power/reach compromised by headroom and working area Less information than total excavation
Window sampling	'D' disturbed samples transferred from small diameter (38 mm diameter) window sampler to jars or bags	Quick and portable Access possible to restricted and inclined areas	Unlined samples, occasional poor recovery, small sample size
Contiguous dynamic samples (using dry boring with sealed sample recovery)	'X' samples: up to 1 m length. 73–114 mm diameter in clear plastic liner	Dry lined and sealed sampling of large diameter retains soil chemistry Quick and portable. Access possible to restricted and inclined areas Occasionally able to recover thaumasite at the basal contact with the top of the footing	Limited depth of penetration Occasionally poor sample recovery in wet conditions or granular material Uncased (may be unsuitable for piezometer installation)
Dry percussive boreholes (air or air/mist coring in rock and sealed sample recovery)	'X' samples: up to 1 m length. 73–114 mm diameter in clear plastic liner (fill, gravel and clay) C' core samples up to 1 m length. 73–114 mm diameter in clear plastic liner (mudstone)	Dry boring and coring with sealed sample recovery retains soil chemistry Small mobile rig for restricted access Quick Allows piezometer installation	Limited depth of penetration Air flush creates dust Noise Occasionally poor sample recovery in very wet conditions or granular material

lowered down the hole with a double-ended hypodermic needle that penetrates both the seal and the vial at the same time. The groundwater is sucked from the tip into the glass vial. On extraction of the glass vial the needle pulls out of the tip and from the vial and both are self-sealed. The glass vials are sent to the testing laboratory without being opened. Glass vials are sterilised before re-use and new needles are used at each piezometer. In this way there is minimal cross contamination from the equipment and there is minimal exposure of the groundwater to the atmosphere. To measure the piezometric head in BAT piezometers a hypodermic need is attached to a pressure transducer and then lowered down the hole.

The technical disadvantages of the system are that it is difficult to purge the response zone and downhole temperature and dissolved oxygen readings of the water cannot be made. The sample volume that can be recovered at one time is limited to 150 ml using the standard glass vial equipment. In inclined boreholes, the system had to be modified by adding guidance discs to allow the equipment to be lowered down the hole and centre on the tip. Care must be taken to prevent material falling down the hole causing obstruction to the rubber disc.

Slotted screen standpipes were also installed to provide a calibration check for the piezometric head measurements in BAT piezometers and to allow the downhole measurement of temperature and dissolved oxygen. Electrical conductivity, redox potential and pH were also measured on site.

Piezometer monitoring and sampling was generally undertaken within one month of piezometer installation. This was followed by a 'snapshot' of the winter groundwater condition for all of the piezometers in January 1999 and of summer conditions in July 1999.

5. Concrete sampling and in situ testing

The principal objective of the survey work was to establish the spatial distribution of attack to the con-

Table 3
Summary of the soil sampling regime adopted at each structure type

Structure	Generalised soil sampling regime per pier
Overbridge with repair works	Window or dynamic probe sampling onto base followed by Complete excavation of pier foundations (for repair works) 2 boreholes in fill and one though fill into undisturbed ground, all offset from repair works 1 borehole in undisturbed ground offset from motorway
Overbridge	2 boreholes through fill onto the top of the footing 1 borehole through fill into undisturbed ground adjacent to footing 1 trial pit onto top of footing Dynamic probes onto base at some sites
Underbridge	2 or 3 boreholes at each end of abutment (1 in fill, 1 through fill into undisturbed ground) 2–4 boreholes though the abutment wall inclined at 45°, some terminating on top of footing, some penetrating footing into undisturbed ground 2–4 dynamic probes onto toe of footing at trial pit locations 2 trial pits in front of abutment wall to expose toe of abutment
Culverts	Soil samples from ends of concrete cores through culvert walls and base
Others	Combination or trial pits and/or dynamic probe sampling

Note: All boreholes have either BAT piezometers or slotted screen standpipes installed for groundwater monitoring and sampling.

crete in terms of the area and approximate depth of softening. Secondary features examined included the profile of the concrete surface and depth of cover. The latter was used in conjunction with the depth of softening and laboratory data to confirm the vulnerability of the steel reinforcement. A summary of the survey techniques is given in Table 4.

