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A summary of the Highways Agency Thaumasite Investigation in Gloucestershire: the scope of work and main findings

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Abstract

A summary of the scope of work, the interpretation approach and some of the main findings of the Thaumasite Investigation carried out on behalf of the Highways Agency on the trunk roads in Gloucestershire is given. The reinforced concrete structures investigated were approximately 30 years old and had been cast in situ using predominantly Grade C35-C40 concrete made using Portland cement with limestone coarse aggregates.

All of the backfill surrounding the buried concrete at each structure predominantly comprises reworked Lower Lias Clay, occasionally mixed with some alluvium. There was found to be an decrease in pyrite content and an increase in acid-soluble sulfate as the Lower Lias Clay weathered. The amount of pyrite lost in the Made Ground was generally found to be in the range 50–75%. There was no evidence of acidic ground conditions at the time of the investigations. No significant relationships were found between chemical, mineralogical or physical soil parameters and distance from concrete or degree of thaumasite attack.

Groundwater characterisation by means of Piper plots indicated that the groundwater in the Made Ground classifies as a sulfate-type and in the Lower Lias Clay as a sulfate/chloride-type. Sulfate levels in the groundwater extracted from the backfill showed a good correlation with the amount of TSA at a structure.

The extent of thaumasite attack was found to be strongly related to groundwater level. Where there was no attack, the concrete was usually above the maximum water level (i.e. permanently dry, except for percolating water) and where there was full attack, the concrete was usually below the minimum water level (i.e. permanently wet). It was found that the process of thaumasite formation leading to TSA creates four zones within structural quality concrete with a sharp reaction front. In the most severe cases of attack, the surface had a white pulpy appearance and often there was expansion. The typical pattern of attack to the buried vertical members was: no attack within 1 m of ground level; local patches of softening or blistering at mid-height; increasingly severe and more widespread attack towards the base. The maximum depth of softening was found to be approximately 45 mm and the maximum amount of expansion of the face of the concrete was 33 mm.

Bituminous coatings appeared to have provided partial protection to some structures.

Keywords: Field investigations; Concrete; Lower Lias Clay; Thaumasite; TSA

1. Introduction

The project was started in March 1998 and initially concentrated on three structures where bridge repair works were underway. By February 1999, when site works had been completed, a total of 28 structures had been investigated, working to a staged programme and to several different levels of investigation. The objective was to provide information that would assist in the management of existing structures and in the design and construction of new works in Gloucestershire. Information was also provided to the Thaumasite Expert Group to assist in the production of their report [1].

This paper summarises the main scientific conclusions only from the wide-ranging investigation undertaken. For brevity, only a selection of the data is presented and particular areas of the investigation have been reported elsewhere [2–5].

2. Scope of work

The work was carried out in 16 work packages, which ranged from a desk study of over 300 references, to a

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mass balance assessment of the chemical species involved in the formation of thaumasite (outlined below).

Structures investigated included 11 road overbridges, 3 underbridges, 3 footbridges, 1 underpass, 2 pipe bridges and 4 box culverts. The procedures used to select sites, carry out sampling and testing and data management have been described by Floyd and Wimpenny [2]. The interpretation of the data has been outlined by Wimpenny and Slater [3].

3. Interpretation

A total of 23,000 soil and 5000 concrete records were created in the database, comprising individual entries totalling 175,000 for soil and 80,000 for concrete. Parameter versus depth and parameter versus parameter plots were produced in addition to summary statistics and tables. Correlation matrices and scatter plots of the soil data were examined to assess the relationships between the location and amount of thaumasite and the main soil parameters in the adjacent ground. This was supported by statistical analysis.

In order to correlate the degree of attack with other parameters, five classification schemes were developed to summarise the attack applying to the whole structure down to parts of individual elements. The severity of attack ratings used to classify degrees of damage to structural members, piers or the overall structure, were based on the area of softening recorded on the face logs and the maximum depth of attack as indicated in Table 1. Zones of attack were used to describe the amount of attack on the face of a member and were used to establish the horizons between full attack (damage zone 3), partial attack (damage zone 2) and no attack (damage zone 1) for comparison with the soil and groundwater data at various levels.

The soil results were considered as a combined set from all structures and individually for each structure. Only those soil types considered to be similar between structures were included, i.e. Made Ground consisting of Lower Lias Clay and alluvium, and unweathered and weathered Lower Lias Clay. Other soil types (alluvium, terrace gravel, demolition debris, etc.) were not assessed due to a limited number of results and often a large variation within the soil type.

A 'mass balance assessment' was carried out by considering the molecular weights of the chemicals involved in the principal balanced chemical reactions, shown below.

(a) Hydration:

$$3CaO \cdot SiO_2 + 3H_2O = 0.5(Ca_3 \cdot Si_2O_7 \cdot 3H_2O) + 1.5Ca(OH)_2$$

(b) Thaumasite formation:

$$0.5(Ca_3 \cdot Si_2O_7 \cdot 3H_2O) + 1.5Ca(OH)_2 + SO_4^{2-} + HCO_3^{1-} + 10H_2O + 3H^+ = [Ca_3Si(OH)_6 \cdot 12H_2O](SO_4)(CO_3).$$

From these the chemical mass balance of thaumasite formation (Table 2) was used to obtain the stoichiometric mass ratios of the reactive species and calculate the masses of calcium silicate hydrate in the hardened cement paste and masses of bicarbonate and sulfate needed to produce the mass of thaumasite found.

