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Thaumasite investigations to M4 overbridges

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Abstract

In March 1998, thaumasite sulfate attack (TSA) was discovered affecting several buried raking supports of the Golden Valley Interchange at Junction 11 of the M5 Motorway in Gloucestershire. Following this discovery and the subsequent issue of the Thaumasite Expert Group Report in January 1999, the Highways Agency required all Network Agencys to investigate the likelihood and extent of any such deterioration. The investigations were to be targeted to all suspect structures, i.e. those with some or all of the details and conditions thought necessary for the initiation of TSA.

The thaumasite investigation undertaken by Parsons Brinckerhoff Infrastructure as agents for the Highways Agency Area 5 Network commenced with a desk study to determine the structures most at risk from the initiation of the TSA. Of the 675 bridge structures within this network, the total with an identifiable risk priority of 1 was found to be 50; these having some form of buried foundations in reworked sub-soils affected by either natural ground water sulfates or contaminated road run-off. Of these 50 structures, 18 were initially selected for Phase 3 detailed site investigations.

Following the identification of those structures which would most likely have TSA, site investigations were programmed and undertaken in October 1999. Five structures were initially investigated, with concrete cores being removed from selected locations of the buried post-tensioned ground beams. These core samples were subjected to petrographic, scanning electron microscopy and X-ray diffraction examinations following discussions with experts from the Building Research Establishment.

This paper discusses the methodology adopted in the preparation of the desk study, the Special Inspection and the means by which the samples were extracted, tested and examined. This paper focuses on the 'Engineers methods' for the identification of thaumasite and the results of the investigations are presented.

Keywords: Thaumasite; Foundations to M4 overbridges; Methodology; Desk study

1. Introduction

In March 1998, whilst carrying out strengthening and refurbishment work to the Golden Valley Interchange bridges at junction 11 of the M5, thaumasite sulfate attack (TSA) was found to be affecting areas of the pile caps and buried support piers. The site was subject to a thorough investigation by members of the Building Research Establishment (BRE) in order to advance the understanding of this form of sulfate attack.

The results of the M5 site study, together with those from other sites, and from ongoing research, were used by the UK Government Thaumasite Expert Group (TEG) to formulate the advice contained within their subsequent report [1], published in January 1999. Within this report, the factors required for TSA were detailed, as were indications of the most likely locations for TSA in the UK. Following the publication of this report, the Department of Transport issued Interim Advice Note IA 25 [2] followed by a directive to agents for its Super-Area Networks to undertake studies to investigate the likelihood, or even presence, of TSA in foundations within their respective bridge stock.

Parsons Brinckerhoff were agents to the Highways Agency (HA) for the initial "Area 5" Network which encompassed the M4 Motorway from its interchange with the M25, westwards up to junction 15, near Swindon, and a section of the M25 and parts of other motorways and trunk roads generally to the north west of London. A schematic plan of the routes within the initial Area 5 is shown in Fig. 1. The information contained within the TEG Report showed that some areas of the UK were more likely to support the formation of TSA than others. It was shown that the M4 corridor in general was a zone where the risk of TSA needed to be considered.

A desk study was consequently undertaken, with a brief to consider all the structures in the network, but