The samples of concrete comprised 50–100 mm diameter cores, drilled dust or chiselled fragments and lump samples. The in situ testing involved hammer

Table 4
Summary of survey techniques

Survey method	Objective
Visual assessment and photography	
Photography of surface at nominal 1 m intervals using Minolta Vectis S100 splash-proof APS camera	Record of all salient features, including breakouts at rust-staining and subsurface cracking revealed at core hole, to supplement the information given on the face logs
Hammer soundness	
Tapping at regular intervals over the full area of exposed vertical surfaces using 0.5 kg lump hammer, following removal of loose soil deposits	Subjective assessment of area of concrete with evidence of attack in the form of softening
Depth of softening	
Penetration depth at 0.5 m intervals until persistent resistance felt using an 8 mm masonry bit fitted in an 14V Elu cordless hammer drill	Approximate measure of softened material for use in conjunction with hammer soundness to assess extent of attack
Face logs	
Proforma sheets marked with 100 mm grid squares to record salient features of the exposed vertical concrete surfaces, including sample locations, rust staining, in situ testing	Accurate record of in situ testing, ground level and sample locations on a developed elevation for comparison with laboratory results and soils data
Rebound values	
Rebound numbers using a Type 'N' Schmidt hammer. At least 10 readings obtained on a 20 mm grid in accordance with BS1881 Part 202 [4]	Correlation between depth of softening and standard test method and confirmation of attack in areas where softening by tapping appears marginal
Cover survey	
Minimum cover at 0.5 m intervals using a Protovale CM5 covermeter in accordance with BS1881, Part 204 [5]	Comparison of the depth of deterioration from drilling and cores to assess the residual cover to the steel reinforcement and risk of corrosion and reduced bond
String-line measurements	
Offsets taped from the concrete surface to a string-line suspended from angle brackets secured to the concrete using straps. Measurements at 0.5 m intervals	Record of profile of concrete to assess expansion and loss of section due to attack

soundness survey, depth of softening by drilling, covermeter survey, rebound hammer tests, string-line measurements and localised breaking out of the concrete. The non-destructive testing was carried out in accordance with relevant parts of BS1881 [4,5]. A record of the concrete condition and the location of the samples was made in the form of a 'face log' and by photography. An example of a face log is given in Fig. 1.

To ensure a degree of uniformity in approach between different sites and individuals a set of project specific procedures were established early in the work. The precise methodology adopted has inevitably varied due to constraints imposed for each site, e.g. access and structural form. Concrete coring generally used a water-flush diamond tipped barrel and an air-driven coring rig, either hand-held or mounted on steel props. Hand-held