The calcium silicate content was determined using the cement content of the concrete from petrographic examination of core samples. From the mass of thaumasite, the masses of bicarbonate and sulfate that had reacted with the concrete at each site could be calculated. The results from chemical testing of soil and groundwater samples were used to calculate the minimum volumes of groundwater and soil needed to supply the reactants at each site. The volume of groundwater contained within a unit volume of soil was estimated from the difference between the calculated bulk and dry

Table 1
Thaumasite severity of attack rating scheme for members, piers or overall structure

Rating	Description	Definition
1	None	No softening in areas surveyed and no damage due to thaumasite attack observed
2	Slight	Less than 15% of buried area surveyed is softened or maximum depth of attack does not exceed 15 mm
3	Moderate	At least 15% of buried area surveyed is softened or maximum depth of attack exceeds 15 mm
4	Severe	At least 25% of buried areas surveyed is softened and maximum depth of attack exceeds 25 mm

Table 2
Chemical mass balance of thaumasite formation

Cement		Water of hydration		Sulfate		Bi-carbonate		Water		Hydrogen ions		Thaumasite
$3CaO \cdot SiO_2$		$3H_2O$		SO_4^{2-}		HCO_3^{1-}		$10H_2O$		$3H^+$		
228 g	+	54 g	+	96 g	+	61 g	+	180 g	+	3 g	=	622 g

densities obtained from testing the natural moisture content and particle densities. The results were compared for carbonate and sulfate species at each site and between sites.

Concrete columns removed during the repair works at the Tredington Ashchurch Road Bridge were subject to dust sampling and then water jetting with full visual logs recording the concrete condition at incremental depths. This provided information to improve the specification of remedial works [4]. The interpretation of all the results has been reported elsewhere [6].

4. Main findings

4.1. General conditions

The founding stratum of all of the structures investigated is the dark blue grey mudstone with interbedded limestone of the Lower Lias Clay Formation of the Severn-Midlands Basin which is of low permeability with some localised flow at limestone bands.

All of the backfill (excluding some gravel in the top 2 m) surrounding the buried concrete at each structure predominantly comprises locally won, reworked Lower Lias Clay, occasionally mixed with some alluvium. All of the backfill contains lithorelicts of Lower Lias Clay (generally fine to medium gravel size) in a clay matrix.

All of the structures that have been investigated in detail have the following design similarities:

- cast in situ reinforced concrete
- limestone for the coarse aggregate
- typically quartz and metaquartz natural sand and/or crushed limestone for the fine aggregate
- the concrete mixes used are predominantly: Grade C35-C40, made using Portland cement and meeting the requirements of sulfate resistance Classes 1–2 in BRE Digest 363 [7]
- the majority of the structures investigated were constructed in approximately 1968–1971.

4.2. Soil conditions

4.2.1. General

The Lower Lias Clay formation is differentiated into 'weathered' (LL_w) and 'unweathered' (LL_f) soil types. There is a large variation in sulfur species contents of the Lower Lias Clay at most sites due to internal variation within each soil type. The sulfur species are present as isolated clusters in the mudstone and clay. Therefore differences in the sulfur species concentrations between sites are difficult to determine. The undisturbed Lower Lias Clay at each site classifies between Classes 1 and 3 (mainly Class 2) in BRE Digest 363 [7].

Most of the foundations investigated are surrounded by cohesive backfill ('MG' in Fig. 1). The fill is heterogeneous, consisting predominantly of reworked and gravel size lithorelicts of unweathered and weathered Lower Lias Clay with some mixing with organic materials and carbonate gravel. The lithorelicts are in a matrix of reworked Lower Lias Clay. The backfill at each site classifies between Classes 1 and 4 (mainly Class 2 or 3) in BRE Digest 363.

At the Tredington Ashchurch bridge site, where the most extensive TSA was found, there is still sufficient

