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Contribution of construction activity to aggressive ground conditions causing the thaumasite form of sulfate attack to concrete in pyritic ground

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Abstract

Historically, the potential for sulfate concentration to be increased as a result of disturbance of pyrite-bearing ground during construction has not been taken into account in UK guidance documents for concrete specification such as BRE Digest 363. This omission was found in 1998 to have contributed to the occurrence sulfate attack in the foundations to several bridges on the M5 motorway founded on pyrite-bearing Lower Lias Clay. The concrete for these was specified to meet the maximum Sulfate Class 2 natural sulfate levels measured during site investigation, however, Sulfate Class 3 and Class 4 levels were generated subsequently by oxidation of pyrite in backfill.

In response to the M5 cases, new UK guidance has been issued for assessing pyrite-bearing ground which may be disturbed by construction activity, this being based on the newly defined parameter total potential sulfate.

Keywords: Lower Lias Clay; Pyrite; Oxidation; Sulfate attack; Concrete; Thaumasite

1. Introduction

In the last decade a new form of sulfate attack, the thaumasite form of sulfate attack (TSA) has been found in buried concrete in the UK. Two such cases [1,2] have been investigated by BRE in the foundations of domestic properties on Lower Lias Clay in the Cotswolds area. In March 1998 TSA was also found to have caused deterioration of concrete in the foundations of some 30-year-old motorway bridges constructed on Lower Lias Clay in Gloucestershire. The concrete was affected to a depth of up to 50 mm, the surface being transformed into a soft white mush, as seen in Fig. 1. These foundations were constructed with good quality concrete which had been specified, in accordance with then-current guidance, to cater for the perceived ground sulfate conditions. An investigation of the cases of TSA found that the ground conditions had been significantly changed due to construction processes. The concentrations of sulfate in the Lower Lias Clay had been enhanced to detrimental levels by the oxidation of the sulfide mineral, pyrite, due to its excavation and use as backfill.

This paper describes the ground conditions which contributed to the TSA occurrence in the motorway bridge foundations and describes the development of a new assessment procedure to cater for such site conditions in new construction.

2. Oxidation of sulfides in clays and mudrocks

Sulfide is generally found in natural ground as the mineral, pyrite (FeS_2), other less common sources being marcasite (FeS_2) and pyrrhotite (FeS to $FeS_{1.8}$). Pyrite is an original constituent of many ancient marine sediments [3,4] and is particularly abundant (proportions of up to 5% being common) in dark marine clays and mudrocks such as some Carboniferous mudstones, Lower Lias Clay, Kimmeridge Clay and Oxford Clay. It can also occur in significant quantities in ancient and recent silts and sands. In mudrocks and clays, most of the pyrite occurs as microscopically small black-coloured framboidal particles, although well-formed small crystals can often be seen sparkling in direct sunlight on

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Fig. 1. Severe TSA at the base of a 29-year-old bridge column exposed to wet, reworked Lower Lias Clay.

fracture surfaces. Fig. 2 is a scanning electron microscope image showing a typical cluster of small octahedral pyrite crystals in a sample of unweathered Lower Lias Clay. Under typical atmospheric conditions such pyrite readily decomposes due to oxidation, leading to the formation of sulfates, the most common of which is gypsum. The processes involved in pyrite decomposition have been widely discussed in print as they lead to a number of engineering problems, including expansion and heave of pyritic shales [5–8], interference with soil stabilisation [9,10], reduction of shear strength [8,11] and acid corrosion [12,13]. Particular strata for which the process of pyrite oxidation has been investigated include Namurian mudstones [14], Oxford Clay [15], Lower Lias Clay [9,10], Upper Lias Clay [16], Rhaetic mudstones [17], and London Clay [18].