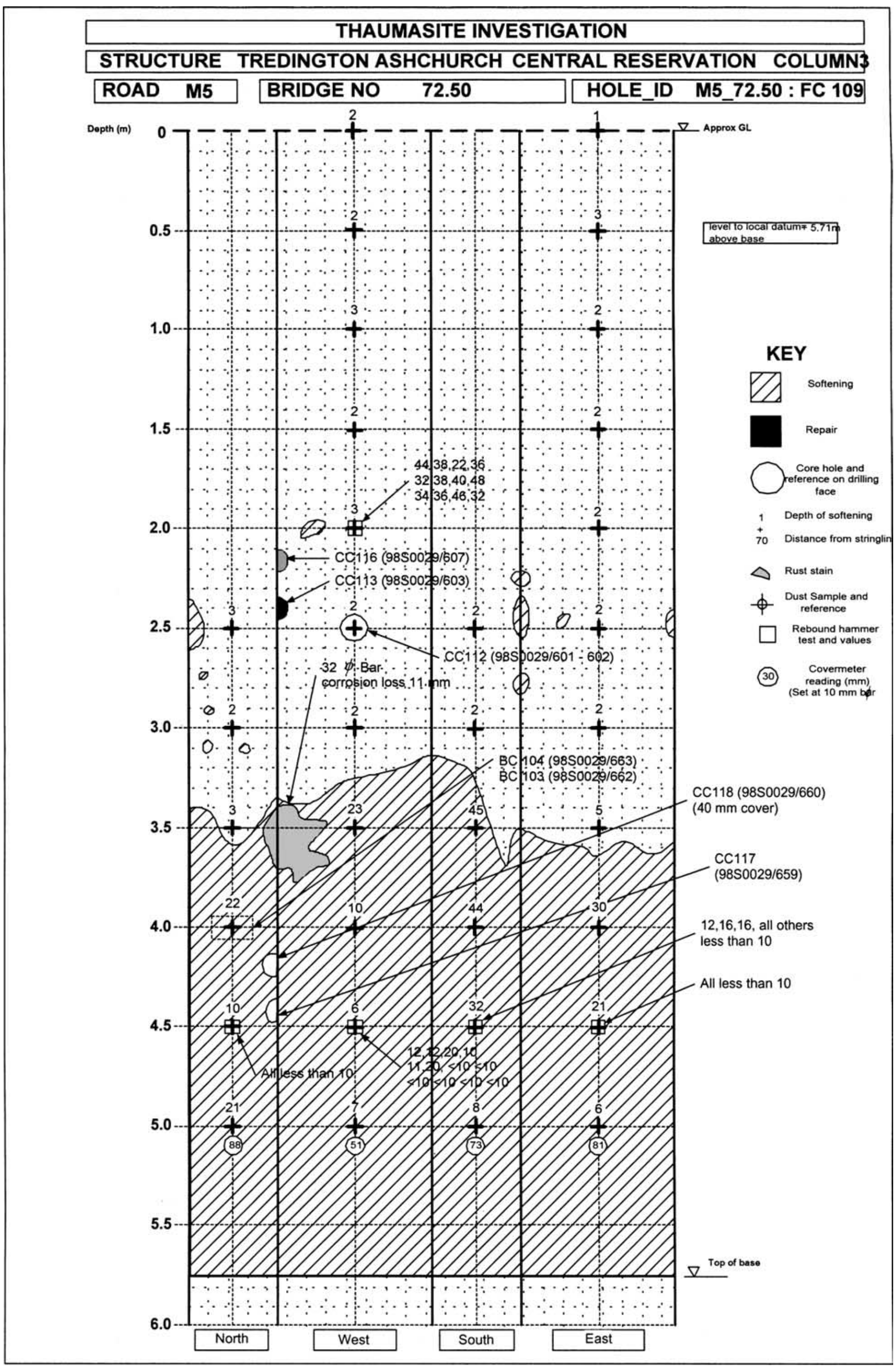

Fig. 1. An example of a face log for mapping TSA at concrete structures.

coring using a dry diamond bit and portable coring rig was also occasionally used. Concrete core samples were also obtained from the dry percussive boring and rotary coring rig used to produce inclined boreholes through the abutments to three underbridges. Particular care was needed during coring to preserve the softened deposits from the surface of the concrete. Cores were normally wrapped in cling film and placed within a polythene bag on site to prevent contamination and minimise drying and loss of material.

Freyssinet hinges to four bridge piers were examined for evidence of white reaction products or rust staining using an 8 mm forward pointing boroscope. Access for the boroscope was gained at 300 mm intervals along the excavated portion of each hinge by carefully drilling 14–16 mm diameter holes through the sealant and fibreboard using a drill operating in a non-hammer mode.

In order to examine in more detail the correlation between the soil in contact with attacked and unaffected areas of concrete, samples of the soil-concrete interface were taken at four sites by continuous coring of both soil and concrete. The excavation of the backfill proceeded with care to leave a nominal 250 mm thick layer of soil to a maximum height of 1.5 m adjacent to column faces and a 500 mm thickness of material over an area at least 1×1 m^2 on the top of the base. Care was taken to protect this layer from unnecessary disturbance and contamination. The locations for interface sampling were chosen at the same elevation as the existing soil samples.

The interface samples were drilled using a hand-held coring rig fitted with 75 or 100 mm nominal diameter core barrels. Water flushing was kept to a minimum and where possible the water was channelled away from the sampling locations. Coring both normal and parallel to the concrete–soil interface was attempted. Coring normal to the interface proved problematical due to clay blocking the water flush of the concrete and the clay often separated from the face becoming trapped in the barrel. Coring parallel to the interface yielded samples with semi-circular portions of clay and concrete in close contact, typically 200 mm in length.