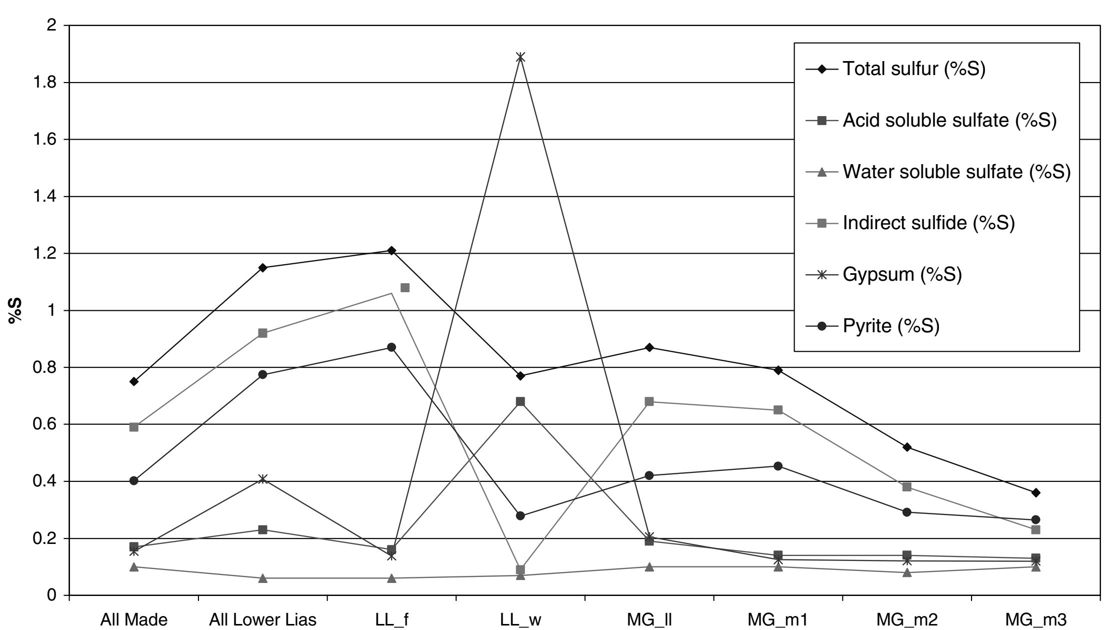

Fig. 1. Mean concentrations of sulfur species (as %S) for each soil type.

water-soluble sulfate in the Made Ground within approximately 0.25 m of the concrete to create the amount of TSA already seen, from the mass balance calculations.

4.2.2. Soil composition

The 'combined' Lower Lias Clay in the project area contains much more calcite and less pyrite and clay minerals than the Lower Lias Clay compositions reported in the published literature. This suggests that there is both more limestone bands and also more fine grained calcite in the project area due to local variations in the composition of the Lower Lias Clay.

The only sulfur-bearing minerals that have been identified by logging are pyrite, which is mainly in the unweathered Lower Lias with some in the Made Ground, and selenite (gypsum), which is mainly in the weathered Lower Lias Clay and Made Ground. Chemical testing also indicates the presence of organic sulfur compounds and a correlation between water-soluble magnesium and water-soluble sulfate. This suggests the presence of the highly soluble magnesium sulfate in the soil.

The changes due to weathering of the Lower Lias Clay found in the project area were:

- Pyrite and indirect sulfide (the difference between total sulfur and total sulfate results) contents were highest in the unweathered Lower Lias Clay.
- There was a decrease in pyrite content and an increase in acid-soluble sulfate as the Lower Lias Clay weathered, because of the well-documented reaction of pyrite oxidation to form sulfuric acid which is buffered by calcium carbonate to precipitate gypsum (selenite) crystals. The process was confirmed by laboratory storage tests.
- The gypsum concentration was greatest at approximately 3–4 m depth in the Lower Lias Clay (possibly the depth of the former tree root zone).

The variation of the main concentrations of sulfur species for each soil type are shown in Fig. 1. MG_II in Fig. 1 refers to Made Ground comprising reworked Lower Lias Clay. MG_m1 to MG_m3 refer to Made Ground comprising reworked Lower Lias Clay and increasing amounts of alluvium.

Based on the calculated content of pyrite remaining in the Made Ground and the global average for the unweathered Lower Lias Clay, it would appear that the amount of pyrite lost is generally in the range 50–75% (from the seven sites where there is a sufficient number of analyses).

Mean pH values are very consistent between all soil types in both the Lower Lias Clay and Made Ground, varying from 8.08 to 8.60. There was no evidence of acidic ground conditions at the time of the investigations.

4.2.3. Variation in soil parameters with proximity to concrete or degree of thaumasite attack

No significant relationships (defined in this study as a correlation coefficient greater than 0.7 and significance greater than 95%) were found between chemical, mineralogical or physical soil parameters and distance from concrete or degree of thaumasite attack. However, sev-

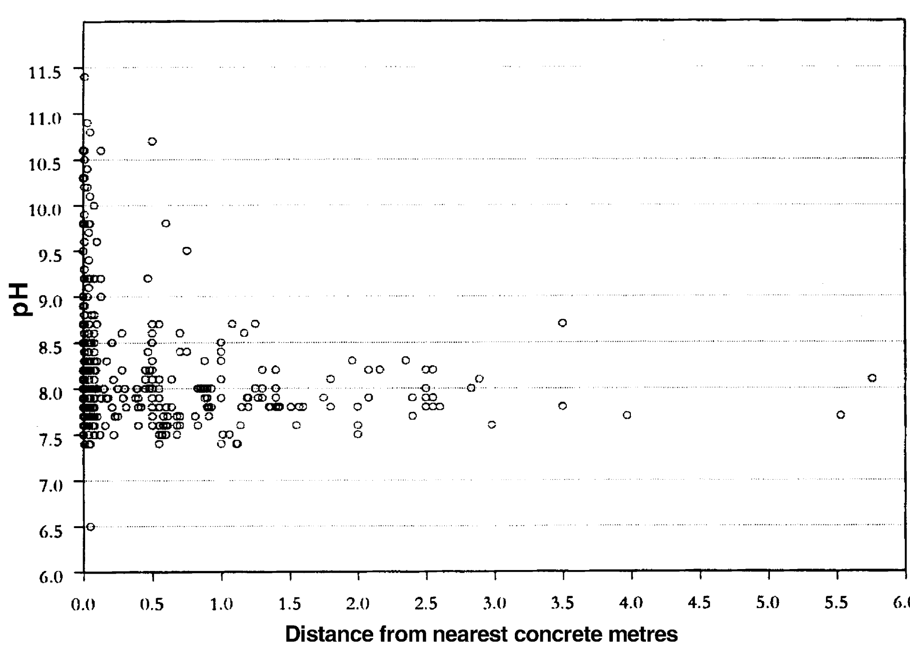

Fig. 2. pH of backfill versus distance from concrete.

eral trends in the data with offset from concrete were identified.