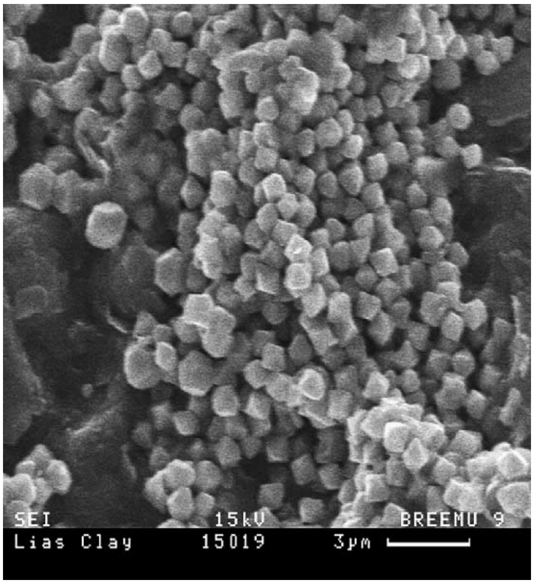

Fig. 2. Scanning electron microscope image of unweathered Lower Lias Clay. Clusters of minute octahedral pyrite crystals are seen on a clay fissure surface.

The process of pyrite oxidation can be complex and involve bacterial action but may be simply expressed as follows. If oxygen in air or groundwater has access to unweathered pyritic soil/rock it oxidises the pyrite (FeS_2) to form red-brown ferric oxide (Fe_2O_3), usually as a hydrated form, together with sulfuric acid (H_2SO_4). The latter is the initial source of sulfate. If calcium carbonate ($CaCO_3$) is present in the material, the H_2SO_4 will react with it further to produce calcium sulfate which crystallises as gypsum ($CaSO_4 \cdot 2H_2O$). Gypsum has low solubility, but it will dissolve in ground water to produce a maximum concentration of sulfate ions of 1.4 g/l (SO_4^{2-}). Under certain conditions the H_2SO_4 can also react with clay minerals and leach them of exchangeable cations such as K^+, Mg^{2+} and Na^+. The mineral jarosite ($KFe_3(SO_4)_2(OH)_6$) may also be formed [14]. The presence of K^+, Mg^{2+} and Na^+ in groundwater supports a larger number of sulfate ions in solution than does the presence of Ca^{2+} alone. The resultant concentration of SO_4^{2-} therefore can be several times greater than that associated solely with the dissolution of gypsum.

If there is insufficient calcium carbonate to neutralise the sulfuric acid, the soil/rock may become acidic. Cripps and Edwards [5] describe a site on Oxford Clay in Wiltshire where such acidic conditions were found in the trial pits and boreholes in one part of the investigated area. Acid conditions were also developed in the Carboniferous mudstone fill used in the embankment of Roadford dam [19] which had an average pyrite content of 2.4% and a very small calcium carbonate content of less than 0.5%.

For natural weathering in undisturbed pyritic ground a relatively high sulfate content may be expected throughout most of the ground profile that has been subject to substantial ‘weathering’. The extent of this zone will normally be indicated by brown colouration of the ground resulting from the ferric oxide produced by oxidation of pyrite. Under natural conditions the downward progress of weathering and accompanying oxidation of pyrite is reported by Chandler [16] to be extremely slow, taking of the order of thousands of years to penetrate several metres below ground surface.

If initially unweathered ground is substantially disturbed, e.g. by cutting and filling to terrace a site, or by excavation and backfilling, there is good evidence to show that the oxidation of pyrite in the material to produce sulfate can be relatively rapid due to the ready availability oxygen and water:

- Rapid oxidation of Lias Clay samples has been reported by Hawkins and Wilson [17] and of Rhaetic mudstones samples by Hawkins and Pinches [6].
- Complete oxidation of pyrite (initially comprising up to 5% of the mass) in some areas of Lower Lias Clay, which was macerated during lime stabilisation, is reported to have taken place within a two year period on the site of the M40 motorway near Banbury [10]. The resultant sulfate content was substantially increased, as compared to a content of typically less than 0.5% present in the undisturbed ground.
- Rapid oxidation occurred in Namurian mudstones used for fill in the Carsington Dam [14]. It was concluded that 'significant oxidation of pyrite occurred during and shortly after emplacement of the embankment fill' and led to 'the formation of authigenic alteration products, notably gypsum and jarosite'.

The assistance of bacteria in the process of oxidation of pyrite has been extensively discussed in print [6,8,14,20,21]. Hawkins and Pinches [8] have listed several bacteria which may assist in the process, some of which thrive in alkaline conditions and others in acidic environments. Most sources identify Thiobacillus ferrooxidans as a principal bacterial agent. It should be noted, however, that this prefers relatively warm acid conditions, being most active at 15–20 °C [8]. Pye and Miller [14] noted the presence of the bacterium Thiobacillus ferrooxidans in some samples of fill at Carsington. Hawkins and Pinches [8] similarly found Thiobacillus ferrooxidans in samples of Rhaetic mudstone. The detailed biochemistry is discussed by Jackson and Cripps [20] and Vear and Curtis [21].