The interface samples were easily damaged and plastic pipe was therefore cut to form splints, which were used to support the samples along their axis. The samples were immediately wrapped in cling film and aluminium foil and sealed in polythene bags to prevent drying out. Where the soil became detached from the concrete the samples were bagged separately. The samples were kept in a cool box prior to being transferred daily to a refrigerator within the laboratory.

6. Location and extent of sampling

The location and extent of sampling were designed to allow the soil and concrete to be classified and compared at five different scales for each site: structure, pier, member, horizon within member and member face.

A detailed and robust reference system was used to ensure that all samples and concrete face logs, test results, classifications and groundwater monitoring results could be linked. This used the following key information to locate all samples:

(a) Site number, pier orientation, member number at the pier, and concrete face orientation on the member.
(b) Horizontal offset of sample in metres from the face (both into and away from concrete).
(c) Vertical elevation of sample above the top of the concrete footing (the datum at each pier).

The degree of sampling and concrete exposure varied between sites, but wherever possible, soil samples of backfill were located at the same face and elevation as concrete samples and with specific offsets from the face that were, as far as possible, constant at all sites. These offsets were 0–20 mm, 20–60 mm, 60–100 mm, 0.5 m and 1.0 m. At most sites, soil backfill and concrete were sampled at several elevations to try to ensure that samples were obtained from horizons where there were different degrees of attack apparent on the concrete face.

Undisturbed soil adjacent to the foundations was sampled as close to the backfill as possible at depths equivalent to that of the backfill samples to try to provide the most similar conditions to the backfill for the best assessment of variation in the soil caused by excavation, reworking and backfilling. Piezometers were placed in both the backfill and undisturbed ground at equivalent depths, again to allow the most direct comparison to be made.

7. Sample storage, and handling

All soil and water samples collected on site were transferred to the laboratory the same day. The samples were stored in a cool box on site prior to being transferred to a refrigerator at the laboratory. Soil was recovered from boreholes and from the dynamic sampler 'Scout' rig in one-metre length clear plastic liner that was too large to store in cool boxes on site. Therefore, the material was logged on site through the liner to select the sections required for chemical or mineralogical testing. The one-metre length was then divided into approximately 250 mm long cylindrical samples by cutting across the diameter of the liner with a hacksaw and resealing the ends. Only those samples selected for chemical or mineralogical testing were placed in the cool box.

Sample data, such as location, description and other key features, were required to be part of a

THAUMASITE INVESTIGATION CERTIFICATE OF SAMPLING

ROAD : STRUCTURE NO:

STRUCTURE NAME:

EXPLORATORY METHOD: Coring, Drilling, Breakout, other (specify)

SAMPLE IDENTIFICATION: Location Number:
Site sample ref (if any):

GENERAL LOCATION: NB, SB, EB, WB (motorway bridges)
N, NE, E, SE, S, SW, W, NW (other structures)

MEMBER TYPE: Leaf pier, Column, Base, Abutment, other (specify)

MEMBER NUMBER:

FACE ORIENTATION: N, NE, E, SE, S, SW, W, NW

POSITION WITHIN MEMBER: (see overleaf for diagram)

Depth (m)	Height from base (m)	Chainage(m)	Offset(m)

DETAILS OF SAMPLE HOLE:

Orientation	Size (mm)	Depth Increment (mm)

SAMPLE TYPE AND DESCRIPTION: Core, Dust, Fragment, Lump, other (specify)
DATE OF SAMPLING: / /

PERSON TAKING SAMPLE:

CONDITIONS OF STORAGE:

SAMPLING INSTRUCTION REF:
TESTING INSTRUCTION REF:

NOTES:

SIGNED: DATE:

DATABASE SUMMARY (see overleaf for continuation)

HOLE_ID _ :

SAMP_TOP . SAMP_TYPE

HOLE_LOCZ . HOLE_LOCX HOLE_LOCY .

HOLE_ORNT HOLE_INCL HOLE_FDEP .