The pH value and calcium concentration were found to increase towards concrete (both vertical members and footings) at less than 1.5 m offset, possibly due to leaching of calcium hydroxide from the concrete (Fig. 2). Total sulfur and moisture content also increased. Water-soluble magnesium decreased with proximity to concrete; there was an inverse relationship between water-soluble magnesium and pH.

There was less pyrite and indirect sulfide in thaumasite damage zone 3 (full attack) than in zones 1 and 2 (none and partial attack). This suggests that the most thaumasite attack was occurring where there was the most pyrite oxidation, generally in the deepest and wettest section of fill at each structure. This was unexpected as greater loss nearer the surface had been expected where there may be more oxygen circulating, and suggests that the groundwater was oxygenated and mobile.

Water-soluble sulfate, acid-soluble sulfate and total sulfur increased with increasing thaumasite attack at the structure and pier scale. At the member and face scale, the water-soluble sulfate and acid-soluble sulfate and, to a lesser degree, total sulfur showed low values where there was no thaumasite. The highest values occur where there was partial attack (with the values decreasing away from the face) and consistently high values occurred where there was full attack. This may be partly related to groundwater level.

Gypsum results were limited but values were highest where there was partial attack but appeared to be depleted where there was full attack. The pH value increased with increasing thaumasite zone and code. Water-soluble magnesium decreased with increasing thaumasite attack.

4.3. Groundwater

4.3.1. Groundwater level

The extent of thaumasite attack was strongly related to groundwater level. Thaumasite damage zones correlate with the maximum and minimum groundwater levels measured at the structures over the 12–18-month monitoring period. Where there was no attack (damage zone 1) the concrete was usually above the maximum water level (i.e. permanently dry, except for percolating water) and where there was full attack (damage zone 3) the concrete was usually below the minimum water level (i.e. permanently wet). Where there was partial attack (damage zone 2) the groundwater level was in transition between a maximum and minimum value. This is shown in Figs. 3 and 4, where the elevations of the boundaries between severity of attack zones have been plotted against maximum or minimum groundwater level.

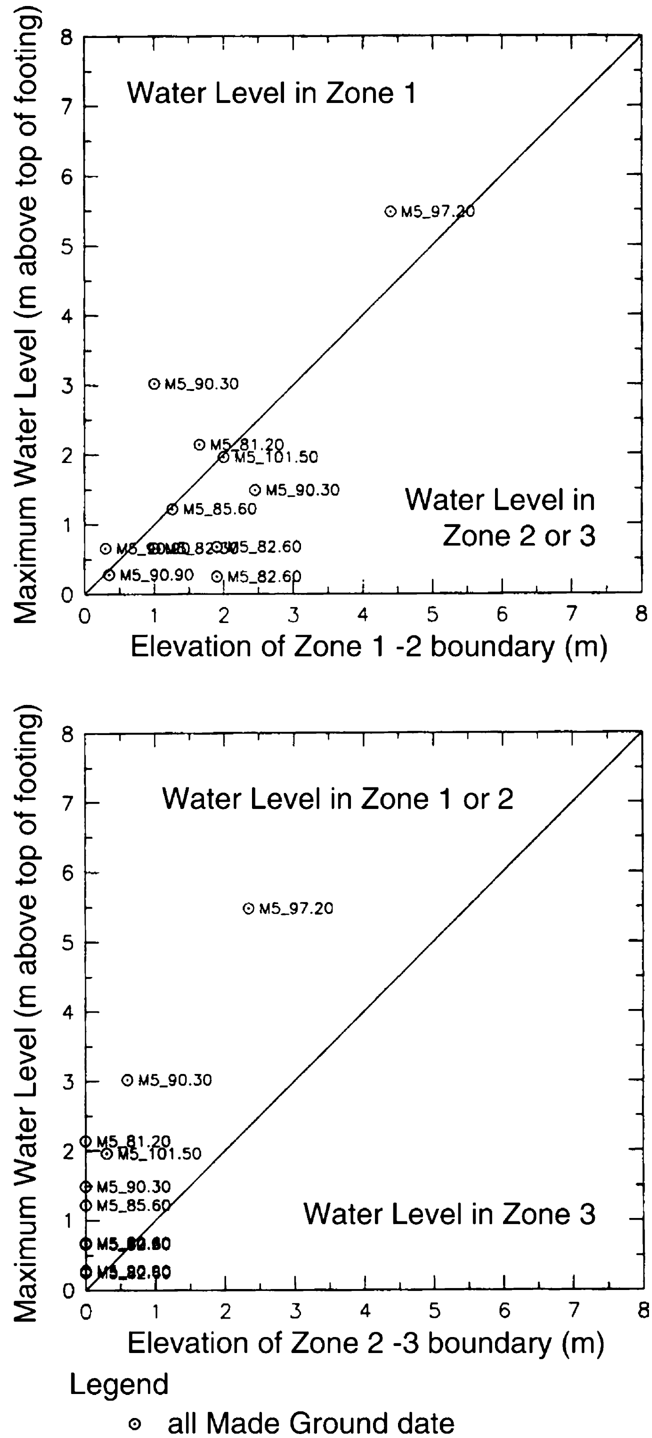

Fig. 3. Level of thaumasite attack versus maximum groundwater level.