3. Occurrence of TSA in M5 bridge foundations

3.1. Location, geology and geotechnics of the bridge sites

The affected bridges were on the Gloucestershire section of the M5 motorway, between Stroud and Tewkesbury in Central England. The regional geology comprised Jurassic Lower Lias Clay overlain in places by terrace sands and gravels of the River Severn and River Avon. The bridge sites varied somewhat in local topographical features and detailed geology, but the site of the worst affected motorway bridge (Tredington–Ashchurch) is fairly typical of the conditions encountered. Here, the bridge was constructed on a former floodplain of the River Avon, adjacent to a small stream which arises at the foot of the Cotswold scarp and which flows through a culvert under the motorway some 3.5 m below pavement level. The 1:50,000 geological map, Sheet 216, [22] shows the site to have Lower Lias Clay overlain by a narrow strip of alluvium which follows the course of the stream.

The logs of two boreholes, 4.6 and 9.1 m deep, drilled at this location as part of the original site investigation for the motorway show approximately 0.3 m of top soil overlying firm brown mottled silty clay (weathered Lower Lias Clay) down to about 2.0 m, and below that stiff blue-grey fissured silty clay (unweathered Lower Lias Clay). Geotechnical data for the Tredington–Ashchurch bridge site, given in the 1965 'geotechnical report' for the M5 [23], is summarised in Table 1.

Only one sulfate determination was made on this site, that for unweathered Lower Lias Clay at a depth of 2.4 m. The result, determined by the acid extraction procedure, was a 'total' sulfate content (SO_4) of 0.12% of dry soil mass. The relevance of this result is commented on later in Section 3.5.

3.2. Construction details of M5 bridges

The bridges found to be affected by TSA were constructed about 1970 and were made of reinforced concrete containing carbonate-rich aggregates, including both calcium carbonate and dolomite. The affected foundations were either constructed within excavations in the Lower Lias Clay which were then backfilled with the same clay, or passed through embankments constructed of Lower Lias Clay. All sites in which affected concrete elements were identified were wet. Most of the backfilled excavations were crossed by French drains that could channel water into the fill. Other water sources included granular layers within the embankments and also carriageway run-off channeled through expansion joints. Fig. 3 shows the principal construction features of the Tredington–Ashchurch bridge relevant to the TSA occurrence.

Table 1
Geotechnical data from original site investigation of Tredington–Ashchurch bridge

Borehole	Depth (m)	SO_4 as % of dry wt%	Bulk density (t/m^3)	Moisture content (%)	Shear strength CU (kPa)
BH23A	2.4	0.12			
BH23B	2.7		1.95	26	120 (stiff)
BH23B	9.0		2.07	15	550 (hard)

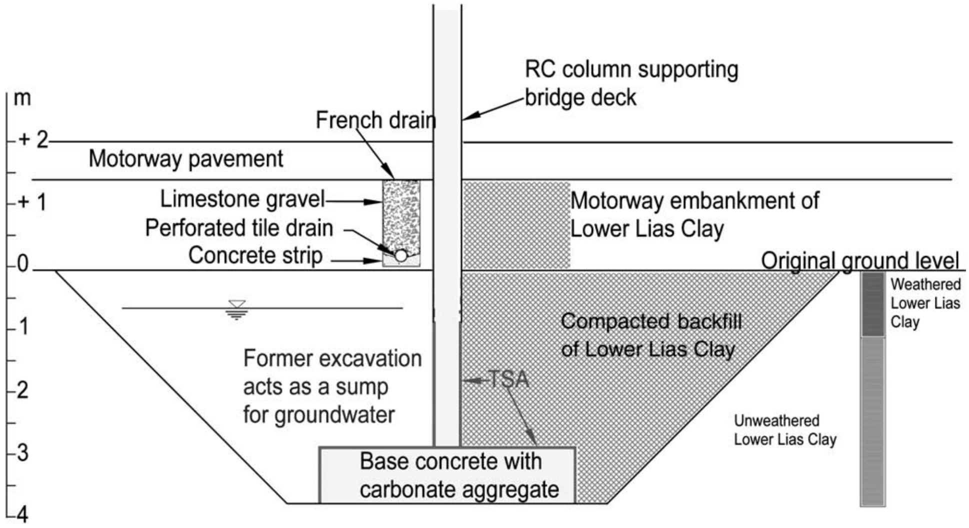

Fig. 3. Principal construction features of Tredington–Ashchurch bridge relevant to occurrence of TSA.