Hole_pier Hole_colm Hole_face

Member Type HOLE_LOG

HOLE_NATE HOLE_NATN

Fig. 2. Concrete sampling certificate.

project database. The engineer responsible for sampling supervision recorded this information using a sampling certificate. A blank certificate for concrete sampling is shown in Fig. 2. Occasionally samples were split in the laboratory prior to being sent for testing. In such circumstances the sample reference number was usually amended with a suffix ‘a’ and ‘b’, etc. Testing schedules/instructions for the testing house were wherever possible provided by the engineer that supervised the sampling and described the samples.

8. Laboratory testing of soil and groundwater samples

The soil samples were subject to physical, chemical and mineralogical tests and the groundwater samples were subject to chemical testing as briefly described below. The general objectives of the laboratory testing were to:

(a) Classify the sites according to current guidance and practice, e.g. BRE Digest 363 [1] and the TEGR [2] (now superseded by BRE Special Digest 1 [3]).

(b) Identify simple physical tests that might permit the routine screening procedures to be adopted for general investigations of existing structures and potentially aggressive sites.
(c) Establish the characteristics of the site which might be risk factors in the occurrence of TSA, e.g. soil permeability.
(d) Gather data to help explain the formation of TSA and TF at the structures.

Physical tests were undertaken to determine the properties of the soil that are commonly used for geotechnical design or classification purposes, including:

- Natural moisture content;
- Atterburg limits;
- linear shrinkage;
- particle size distribution;
- dispersion test;
- particle density;
- dry and bulk density.

These were undertaken in accordance with BS 1377: 1990 [6], except the dispersion test that used the pipette analysis instead of the hydrometer.

Chemical testing of soil and groundwater concentrated on the determination of a wide range of ubiquitous elements and compounds, with special emphasis on those that are known to be aggressive towards concrete or which are involved in its deterioration. Chemical tests were scheduled as 'suites' of tests, as summarised in Table 5.

Generally, for chemical testing each laboratory used in–house methods. The laboratories were consulted beforehand on their proposed analytical and testing strategy to ensure that the testing methodology chosen was appropriate to the sample type. For most substances the "total" concentration in the soil was determined and where appropriate "available" concentrations were additionally determined. Generally this related to the water-soluble content, such as the water-soluble sulphate content for comparison with total (acid-soluble) sulphate content, to allow assignment of concrete class in accordance with the BRE 363 guidance [1].

When sampling water from BAT piezometers, the sample volume was often restricted due to the small size of the vials and the low permeability conditions in the response zone, which meant it was not always possible to fill duplicate vials. This was an important restraint on the test methods that could be adopted, and as a consequence priority was given to testing for sulfate, pH, and sulfide.

Mineralogical and geochemical testing of the soil was undertaken by X-ray diffraction (XRD) analysis and X-ray fluorescence (XRF) analysis. The XRD analysis provides a bulk mineral analysis of the whole sample and clay mineral analysis on the clay fraction and the XRF analysis identifies the proportion of all the major and minor cations that are present in the sample. The cation content is matched to the XRD trace to 'pair off' elements with minerals.

In addition to the routine suite of chemical and mineralogical tests, segments of the soil–concrete interface samples were examined using high and low vacuum

Table 5
Summary of soil and water chemical testing suites used for the detailed investigation of TSA

Testing suite	Soil and water chemical tests	Objectives
Suite 1 basic soil chemistry (all sites)	pH (BS1377), Total (acid soluble) sulfate (BS1377), Water soluble sulfate (BS1377), sulfide, total sulfur, water soluble magnesium, total (acid soluble) chloride (BS1377), water soluble chloride (BS1377), carbonate, organic content (BS1377)	BRE digest 363[1] and Thaumasite expert group [2] sulfate classification Measuring main components of chemical attack of concrete
Suite 2 detailed soil chemistry (major sites in Phases 1 and 2)	*All Suite 1 plus:* calcium, potassium, magnesium, sodium, aluminium, iron, silicon	Determining major cations and anions for ionic balance, assist XRD analysis, assessment of cations for weathering of Lias Clay and influence of concrete
Suite 3 basic groundwater chemistry (all sites)	*Equivalent tests to all of Suite 1:* pH, sulfate (BS1377), sulfide, total sulfur, chloride carbonate, bicarbonate, electrical conductivity	BRE Digest 363[1] and Thaumasite Expert Group [2] sulfate classification Measuring main components of chemical attack of concrete
Suite 4 detailed groundwater chemistry (major sites in Phases 1 and 2)	*All Suite 3 plus*: calcium, potassium, magnesium, sodium, aluminium, iron, silica, REDOX potential	Determining major cations and anions for ionic balance and classification of groundwater types, to determine whether there is oxidising or reducing conditions
Suite 5 background soil chemistry (minor sites in Phases 2 and 3)	pH (BS1377), total (acid soluble) sulfate (BS1377), water soluble sulfate (BS1377), water soluble magnesium	BRE Digest 363 sulfate classification [1]