4.3.2. Groundwater characterisation

The groundwater characterisation has included the use of Piper plots. These are trilinear diagrams which can show the percentage composition of three ions as shown in Fig. 5 [8]. The major ion species in most natural waters are Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, CO_3^{2-}, HCO_3^- and SO_4^{2-}. By grouping Na^+ and K together, the major cations can be displayed on one trilinear diagram.

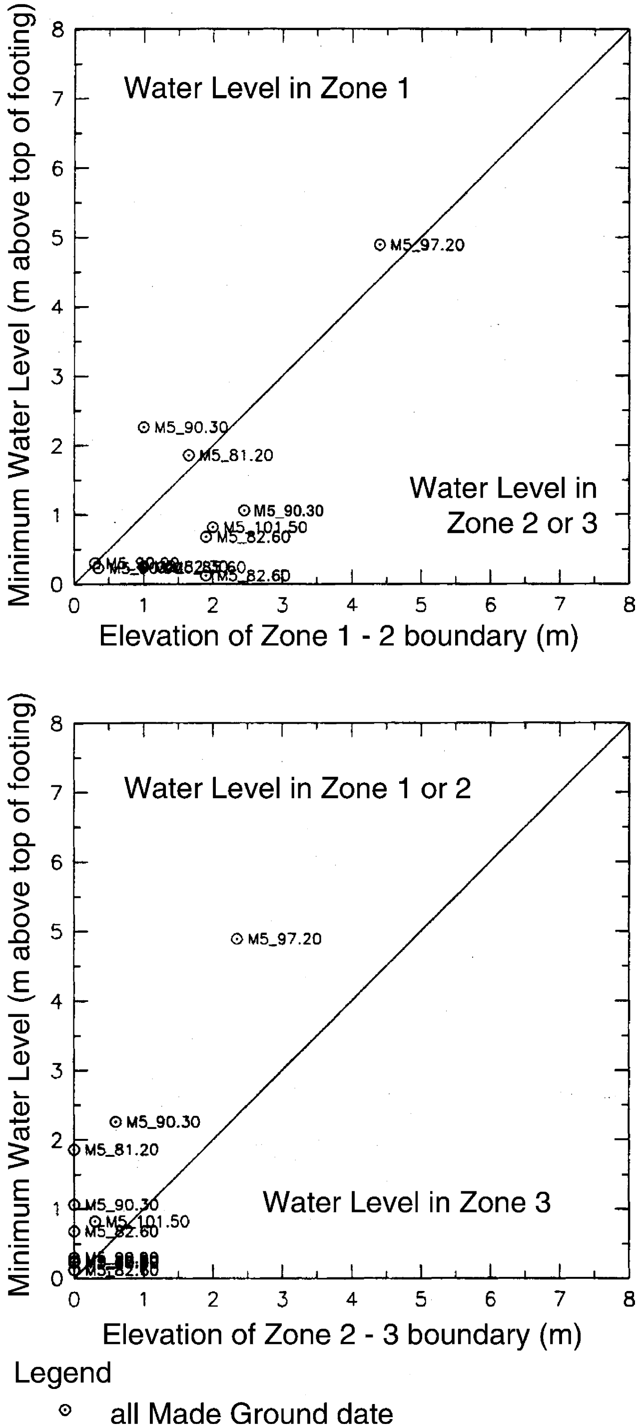

Fig. 4. Level of thaumasite attack versus minimum groundwater level.

Similarly, if CO_3^{2-} and HCO_3^- are grouped together, the major anions can be displayed on one diagram. Analyses are plotted in terms of percentage concentration with 100% concentration of one of the three cations or anions represented at the apex of each triangle. If a sample has two constituent groups present, the point representing the percentage of each would be plotted on the line between the apexes for the two groups. If all three constituent groups are present, the analyses would fall in the interior of the triangle. The diamond-shaped field between the two triangles is used to represent the composition with respect to both cations and anions, with the results from the two triangles projected into the diamond-shaped field. The cation point is projected onto the diamond-shaped field parallel to the side of the triangle labelled magnesium and the anion point is projected parallel to the side labelled sulfate, with the intersection point of the two lines plotted as a point on the diamond-shaped field. These diagrams are used to visually describe differences in major ion chemistry, or hydrochemical facies, in groundwater flow systems and permit the hydrochemical facies to be classified on the basis of the dominant ions [9]. The Piper plots shown in Figs. 6 and 7 indicate that groundwater in the Made Ground classifies as a sulfate-type groundwater and in the Lower Lias Clay as a sulfate/chloride-type groundwater. The differences in composition between the two groundwaters suggests that there is limited mixing between water in the Made Ground and that in the undisturbed ground.