3.3. *TSA-affected foundations*

TSA was found to be most prevalent within the lower parts of foundation columns, below the level of the French drains, where conditions are likely to have been very wet for long periods due to the backfilled excavations acting as sumps. The average depth to which the concrete was affected was 25 mm, though in places on the M5 bridge foundations TSA has penetrated some 50 mm, occasionally exposing the steel reinforcing bars to corrosion. The affected surface zone comprised aggregate particles embedded in a soft white crystalline 'mush', composed mostly of thaumasite.

3.4. *Description of clay fill adjacent to bridge foundations*

The clay fill was examined by BRE in trial pits dug to expose the TSA-affected bridge foundations. The fill was generally well-compacted and only a few small voids were evident. While there were numerous sub-horizontal laminations in the fill resulting from layered compaction, there were no obvious continuous horizontal or vertical seepage pathways. Some areas of blue-grey clay, however, comprised relatively loose friable material that appeared to have a locally high permeability. There was no evidence of appreciable seepage from the fill. Close inspection of the fill, however, revealed small amounts of free water in some voids and cracks.

The fill was observed to range in composition from yellowish-brown clay, through darker and olive-brown clay, to dark blue-grey clay. Examination indicated that the bulk of the backfill had initially consisted of unweathered dark blue-grey Lower Lias Clay. This is known to have been a preferred fill material, and was locally dug from borrow-pits, selected for its good handling and compaction characteristics. Much of this initially unweathered material had subsequently become softer, wetter, less-structured, and browner in colour as a result of disturbance and 30 years exposure to air and water, possibly including surface stockpiling between excavation and use as backfill. Table 2 gives descriptions of the materials in the backfill together with chemical analyses: the principal materials constituting approximately 90% of the backfill are shown in bold. The proportions of these materials varied with location, but a typical composition as recorded in a trial pit at the Tredington–Ashchurch bridge was: dark blue-grey clay about 30%; dark olive-brown clay about 60%; and yellowish-brown clay about 10%. Dissection of some lumps of olive-brown clay revealed large clusters of small grey crystals. These were confirmed by mineralogical analysis at BRE to be gypsum. It was concluded that:

- The yellowish-brown clay (sometimes found with organic soil inclusions) was highly weathered clay that had come from the upper part of the Lower Lias Clay in situ profile.
- The dark blue-grey clay in the backfill was a remnant of the initially blue-grey unweathered clay not yet degraded, possibly due to larger block size and/or stronger bonding.
- Most of the dark olive-brown clay (typically rich in gypsum) originally had been unweathered dark blue-grey clay. However it had become softened and oxidised either during stockpiling after excavation and/or in the 30 years since backfilling.

3.5. *Changes in sulfate content of the Lower Lias Clay resulting from the construction process*

At the outset of the investigation, the fact that all of the significantly affected bridge foundation elements

Table 2
Descriptions of the principal materials found in the backfill to Tredington–Ashchurch bridge

Description	pH[a]	Total sulfate by acid extraction[b]	Sulfate by 2:1 water extraction[c]	Total sulfur (by Leco)[d]	Total sulfur as SO_4[e]	Ca^+ By AAS[f]
		SO_4%	SO_4 g/l	S%	SO_4%	Ca%
1. Occasional hard calcareous-cemented blocks of LLC.						
2. Frequent intact lumps of stiff, dark blue-grey LLC with well preserved structure (bedding planes and fissures) and occasional fossils.	7.8	0.3	1.1	0.76	2.3	8.9
3. Large amount of **dark blue-grey clay** comprising intact lithorelicts of LLC to 50 mm diam. Larger lumps firm, smaller lumps and matrix soft.	7.3	0.3 0.4	1.3 1.7	0.94 1.21	2.8 3.6	 9.8
4. 50/50 dark blue-grey clay and dark olive-brown clay.	7.4	2.7	2.1	0.92	2.7	9.2
5. Large amount of soft **dark olive-brown clay**—some in lumps 2–30 mm diam with LLS structure still apparent–some structureless. Some with visible gypsum crystals and shell fragments.		3.0 3.1	3.4 2.6	1.00 1.46	3.0 4.4	
6. Small amounts (<10%) soft structureless yellow-brown clay.	7.2	0.2	0.7	0.07	0.2	5.8
7. Occasional lumps of organic soil (peat) (often associated with yellow-brown clay).						