Note: the above tests were designed for the detailed assessment of TSA; the recommendations of BRE Special Digest 1 [3] should be followed for the routine assessment of aggressive ground conditions.

SEM to provide a qualitative assessment of features and structure within the soil and a quantitative indication of its composition and mineralogy at different distances from the interface. Low vacuum SEM has the advantage that there is less potential for modifying the samples during preparation compared with high vacuum SEM, which requires samples to be dried prior to being coated.

9. Laboratory testing of concrete samples

The testing undertaken on concrete can be grouped as follows: physical testing, chemical testing, petrographic examination and SEM Microprobe analysis. The testing, which is summarised in Table 6, had the following overall objectives:

- to characterise the concrete within different members at each site for comparison against the severity of attack to assess any trends;
- to determine the extent and nature of the deterioration to assist in formulating repair strategies;
- to establish a database of fundamental information on the concrete so that the processes and factors associated with thaumasite attack can be better understood.

The physical and chemical testing was generally undertaken in accordance with BS1881, Part 120 [7] and Part 124 [8]. The potential composition of the cement was estimated in terms of tricalcium aluminate, tricalcium silicate, dicalcium silicate and tetracalcium aluminoferrite content using the standard Bogue equations [9]. Ratios of tetracalcium aluminoferrite to tricalcium aluminate of less than 2:1 and greater that 5:1 were assumed to indicate Portland cement and sulfate-resisting Portland cement, respectively.

The samples for petrographic examination were examined visually and under lower magnification binocular microscope to establish general features [10]. Thin-sections, typically 50×70 mm^2 in area and 20–30 μm in thickness, were prepared from a plate cut at right angles to the outer surface of the concrete following epoxy resin impregnation. In some cases this included traces of soil adhered to the concrete. This work provided information on the composition of the concrete, e.g. aggregate type, and extent and nature of the deterioration. The presence of thaumasite was determined with up to 90% certainty from its high birefringence compared to ettringite and confirmation was provided using Scanning electron microprobe microanalysis. This analysis which uses an energy dispersive system fitted to a scanning electron microscope gives major oxides normalised to 100%, excluding water and carbon dioxide, within an

Table 6
Summary of laboratory test methods for concrete

Laboratory test method	Objective
Physical testing	
Compressive strength testing to BS1881, Part 120 [7] • Estimated In situ cube strength • Hardened density and excess voidage • General description of sample, including dimensions and presence of reinforcement	*Primary:* characterise the quality of the concrete in respect of the basic engineering properties of strength, density and compaction for comparison with other sites and to facilitate structural analysis *Secondary:* provide information on the concrete to confirm the findings of the site testing, e.g. cover and rebound values, and the other laboratory testing, e.g. composition and excess voidage from petrographic examination
Chemical testing	
Testing to BS 1881, Part 124 [8] • Chloride ion content (Cl^-) • Sulfate content (SO_3) Limited standard testing for alkali content as (Na_2O equivalent) and non-standard testing for nitrate and sulphide content	*Primary:* provide standard data for assessing the risk of sulfate attack to concrete and chloride induced corrosion of reinforcement for comparison with the evidence of the thaumasite attack *Secondary:* confirm the potential for alkali aggregate reactions following repair and establish profiles into the concrete to match equivalent profiles in the soil
Petrographic examination	
Examination and point count to ASTM C 856 [10] and ASTM C457 [11] to give: • Aggregate and cement type • Estimated composition and density • Nature and extent of deterioration, including reaction products, voids, cracks and carbonation	*Primary:* provide objective quantitative information on the depth and nature of the deterioration *Secondary:* confirm the quality of the concrete in respect the BRE Digest 363 [1] guidance on sulfate resistance, i.e. cementitious content and type and w/c ratio, and the aggregate type in relation to thaumasite formation
SEM Microprobe analysis	
Analysis of major oxides (including SO_3, CaO, SiO_2, Al_2O_3, MgO and Na_2O equivalent) within a 0.1×0.1 mm area. Results reported on a normalised basis equivalent to a percentage of the anhydrous cement ;paste	*Primary:* confirm the nature of the reaction products within cracks and voids *Secondary:* provide a profile of the chemical composition close to the soil-concrete interface in order to assess the reaction processes