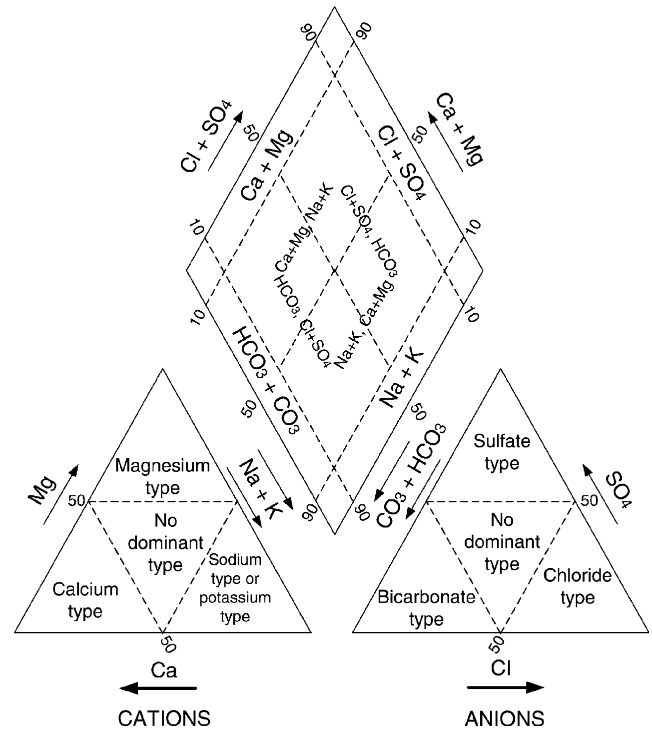

Fig. 5. Hydrogeochemical classification system [9].

The groundwater in both the undisturbed ground and backfill classify as Classes 1–4 (mainly Class 2 or 3) in BRE Digest 363. Generally the groundwater is classified the same or one class higher than the soil at the same site. Sulfate levels in the groundwater extracted from the backfill show a good correlation with the amount of TSA at a structure, as described by Floyd [5]. Groundwater temperatures measured in the winter months were

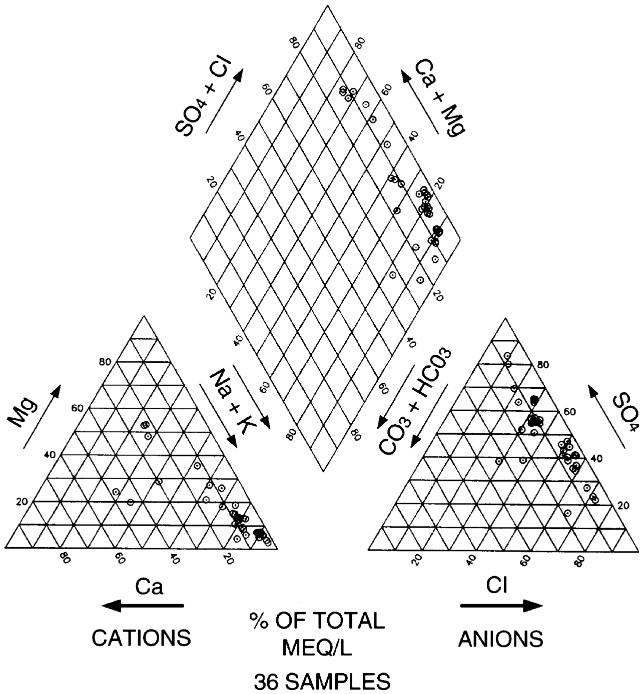

Fig. 6. Piper analysis of groundwater in Lower Lias Clay.

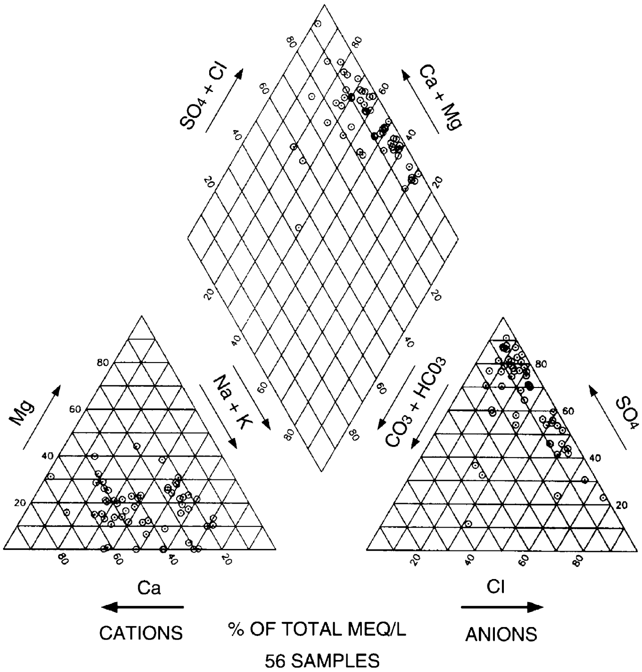

Fig. 7. Piper analysis of groundwater in Made Ground.

between 5 and 13 °C. The summer temperatures recorded were generally higher than 15 °C.

4.3.3. Groundwater chemistry

From the mass balance calculations, there was found to be sufficient sulfate in the groundwater at the Tredington Ashchurch bridge site within approximately 1.3 m of the concrete to create the amount of TSA already seen. There was also found to be sufficient carbonate in the groundwater within approximately 9 m of the concrete to create the amount of TSA already seen, assuming that the aggregates in the concrete do not contribute carbonate to the reaction.