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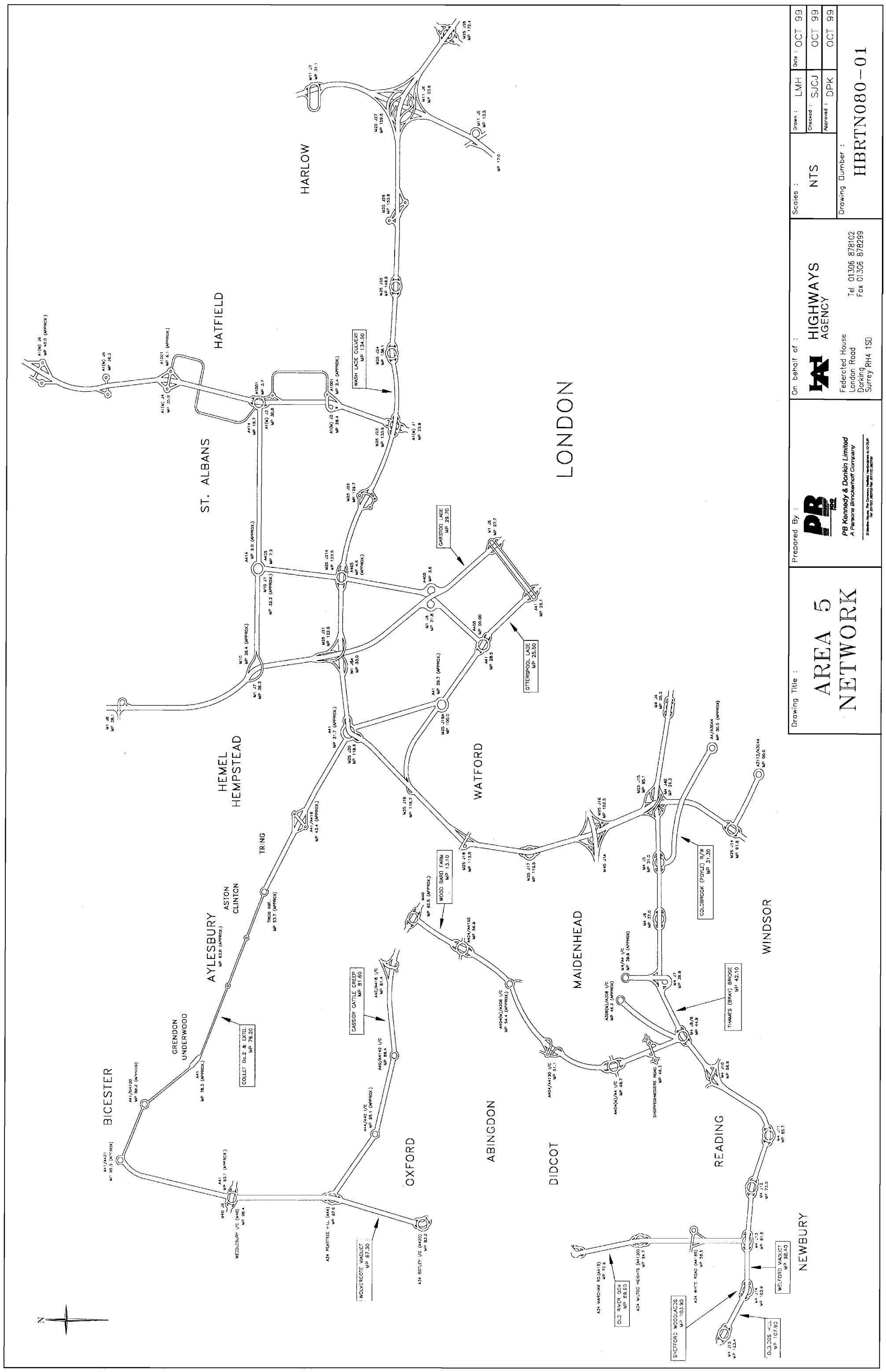

Fig. 1. A schematic plan of the routes.

primarily those along the M4, where it was known that these structures were more likely to be at some risk due to the prevailing ground conditions.

It was deemed necessary to physically investigate selected structures or parts thereof to confirm the presence, or otherwise, of signs of the development of TSA where the risk analysis in the desk study identified the structures as being most at risk. The structures were considered for particular forms of construction as well as prevailing ground conditions and the construction materials used.

This paper describes the processes employed, results from the Special Inspections and from the laboratory investigations into the presence of TSA in buried elements of selected bridges on the M4.