area of cement paste 0.1 mm square. The results are very sensitive to the position of the probe and typically ten locations were selected within an area 40 mm square using the using the scanning electron microscope image. The ratio of silica to alumina in the reaction products was used to differentiate between ettringite and thaumasite; the latter having little or no alumina.

Polished plates were also prepared and subject to point-counting to provide an estimate of the volumetric proportions of the concrete [11]. The mass proportions, including the cement content, of the concrete were calculated from the volumetric proportions using assumed densities for the aggregate and cement. The water–cement ratio was estimated from the proportion of unhydrated cement observed in the sample.

10. Database procedures

A relational database management system designed for use with engineering and other technical data, was used to facilitate the storage, manipulation and transfer of the large amount of data that were gathered during the investigation. All data collected during the fieldwork

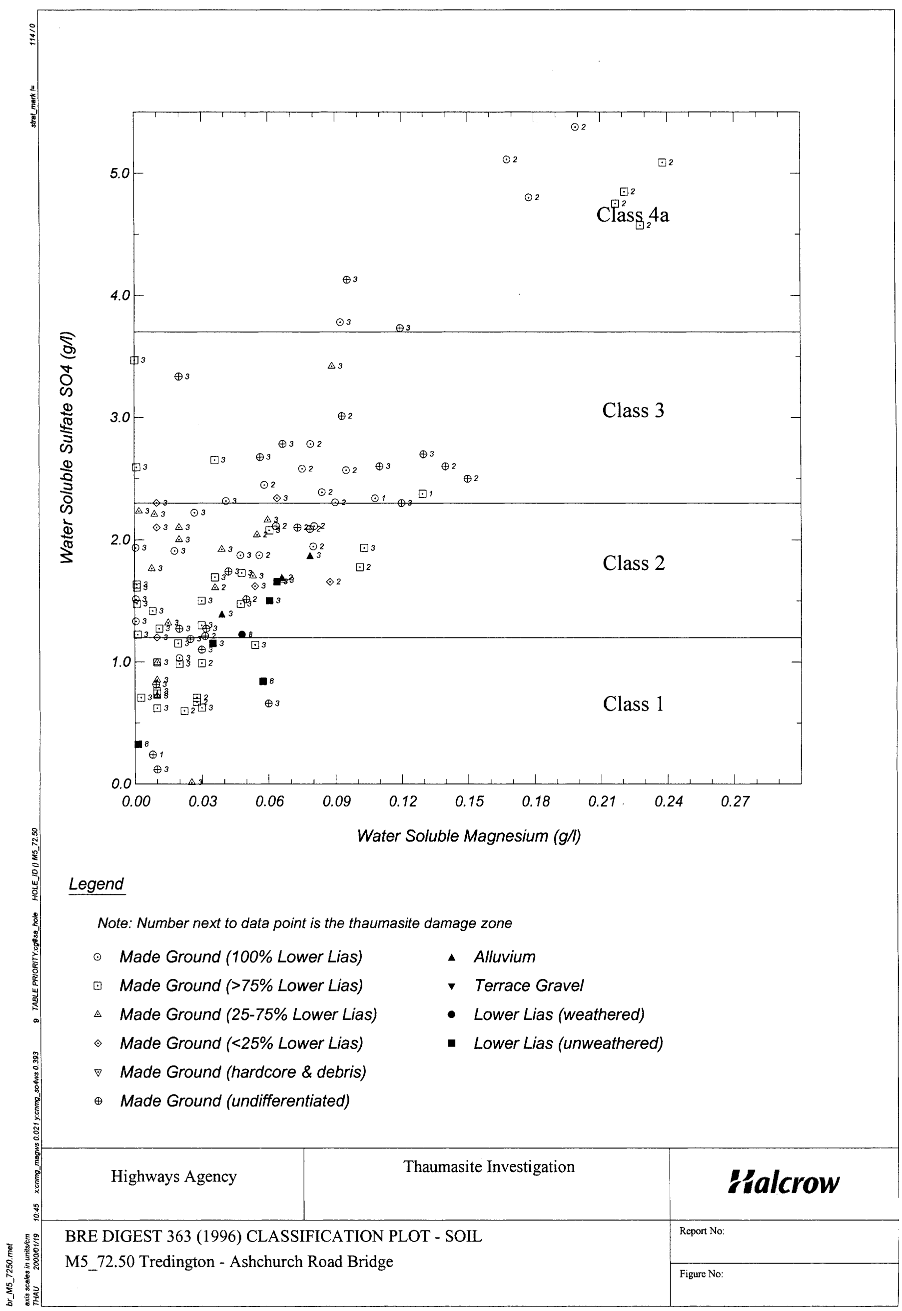

Fig. 3. Example of output plot from the project database.

were entered into the database except for trial pit/excavation logs, concrete face logs and the site photographs. The data from the concrete face logs were summarised in the database terms of a 'damage code' to describe the extent of concrete softening at different horizons (code 1 = none, code 2 = partial width of survey area, code 3 = full width of survey area). In addition to hard copy reports, data from laboratories were requested in digital format. Wherever possible, the import, storage and export of such data adopted the Association of Geotechnical and Geoenvironmental Specialists (AGS) Geotechnical Data Interchange Format [12].

Each sample is identified in the database using a 'Hole ID', sample depth and unique sample reference number taken from the sample certificate. Each sample is located by reference to the offset from the face of the nearest concrete element (a negative offset if it is a sample within the concrete element) and by elevation above the foundation footing. This allowed test data to be given site-specific co-ordinates, which for detailed sampling locations was to the nearest 5–10 mm.