4.4. Concrete

4.4.1. Characteristics of TSA

Thaumasite attack was found to be characterised by softening and often expansion of the concrete surface. The surface had a white pulpy appearance and clay was often strongly adhered to the surface and appeared to be desiccated. The expansion and softening could take the form of discrete blisters or uniform expansion and softening across the full width of the face. Immediately after exposure the softened surface could appear sweaty and be easily scraped away by hand. If permitted to dry, the surface became harder and friable. The concrete surface occasionally had a 'crust' of apparently unattacked concrete. Underneath this layer the exposed coarse aggregate was surrounded by white rings or halos of reaction products.

TSA was identified by its high birefringence under optical microscopy using cross-polars and confirmed by its high sulfate content and silica to alumina ratio (>9) using SEM Microprobe analysis. The process of thaumasite formation leading to TSA was found to create four zones within structural quality concrete with a sharp reaction front, as shown in Fig. 8. Whilst the depth of TSA may be assessed visually, this was found to have limitations when assessing the concrete to be removed prior to reinstatement as sulfate levels remain high even when concrete appears sound [4].

Rust staining was occasionally present in TSA affected concrete and breakout to the reinforcement revealed pitting corrosion and soft black or green deposits that turned brown on exposure to air. Chloride contamination on the concrete was found at depths of several metres below ground level. This had not been recognised previously by inspection regimes.

4.4.2. Occurrence of TSA

Of the concrete structures inspected and tested the following severity of attack ratings were assigned: no attack 25%; slight 12%; moderate 46% and severe 17%. The percentage of member types with a severity rating of 3 or more were as follows: abutments 100%; columns 74%; spread footings 45% and pile caps 43%. Wing walls and culvert walls and bases had no attack. Two structures with concrete hinges were found to have TSA but there was no evidence of attack or steel corrosion within the hinges.

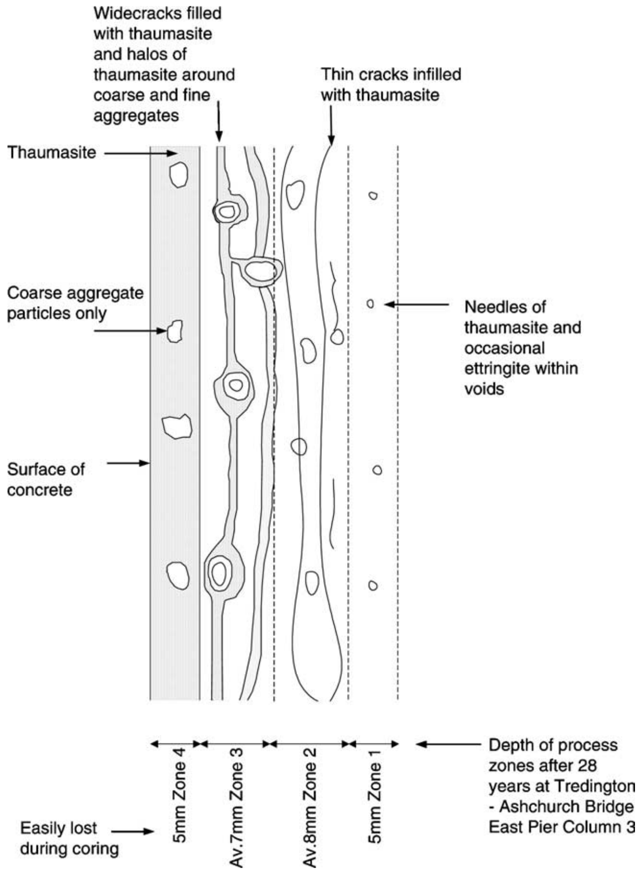

Fig. 8. Schematic representation of thaumasite damage.

Tredington Ashchurch Road Bridge was the most severely affected structure. At the northbound and southbound piers the average and maximum depths of softening were approximately 9 and 45 mm respectively. The average and maximum amounts of expansion of the face of the concrete, due to the sub-parallel cracking and deposition of thaumasite within the cracks, were 7 mm (13 mm in areas of full attack) and 33 mm respectively. There appeared to be no significant difference between the softening and expansion values at the northbound and southbound piers. However, the average depth of softening was lowest for columns furthest from the on-coming traffic and faces furthest away from the carriageway.

The typical pattern of attack to buried vertical members was found to be: no attack within 1 m of ground level, local patches of softening or blistering at mid-height and increasingly severe attack towards the base. The position of these areas of none, partial and full attack appears to be associated with the maximum and minimum groundwater level, as shown in Figs. 3 and 4.

Concrete cast directly against undisturbed Lower Lias Clay was often found to have sulfate (SO_3) contents in excess of 5% by mass of cement and TF but there was no evidence of TSA. The absence of TSA may have been connected to a reduced availability of water.

Bituminous coatings appeared to have provided partial protection to some structures but the presence of damage to concrete believed to have been coated suggests the degree of protection is dependent on other factors, such as coating quality.

4.4.3. Management of TSA

None of the structures found to have TSA had weakened so significantly to become a safety risk. The occurrence of TSA suggests that structures, such as culverts, have a lower risk of TSA compared to structures with members below groundwater level in disturbed Lower Lias Clay, such as abutments and columns.

Diffusion calculations indicate that the depth of sulfates in excess of 5% will increase by 8–12 mm over the next 20 years [4]. In the worst cases of attack this could result in the depth of TSA exceeding the depth of cover to the reinforcement with a loss of bond and increased risk of corrosion.