2. Phased investigations

The formation of thaumasite has been known for some time, both as a naturally occurring mineral, and as a cultivated reaction product in the laboratory. It had previously been found in diverse locations such as masonry pointing and domestic shower rooms, however, it was the extent of the deterioration to the foundations at the Tredington Ashchurch Bridge on the M5 that prompted the Highways Agency to require their agents to check for the risk of its formation, and to confirm the subsequent desk study findings. The 950 plus structures in Area 5 were subjected to a phased investigation approach. The initial phase was to undertake a detailed desk study that would use structure data readily available within the Area 5 database to produce a ranking system, with those bridges most at risk having a higher ranking factor.

Having produced a list of theoretical higher risk structures, the second phase entailed prioritisation of the investigations. Although the study might identify a number of structures with the same ranking factor, it might not be economically sensible or practical to carry out the field work to each one. Consequently, considerations of the structures' location along the motorway, the depth of expected excavation and planned network projects or road-space requirements needed to be made. A final consideration would be the cost of the investigations, with all the other Agencies having this work to complete, a significant financial burden would be placed on the HA, hence resources would be focused on the highest risk structures.

The third phase would encompass the field investigations, where material samples were to be collected and laboratory investigations undertaken to confirm whether the formation of thaumasite had been initiated, or would be likely in the future. This phase required preplanning of the site operations so that the appropriate expertise and resources were available on site, and that the proposed programme was achievable. The site work needed to be carefully considered to ensure that the correct amount of sampling was undertaken in the correct manner. It was also imperative that the collected samples were subjected to the appropriate investigations so that TSA could be confirmed as being present or absent, especially if there were no visible signs of the reaction.

3. Phase 1 desk study

Thaumasite formation had been closely studied by members of the Expert Group who had worked together in the production of the TEG Report. This document [1] gives valuable information to engineers on how various components of the structure's environment and its construction can combine to produce thaumasite. It had been found that there needed to be various factors in place before TSA could develop. The report provided information regarding the geographical regions where bridges would be most at risk primarily due to the presence of sulfate bearing soils.

The guidance contained in the TEG Report and the advice contained within IA25 were followed in the preparation of the desk study, or Phase 1 Strategy Report [3] for the structures within the Highways Agency Area 5. The report used a simple equation to take data available from the structures database and from the bridge record sheets as input to a numerical method of identifying structures most at risk. The equation used factors, detailed in the TEG report, derived from the physical characteristics of the structures. Structure age and the presence of vulnerable details were used with weightings for their importance in the production of TSA. There were also factors for the volume of traffic over the structures. These four factors were sourced from BD 54/93 [4] used in the prioritisation of Special Inspections of post-tensioned structures. A final factor to be included in the equation was the composite aggregate/sulfate factor which is detailed in the TEG report, and combines a sulfate risk factor and an aggregate risk factor to produce an overall rating value ranging between 1 and 10. The rating equation gave a score range of 10–50, with the highest scores relating bridges with the highest risk of TSA formation.

$$T_A = 4R_a + 2R_d + R_v + R_u + \text{combined aggregate/sulfate factor}$$

R_a = age factor; R_d = vulnerable detail factor; R_v = traffic on the structure—rating A; R_u = traffic under the structure—rating B.

The combined aggregate/sulfate factor (Table 1) is deduced from an aggregate risk factor (likelihood of carbonate aggregated in the concrete (Table 2) and sulfate risk (clay sub-soil)). A sulfate risk factor of 3 does not require class 3 soil conditions, only the presence of certain clay types (Table 3).

The aggregate and sulfate risk factors are used to derive a composite aggregate/sulfate risk factor. It can be seen from Table 1 that if the sulfate risk factor is "1",

Table 1
Composite aggregate/sulfate risk factor

Sulfate risk factor (known)	Combined aggregate/sulfate risk factor		
1	1	1	1
2	4	6	8
3	6	8	10
	1	2	3
	Aggregate risk factor (known)		

This table is extracted from a report by Atkins [5].