[a] pH determined on 2.5:1 water/soil extract as BS 1377: Part 3 [26].
[b] Acid-soluble sulfate extracted using dilute hydrochloric acid as BS 1377: Part 3.
[c] Water-soluble sulfate in 2:1 water/soil extract as BR 279 [27].
[d] Total sulfur measured in Leco combustion apparatus as BR 279 [27].
[e] The potential % of sulfate if all sulfur is converted to sulfate ($SO_4 = S \times 3.0$).
[f] Total calcium ion as % of dry weight by atomic absorption spectroscopy after extraction with hydrochloric acid.

were in contact with large volumes of re-worked Lower Lias Clay fill strongly indicated that the construction process had resulted in conditions favourable to TSA occurrence. The site investigation at Tredington–Ashchurch bridge supported this by showing that the backfill had initially comprised mostly unweathered Lower Lias Clay, but that this material was now partly oxidised. It was therefore considered likely that much of the pyrite present in the unweathered Lower Lias Clay (typically 5%) had decomposed leading to an increase in sulfate ions in the soil and groundwater.

Sulfate determination data on the pre-construction condition of the Lower Lias Clay from the original M5 site investigation report [23] gave results ranging from 0.8% to 0.48% SO_4 as determined by acid extraction (the water-soluble sulfate and sulfide content were not determined). Assuming the higher values were taken for concrete design purposes, the sites would have been categorised on the basis of then (i.e. late 1960s) current guidance, BRS Digest 90 [24], as Class 2 for sulfate. The one sulfate determination carried out on material from the Tredington–Ashchurch bridge site (see Table 1) was on the relatively unweathered Lower Lias Clay at a depth of 2.4 m and gave a relatively low SO_4 content of 0.12% of dry mass, equivalent to Class 1.

In contrast, sulfate determinations made by BRE during the Tredington–Ashchurch bridge investigation, some 30 years after construction indicated that a substantial increase in sulfate concentration had occurred. The SO_4 content of the clay as determined by acid extraction (see Table 2) ranged from 0.3% of dry mass in the dark blue-grey clay (i.e. a slight increase as compared to the unweathered clay) to 3.1% of dry mass in the more-oxidised dark olive-brown clay (i.e. a large increase as compared to the unweathered clay). The upper limit value is equivalent to sulfate Class 5 according to the old Digest 90.

The water-soluble SO_4 content measured by the 2:1 water/soil extract procedure, used as the basis for classification of soil in BRE Digest 363 [25], the guidance in force in 1998, (Table 2) also showed an increase in sulfate class as compared to the M5 original site investigation data. The dark blue-grey clay material had 1.3–1.7 g/l SO_4, while the olive-brown clay had 2.6–3.4 g/l SO_4. The dark blue-grey clay material was therefore Sulfate Class 2, while the olive-brown clay was Sulfate Class 3. Overall the location was assessed by Digest 363 in 1998 as Sulfate Class 3. Comparing these results with the foregoing likely classification of Class 2 based on the results of the original site investigation, it was concluded that the concrete for the Tredington–Ashchurch bridge was specified for sulfate conditions at least one sulfate class lower than should have been the case.

Two inter-related questions which needed to be answered at this juncture in relation to TSA at sites similar to those of the investigated M5 bridges were:

(1) Was there any pyrite or other sulfide remaining in the fill materials which could be potentially converted to further sulfate?
(2) Could the sulfate class of the fill material, as defined by Digest 363, be subject to future change?