The most robust method of identifying the presence of thaumasite at existing structures is to expose the buried concrete for inspection. Attempts to use the most common soil and groundwater sampling and testing methods to predict the occurrence of thaumasite have to-date proven unsuccessful. Inspection and sampling of the concrete should occur at different depths below ground level and include areas where water is likely to be present, for example below minimum groundwater level and to the faces of members closest to the carriageway.

A possible approach for assessing the depth of concrete with sulfates in excess of 5% by mass of cement to be removed prior to repair has been proposed [4]. The chloride content of the concrete should also be assessed prior to repair.

5. Conclusions

5.1. General

Over 20 structures were investigated including overbridges, underbridges and culverts. Soil and groundwater sampling and testing was undertaken in conjunction with exposure, inspection and testing of the buried concrete.

All of the structures investigated are founded on undisturbed Lower Lias Clay, with backfill predominantly comprising reworked Lower Lias Clay, occasionally mixed with some alluvium. All of the backfill contains lithorelicts of Lower Lias Clay (generally fine to medium gravel size) in a clay matrix.

The majority of the structures investigated were constructed during 1968–1971, using Grade C35-C40 in situ concrete containing limestone coarse aggregate and meeting BRE 363 sulfate resistance Classes 1–2.

5.2. Ground conditions

The BRE Digest 363 [7] sulfate classification for the undisturbed Lower Lias Clay at each site is between Classes 1 and 3 and that for the backfill is between Classes 1 and 4.

Chemical mass balance calculations indicate that there is sufficient water-soluble sulfate in the Made Ground within 0.25 m of the columns at Tredington Ashchurch to create the amount of TSA already seen. The corresponding values for sulfate and carbonate in the groundwater are 1.3 and 9 m respectively.

The soil contains sulfur-bearing minerals in the form of pyrite and selenite. The latter was mainly in the weathered Lower Lias Clay and Made Ground. Chemical testing suggests the presence of organic sulfur compounds and highly soluble magnesium sulfate. The amount of pyrite lost in the Made Ground was estimated to be generally in the range 50–75%.

Mean pH values in the Lower Lias Clay and Made Ground lie between 8.08 and 8.60 There was no evidence of acidic conditions at the time of the investigations.

No significant relationships were found between chemical, mineralogical or physical soil parameters and distance from the concrete or degree of thaumasite attack. However, several trends in the data were identified:

- The total sulfur, moisture content, pH value and calcium concentration increased towards the concrete; the latter consistent with leaching of calcium hydroxide from the concrete.
- Water-soluble magnesium decreased closer to the concrete and had an inverse relationship with pH.
- There was less pyrite and indirect sulfide where there was full rather than partial or no attack suggesting most thaumasite attack was occurring where there was most pyrite oxidation.
- At structure and pier scale, as attack increased sulfates and total sulfur increased.
- At member and face scale, sulfates and total sulfur were low where there was no attack and highest where there was partial attack.
- Gypsum values were highest where there was partial attack and depleted where there was full attack.
- The pH value and water-soluble magnesium increased and decreased respectively with increasing attack.

The extent of thaumasite attack was strongly related to groundwater level. Where there was no attack, the concrete was usually above the maximum water level (i.e. permanently dry, except for percolating water) and where there was full attack, the concrete was usually below the minimum water level (i.e. permanently wet).

Piper plots characterise the groundwater in the Made Ground as sulfate-type and that in the Lower Lias as sulfate/chloride type. These differences suggest limited mixing between the two groundwaters.

The BRE 363 sulfate classification for the groundwater was generally the same or one class higher than the soil at the site and showed a good correlation with the amount of TSA at the structure.

5.3. Concrete

Thaumasite sulfate attack is characterised by softening and expansion of the concrete surface as discrete blisters or across the full width of the face. The surface has a white pulpy appearance, or occasionally a 'crust' of apparently unattacked concrete, underneath of which the coarse aggregate is surrounded by white rings or halos of reaction products.

Thaumasite can be identified by a combination of petrography examination and SEM Microprobe analysis. The process of thaumasite formation leading to TSA was found to create four zones within structural quality concrete with a sharp reaction front.

Rust staining and chloride contamination associated with reinforcement corrosion were present in TSA affected structures several metres below ground level.

The degree of TSA at each site could be classified using depth of attack and area of softening. Of the concrete structures investigated 75% had TSA, with abutments and columns being the most severely affected members.

The typical pattern of attack to buried vertical members was found to be: no attack within 1 m of ground level, local patches of softening or blistering at mid-height and increasingly severe attack towards the base. The position of these areas of attack appears to be associated with groundwater level.

At Tredington Ashchurch Road Bridge, one of the worst affected structures investigated, the maximum depth of softening and amount of expansion were approximately 45 and 33 mm respectively.

Concrete cast directly against undisturbed Lower Lias Clay was often found to have sulfate (SO_3) contents in excess of 5% by mass of cement and TF but there was no evidence of TSA. The degree of attack appears to be related to the availability of water.

Bituminous coatings appear to have provided partial protection to some structures.

Visual assessment of the depth of TSA has limitations for estimating the concrete to be removed prior to repair work as sulfate contents in excess of 5% by mass of cement can occur within apparently sound concrete.

The findings of the investigation were used to help manage the risk of TSA and direct future inspection of buried concrete [6].

Acknowledgement

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