Table 2
Concrete aggregate

Aggregate risk	Aggregate risk factor	Grouping
Low	1	Highly likely that non-carbonate aggregates used in construction.
Medium	2	Equal probability that non-carbonate and carbonate aggregates used in construction.
High	3	Highly likely that carbonate aggregates used in construction.

This table is extracted from a report by Atkins [5].

the overall composite factor will always be "1", as the presence of a sulfate bearing soil is the dominant factor.

The methods used to ascribe risk factors were based on the location of carbonate and non-carbonate source quarries in relation to the structure under investigation. The following risk factors have been adopted and incorporated into the analysis.

The assessment has, to a large extent, been based on the Directory of mines and quarries (1991) [6], which may not truly reflect quarry activity in the late 1960–1970s. A larger number of small quarries may have operated at that time (extracted through internal communications with Parsons Brinckerhoff). It has been generally assumed that concrete will have been sourced local to the relevant structures. Given the large scale of the motorway construction contracts this may not necessarily be the case.

For all the lithologies encountered during the study, the following risk factors shown in Table 3 were ascribed:

The risk categorisation has, to a large extent, been based on Forester et al.'s "Regional distribution of sulfate in rocks and soils of Britain" [7].

The computations of assessment rating were undertaken on all the structures in the bridge stock inventory. An extract of the results is shown in Table 4. Completion of the numerical analysis showed that the structures along the motorways and trunk roads in the network away from the M4 corridor were not at risk from TSA. The M4 structures were more likely to be subject to TSA as they had been constructed (in the 1970s) in areas of London Clay sub-soil (potentially sulfate rich). Although nearly 400 bridges were situated in areas of sulfate bearing soils, it was considered that the M4 bridges should receive the initial round of further study, as they were the most susceptible to TSA. The Phase 1 [3] report concluded that of the 950 plus structures within the Area 5 Network, 390 were deemed potentially susceptible to TSA, however considering the guidance given by the TEG Report and the Interim Advice Note, it was recommended that only 18 representative structures should be subjected to Phase 2 investigations.

4. Phase 2—prioritisation

Before the start of the site work, the severity, extent or even presence of TSA in any of the structures was unknown. It was important not only to check those structures that were most likely to suffer from TSA, but to extend the field of search to encompass a reasonable number of structures having a lesser risk of attack. This would lead to an initial assessment of the level of deterioration for different locations and conditions.

The TEG Report gave information on the conditions necessary for the initiation and development of TSA. Factors such as mobile contaminated ground water, carboniferous aggregates (limestone), and reworked

Table 3
Sulfate risk

Sulfate risk	Sulfate risk category	Lithology
Low	1	Upper, Middle and Lower Chalk; River, Valley and Terrace Gravels; Chert Beds; Pennant Sandstone; Mercia Sandstone (formerly sandstone in Keuper); Tintern Sandstone Group; Quartz Conglomerate; Clifton Down Limestone; Black Rock Limestone; Coral Rag (Limestone); Inferior and Great Oolite.
Medium	2	River Alluvium; Brickhearth; Head Deposits; Estuarine Alluvium; Yeovil Sands; Midford Sands; Pennard Sands; Whitecliff Sands; Upper Greensand; Otter Sandstone; Calcareous Grti; Wittering Formation; Dolomite Conglomerate; Tea Green Marl; Middle Lias (Marlstone Rock Bed); Upper Lias.
High	3	Lower Lias; White and Blue Lias; Kimmeridge Clay; Kellaway Clay; Gault Clay; London Clay; Reading Beds; Forest Marble Clay; Fullers Earth; Oxford Clay; Mercia Mudstone; Penarth Group (formerly Rhaetic); Wenlock Group (shales).

This table is extracted from a report by Atkins [5].