The first question was addressed by analysing the backfill materials for its total sulfur content (using the LECO combustion apparatus), working out the sulfate equivalent of this, and comparing the sulfate equivalent with the total sulfate determined by acid extraction. From Table 2 it can be seen that, for the dark blue-grey clay, the total sulfur constitutes 0.9–1.2% of the dry-mass. This is equivalent to 2.8–3.6% SO_4. This potential amount of SO_4 greatly exceeds the actual amount, 0.3–0.4% of SO_4, measured by acid extraction. It was therefore presumed that the majority of the sulfur still existed in this material as pyrite (FeS_2) and that this could potentially be converted to sulfate by future oxidation. For the olive-brown clay the total sulfur is 1.0–1.5% of the dry-mass, equivalent to 3.0–4.4% SO_4. This only slightly exceeds the 3.0–3.1% SO_4 measured by acid extraction. This material was therefore concluded to be highly oxidised and with much reduced potential for oxidation to lead to further sulfate.

The second question required consideration of the rationale which underpinned the sulfate classification for concrete design, as given in Digest 363. This Digest does not take into account the total amount (reservoir) of sulfates available for attack on concrete, but rather the classification is based on the concentration of sulfate that develops in water which comes into contact with the soil. For a material such as Lower Lias Clay which is rich in calcium carbonate the oxidation of pyrite will mostly lead to the formation of gypsum which has a maximum solubility of only 1.4 g/l SO_4 and therefore remains mostly undissolved. The production of more gypsum, from further oxidation of pyrite, will therefore add to a reservoir of undissolved gypsum. If only calcium sulfate is present, then the maximum concentration of 1.4 g/l SO_4 in associated ground water will lead to Class 2 conditions (Digest 363). However, in cases where additional Mg, K and Na cations are available, e.g. from sulfuric acid leaching of clay minerals, then sulfate ions in solution may increase way beyond 1.4 g/l and sulfate class will be correspondingly higher, e.g. Class 3 in the case of the Tredington–Ashchurch backfill. With respect to future ground conditions, there was no reason to expect any significant change in sulfate class. Further oxidation of sulfide would mostly add to the already present reservoir of sulfate.

4. New guidance for assessment of sulfate class

For new construction that includes buried concrete, it is essential that the sulfate conditions in the ground are realistically assessed. However, in 1998 it became apparent that insufficient guidance was given in the principal guidance document, BRE Digest 363 [25] to allow for the enhancement of sulfate levels resulting from oxidation of pyrite in ground which is disturbed. A new procedure for classifying pyritic sites was therefore needed to remedy this omission. It was foreseen that this would not be easy since the sulfate conditions that would be experienced on such sites would lie somewhere between the limits of (i) no additional sulfate generated by sulfide oxidation and (ii) all sulfide oxidised and all resultant sulfate added to sulfate content of groundwater (an unlikely scenario when substantial quantities of pyrite were present). Consideration was given to development of a test which would measure the sulfate content of samples of pyritic ground after accelerated oxidation, e.g. a humid, high-oxygen atmosphere. However, it was concluded that this would be to slow, too expensive and have results which were too variable for routine application.

After consultation with industry, it was therefore decided to go for a rapid and low-cost procedure to determine the upper-bound sulfate condition. This comprised the determination of the total amount of sulfur in a soil sample, e.g. in a Leco analyser, by combustion in a high temperature oxygen flame and calculation of the sulfate equivalent of this (defined as total potential sulfate, TPS) for classification purposes. It was realised that this would give a doubly conservative estimate of total amount of sulfate that was likely to result from adding that produced by oxidation to that already present in the ground, since any sulfur within organic matter and minerals such as barite, both of which are more inert than pyritic sulfur, would be included. Since this assessment procedure was likely to lead to significantly more costly concrete specification than previously, it was considered important to limit its application to sites where there were substantial amounts of pyrite in the ground. The prerequisite of this was a determination of pyrite content. While a direct determination of pyrite was possible in a research laboratory [28], procedures for this were not seen to be presently commercially viable. The indirect method of finding pyrite content by subtracting acid-soluble sulfate from TPS, as in Tredington–Ashchurch study (Section 3.5), was therefore chosen as a preceding step for assessment of possibly pyritic sites.

The first version of the new procedure was included in January 1999 in the Report of Thaumasite Expert Group [29], a group including BRE representatives, set up by Nick Raynsford, the then Minister for Construction, to review the occurrence of TSA and to produce interim guidance for the design and specification of new construction. Subsequently, in the light of experience, the procedure and terminology was modified for inclusion in a new BRE Special Digest [30]. This latter version issued in October 2001 is discussed here.