Information is stored in a 'data group' or 'Table'. The tables are chosen to relate to specific elements of data, such as project information, exploratory hole details, soil chemical test results, groundwater levels, etc. Data are stored in each table under headings termed 'Fields', such as sample depth, soil moisture content, concrete density etc. Where it was not possible to use the existing AGS format for the data, such as the concrete samples, then a similar and compatible structure was developed. The database was an essential tool for manipulating and sub-setting the data and hence facilitating the analysis of the results and the preparation of summary statistics, tables and figures. In particular the results and classifications from concrete testing and logging can be compared directly against adjacent results and classifications from soil and groundwater testing and logging. An example of output from the database is given in Fig. 3.

11. Conclusions

A procedure is described for prioritising TSA investigations as part of the asset management of highway structures. A number of alternative methods of soil, water and concrete sampling methods are then suggested, including inclined percussive boring and use of BAT piezometers. Correct selection is important to ensure the work is efficient and provides samples that are representative of the in situ conditions. Soil and concrete sampling should be co-ordinated to maximise the value of the opportunity for data gathering when buried concrete structures are excavated. The establishment of fixed written procedures is essential if a consistent approach is to be obtained for the site and laboratory work. Sampling certificates should be used to record the sample details and accompany the samples to the laboratory.

Laboratories often use in-house methods, e.g. for chemical analysis, and it is essential to consult with them to ensure that sample storage, preparation and testing methods are appropriate. Adopting a system for recording the location of soil, water and concrete samples relative to one-another allows the comparison of results between the three media, and is made easier if a relational database is used. A relational database can provide a useful tool for storing, transferring and manipulating data. The provision of test results in digital AGS format simplifies data input to the database. Ensuring that suitable sampling, testing and reporting procedures are adopted requires considerable thought and preparation prior to the commencement of site work.

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