Table 4
Extracts from prioritisation of structures susceptable to thaumasite (3) M4

Route	HA key no.	Structure name	Construction year	Pier type	Abutment type	Foundation	Age rating R_a	Sulfate risk factor	Limestone aggregate risk factor (1–3)	Composite aggregate/ sulfate risk factor	Vulnerable detail rating R_d	Traffic (over) rating R_v	Traffic (under) rating R_u	Total assessment rating T_A	Priority factor
M4/25.20	936	Holloway Lane	1965	Concrete Columns			5	3	3	10	3	5	5	48	1
M4/25.20	937	Holloway Lane North Slip	1965				5	3	3	10	3	5	5	46	1
M4/25.20	938	Holloway Lane South Slip	1965	Leaf Piers (with Cantilever Ext)	Skeleton	Spread	5	3	3	10	3	5	5	46	1
M4/25.20	939	Sipson Rd North Subway	1965				5	3	3	10	1	5	5	42	2
M4/26.00	15,177	Harmondsworth Rd South	1985		Cantilever	Spread	1	3	3	10	1	5	5	26	4
M4/26.00	940	Harmondsworth Rd North	1965				5	3	3	10	5	5	5	50	1
M4/26.40	941	Little Benty F/B North	1965				5	3	3	10	3	2	2	40	2
M4/26.40	15,180	Little Benty F/B South	1985		Concrete Columns	Spread	1	3	3	10	3	2	2	24	5
M4/26.90	942	River Colne	1985	Slab Wall	Strutted	Piles	1	3	3	10	3	5	5	30	4
M4/27.20	943	River Wraysbury	1965	Slab Wall	Strutted	Piles	5	3	3	10	3	5	5	46	1
M4/27.40	944		1965				5	3	3	10	3	5	5	46	1
M4/27.70	945	Staines Branch Line	1985		Cantilever	Slab	1	3	3	10	4	5	5	32	3
M4/28.10	15,169	Colne Brook	1983		Cantilever	Spread	2	3	3	10	3	5	5	34	3
M4/28.50	948	Old Slade Lane	1965	Raked Leaf Piers	Raked Piers	Spread	5	3	3	10	3	2	2	40	2
M4/29.30	949	Old Wood Culvert	1965				5	3	3	10	3	5	5	46	1
M4/30.00	950	Sutton Barn Culvert	1965				5	3	3	10	3	5	5	46	1
M4/30.30	951	Sutton Lane		Raked Bell End Piles	Skeleton	Piles	N/A	3	3	10	3	2	2		
M4/31.00	8229	Langley Interchange Subway	1964				5	3	3	10	2	5	5	44	2
M4/30.90	952	Langley Interchange East	1963				5	3	3	10	5	5	5	50	1
M4/31.10	953	Langley Interchange West	1963				5	3	3	10	5	5	5	50	1
M4/31.50	954	Ditton Road Culvert					N/A	3	3	10	3	5	5		
M4/32.10	955	Gas Main Sway	1963		Strutted	Spread	5	3	3	10	3	5	5	46	1
M4/32.10	956	Hams Farm Footbge	1963	Concrete	Concrete	Spread	5	3	3	10	3	2	2	40	2
M4/33.50	960	Riding Court	1963	Concrete Frame	Skeleton	Spread	5	3	3	10	3	2	2	40	2
M4/32.50	958	Ashleys Arch	1963				5	3	3	10	3	5	5	46	1

sulfide rich soils were identified for some bridges, but there were no instances where buried parts of the substructure were at 10–12 m depth, and would be accessible by excavation. It was considered that the field work should be focused on bridges that fulfilled the most factors, whilst keeping the scope of the investigations within the brief to confirm or otherwise, the presence of TSA within Area 5. The report concluded that 18 structures should be targeted for investigation work. Their priorities ranged from 1 to 3 (1 highest), however, they covered a range of structure types, and geographical locations, an extract from the reports prioritisation procedure is shown in Table 4, and a summary of the prioritisation is shown in Table 5.

After discussion with the Highways Agency, it was accepted that the number of structures to be initially investigated had to be reduced from 18 to 6, with an option to carry out further investigations should the initial work discover TSA. There were also structure selection constraints imposed by the Area 5 Network. The M4 Motorway is regarded as a key route, especially towards London, and day-time closures of any traffic lanes were to be avoided if at all possible. Excavations to expose buried foundations could be expected to require some form of lane closures, if only to allow delivery of plant and equipment. In order to minimise traffic disruption, it was necessary to consider night-time working, with the excavations only being allowed to remain open during the day if vehicles were prevented from entering the work zone by a suitable physical barrier. Alternatively, the excavations could be opened, the investigations undertaken, and the excavations reinstated in one night shift. This second method of carrying out the investigations would rely on the excavations being relatively shallow, as a deep excavation would produce a considerable amount of spoil, and would require the use of extensive temporary works.

The M4 corridor passes through relatively level topography, this being reflected by the limited use of deep foundations for these structures that were designed in the late 1960s. The M4, westwards from London to Wokingham/Reading although not the first motorway built in the UK, was an early construction. At the design stage for the later three-lane plus hardshoulder carriageways (from Wokingham westwards), repetition of structural form reduced the delay between drawing board and site. A common form of overbridge design utilised a post-tensioned pseudo-box deck, with inclined supports and buried post-tensioned tie beams beneath the carriageways providing stability to the structure. The design reduced the amount of excavation needed for the foundations, and could be used with minimal alterations at several locations along the M4. The tie beams were below a French drain positioned along the centreline of the motorway which picked up road drainage. The ground beams were therefore located in an area of excavation, although not necessarily with sub-soil backfill, where ground conditions could be expected to be wet, and with the added bonus of sulfate contamination of the ground/drainage medium from the deicing salts used in winter.

This type of structure can be seen repeated many times between Theale, near Reading, along the M4 towards Bristol. Other designs for overbridges did not use foundation elements that could be readily excavated within the constraints imposed by traffic flow considerations. Underbridges would not normally be subject to the same traffic imposed complications as the overbridges, and most along the M4 also followed a common form, which used foundations that were not in

Table 5
Summary of structure prioritisation

HA str. no.	HA key no.	Structure name	Structure type and comment	Assessment rating	Priority
M4/30.9	952	Langley I/C East	U/B—post-tensioned sub-structure	50	1
M4/35.9	965	Prince of Wales	U/B—pre-tensioned	46	1
M4/44.9	989	Holyport I/C East	O/B—post-tensioned sub-structure	46	1
M4/46.00	994	Stud Green Access	O/B—post-tensioned sub-structure	42	2
M4/56.8	1010	Winnersh I/C Slip Road 7	O/B—post-tensioned superstructure	46	1
M4/65.7	1031	Three Mile Cross I/C East	O/B—post-tensioned sub-structure	48	1
M4/81.9	1057	Scratchface Lane	O/B—post-tensioned superstructure	38	3
M4/103.9	1080	Shefford Woodlands I/C East	U/B	48	1
M25/91.8	13,577	Poyle I/C South	O/B	38	3
M25/102.5	16,229	M40 Overbridge	O/B—pre-stressed	36	3
M25/135.7	13,049	Baker Street Underbridge	U/B	40	2
M25/159.6	17,643	Theydon I/C West One	U/B—post-tensioned	36	3
A4/30.9	6520	Wraysbury River	U/B	34	3
A34/50.9	7334	Ashridge Farm	U/B	42	2
M11/24.9	3019	Mount Street	U/B	42	2
A1(M)/24.4	4953	Cecil Road Flyover	O/B	42	2
5/M1/27.8/1	85	Berrygrove M1 North	O/B	44	2
M1/28.2	87	Otterspool Lane	U/B	44	2

contact with re-worked sub-soil. Where the underbridges were site specific, reference to bridge records indicated that the foundations again were unsuitable for excavation and in any case would have used a granular backfill.

The prioritisation of the 18 overbridges into a shortlist of six structures was accomplished by considering the amount of excavation that would be required, and the areas where this could be undertaken. It was decided that two interchanges and two individual structures should be subject to the Phase 3 work, these being selected for having a relatively shallow fill which would allow one complete structure to be investigated per shift.

5. Phase 3—detailed site investigations

The start of this Phase 3 of the investigations began in August 1999 with preliminary site visits to ascertain the site layout and to facilitate the planning of the forthcoming site activities. The structures each had to be assessed for availability of access, any site specific problems, and local traffic management (TM) issues where the proximity of on/off slip roads would present TM problems. The presence of the French drain at the centre of the M4 meant that this was the location where TSA would be most likely if it was going to be anywhere along the buried tie beams. As a result the investigations would need to be undertaken during night-time closures of lanes 2 and 3 of the motorway. The bridges were all within the section of the M4 where TM could be a sensitive subject, especially if lane closures were needed before 9 p.m., as the resulting tail backs could be considerable.

Having booked the 'Network Space' to ensure that other works did not clash with the TM and resourcing, the planning focused on the Health and Safety aspects of the work, in particular the need for trench supports and the length of time estimated for the completion of a single investigation. It was calculated that the excavation depths would not exceed the maximum depths allowable of 1.1 m, before temporary propping would be required. It was a contingency plan that some sheeting equipment be on site in case the excavations had to be deeper than had been originally estimated.

The method of achieving the required level of investigation was considered with advice gained from members of staff of the BRE. The method of obtaining the samples was to be rotary diamond coring, with a water flush used if there were no signs of any significant formation of thaumasite. If it was suspected that TSA had been initiated, hand samples were to be obtained using other cutting and breaking methods. The number and positioning of the cores was also considered, as it was important to check the foundations in sufficient detail to enable TSA to be clearly identified or dismissed as appropriate. The sampling regime was designed to check the exposed edges of the ground beams, and the heart concrete. As the bases of the ground beams were nearest to the London Clay, it was also proposed that the coring should be full depth, so that the bottom of the tie beam section could be checked also. The final aspect of the sampling was the storage of the concrete whilst awaiting laboratory testing. It was important that the samples were protected from damage, that any concrete deterioration not be lost, and that each core bear a unique reference.

A major consideration relating to the progression of the work was that the post-tensioning system was not to be damaged by the coring operations. This was achieved by selecting locations within the ground team where there were no tendons, and by using percussive drillings to check that there were no displaced tendons before coring operations began. It was suggested that further investigations could be undertaken at the same time as the coring, by carrying out reinforcement cover and half-cell potential surveys. This would give further information regarding the condition of the post-tensioned members and the likelihood for developing deterioration, and would allow an assessment to be formed of the effectiveness of the site applied "black-jack" waterproofing to the sides and tops of the beams.

The site works were undertaken in October 1999, and followed the procedures planned in the office. Diamond coring techniques were used to extract a minimum of two cores from each ground beam (Fig. 2). The cores were 75 mm in diameter to ensure that they would readily pass between the post-tensioning tendons, and were to the full depth of the 300 mm thick beams. The work allowed for two ground beams to be exposed, tested and sampled, and the excavations reinstated within a single night-time shift. This resulted in the site work stage of the investigation being completed in six work periods, all passing without incident. At the time

Fig. 2. Core from ground beam, Theale interchange (W), M4.

of core extraction, an initial examination was made as to the presence of deterioration, both to the upper face of the beams exposed by excavation, and the sides and underside of the beams as freshly exposed by the coring. In each case there was no discernable signs of active or developed stages of TSA.

6. Phase 4—laboratory testing of samples

Having retrieved the necessary samples, quotes for the laboratory testing were obtained. It was understood from members of the BRE that advanced stages of thaumasite may be determined by eye examination, however, to determine whether this form of deterioration is in the early stages of development would require much more involved testing. In addition to the usual determination of the total acid soluble sulfate content of the concrete expressed as a percentage relative to the cement content, it would also be necessary to determine whether other indicators of thaumasite were present. In the early stages of TSA, certain compounds form which later combine to result in the mineral thaumasite. During the process, ettringite crystals are produced which can be detected by various means. It was deemed that in order that a definitive statement could be made as to the presence or likelihood of thaumasite formation, three separate tests would be specified, X-ray diffraction (XRD) which determines the presence of various elements in a compound, scanning electron microscopy (SEM) which will allow very high magnification of areas of interest, i.e. formations of ettringite crystals, and petrography, where changes in the mineralogy of concrete samples can be identified and assessed by experienced personnel.

The winning quote for the lab work was returned by Stanger Testing Services Limited, a firm that was UKAS accredited for this type of work. The samples from all the structures were identified on a testing schedule, with each sample receiving one or more tests, dependant upon the number of samples available for the test type, and distribution of tests throughout the investigation. It was unnecessary to undertake all tests on all samples, so the schedule gave a reasonable spread of tests throughout the six structures.

7. Results

The petrographic and visual examination of the ground beams to the six structures under investigation confirmed that they were in good condition with no evidence of deleterious reactions within the concrete matrix. A summary of findings from one of the six bridges is shown in Table 6. Although there were no indications of TSA, samples of concrete were obtained by slicing the cores into 25 mm thick slices, and these were subjected to laboratory testing for chemical composition and contamination by salts. Even though there was no evidence of TSA, the following points were noted.

Chloride ion ingress into the top face of the ground beams was often above 0.3% by mass of cement at reinforcement depth, this being despite the application of a 'black-jack' coating during the construction phase. All the ground beams were given this form of protection, routinely specified for all buried concrete surfaces of highway structures.

The petrographic examination of the selected cores found the coarse aggregate to be limestone, which, allied to the ready supply of ground water and the low ambient temperature would facilitate the formation of thaumasite in the presence of sulfates. The sulfate levels recorded from the core samples were however, below the level at which sulfate induced deterioration would be expected, and the petrographic examinations reported that only small amounts of non-disruptive ettringite were present as void linings.

The petrographic examinations also found some potentially reactive flint aggregates which would make alkali aggregate reaction (AAR) possible. Alkali levels were well below the accepted critical level for the avoidance of AAR and no evidence was found of AAR activity.

Both the SEM examination and the XRD examination revealed no evidence of the formation of thaumasite and only very minor amounts of ettringite. Both types of examination confirmed that the core samples were not subject to any significant deleterious reactions, major chemical attack or substantial leaching.

All materials testing found the core samples to be structurally and chemically sound and free from TSA or disruptive ettringite formation.

Table 6
Theale interchange west—summary of laboratory results

	Chloride ion concentration by % of cement 0–100 mm	Alkali contents kg/m^3 0–100 mm	Total acid soluble sulfate content % by mass of cement 0–100 mm	Cement contents kg/m^3 (%)	XRD	SEM
Core 1	0.25–0.75	0.54–0.82	1.98–1.83	586 (24)	–	–
Core 3	0.52–0.83	0.44–0.47	2.10–1.95	550 (23)	✓	✓

Typical results for all the structures investigated.

8. Conclusions

The desk study showed that there were some structures along the M4 that might be susceptible to TSA, given their geographical location and environmental conditions. The laboratory work showed that the concrete contained limestone coarse aggregate, which would be a main ingredient for TSA formation.

The depth of fill was only 1 m and the concrete had a semi-impervious protection, which may also be the reason why TSA was not found.

Perhaps most importantly, the beams were not covered by a reworked sulfide contaminated soil—the material above the beams was mostly granular fill, (French drain) although it did contain some clay contamination.

There were no recommendations made at the time of reporting for further Special Investigations, although it was thought prudent to re-test the ground beams on a 10 yearly cycle due to presence of the majority of the components required for the development of TSA, and the chloride ion contamination to certain beams at the depth of reinforcement.

Although there were no indications of TSA, the investigation procedure of using a desk study and targeted site works was deemed a valid exercise, and one in which the investigations of a few selected structures gave an indication that the structures in Area 5 had a low likelihood of thaumasite formation.

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