The starting point for the new assessment procedure is an initial filter question which asks whether there is a possibility of sulfide minerals (e.g. pyrite) in the ground which might undergo oxidation, so causing a future increase in the level of sulfates. The likely presence of such minerals should be apparent from the desk study and visual examination of the ground by suitable qualified personnel. If the answer to the question is 'yes', then a second filter question is posed 'will concrete be exposed to disturbed ground in which pyrite may oxidise to sulfate?' As well as including cases where concrete will be in direct contact with pyritic ground disturbed by excavation and filling operations, this question is intended to cover sites where buried concrete will be in close proximity to the disturbed ground and there is a route by which groundwater can transport the sulfate from this disturbed ground to the concrete. If the answer to this second question is also 'yes' then the following test and calculation procedures are recommended for site assessment:

(i) Determine the total sulfur content, TS, as S% of dry soil mass.
(ii) Calculate the TPS content equivalent to this from the formula: TPS% SO_4 = total sulfur S% × 3.0.
(iii) Determine the acid-soluble sulfate AS% SO_4.
(iv) Subtract AS from TPS to determine 'oxidisable sulfide' OS% SO_4, this being taken as being equivalent to the pyrite content, i.e. pyrite content = OS = (3 × TS) – AS as %SO_4.
(v) If the above determined pyrite content is greater than 0.3%, then classify the site on the basis of TPS content, unless the design or method of construction can be modified such that concrete will not be exposed to the disturbed clay (see Section 5 for typical measures).
(vi) Use the following correlation [1] to determine sulfate class:
Sulfate Class 1 for TPS <0.24% SO_4, Sulfate Class 2 for TPS 0.24–0.6% SO_4,
Sulfate Class 3 for TPS 0.7–1.2% SO_4, Sulfate Class 4 for TPS 1.3–2.4% SO_4,
Sulfate Class 5 for TPS >2.4% SO_4.
(vii) Determine the 'Design Sulfate Class' for the site by taking the highest of the sulfate classes derived both from the (usual) tests on 2:1 water/soil extracts and from groundwater. Because of the inbuilt conservatism of the procedure for pyritic ground, the procedure allows the Design Sulfate Class to be capped at two classes above the class derived from 2:1 water/soil extracts.
(viii) Determine the (newly defined) Aggressive Chemical Environment Class (ACEC) Class of the site by taking into account whether the site is 'natural, or 'brownfield', whether the groundwater is 'mobile' or 'static', and the level of ground acidity (pH). [2]

Using the test data for the Tredington–Ashchurch bridge site given in Table 2, the new appraisal procedure indicates that this site should be classified for new construction, e.g. remedial works, as Design Sulfate Class DS-5, the most severe class. The reasoning is as follows: since the concrete is in contact with reworked sulfide-bearing clay the potential sulfates resulting from oxidation of sulfides have to be taken into account. The values of TPS calculated from the total sulfur content, range from 2.3% to 4.4% SO_4, the highest value correlating with Sulfate Class 5. This compares with a Sulfate Class 3 that Digest 363 would have given based on results of 2:1 water/soil extract tests which range from 0.7 to 3.4 g/l SO_4. Because the sulfate class based on TPS is already only two classes above the class derived from 2:1 water/soil extracts, capping to a lower value under the BRE SD1 procedure is not applicable.

From a consideration of the type of site (natural ground), groundwater mobility (mobile), and acidity (pH 7.2–7.8). The site would be assessed as AC-5 for new construction.

5. Construction measures to minimise exposure of concrete to enhanced sulfate levels

Where concrete is to be placed in or adjacent to pyrite-bearing ground and some disturbance of that ground is unavoidable, the composition of concrete

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[1] This correlation was not considered ideal, but it was the only reasonably acceptable one available. It was used by the former BRE Digests 90: 1968 [24] and 250: 1981 [31]. Experience had shown this correlation to be overly conservative at higher sulfate levels and it was discontinued in favour of sulfate classification based solely on 2:1 water/soil extract tests. For assessment of pyritic ground this overlays an already conservative procedure with yet another layer of caution.

[2] Incremental adjustments to sulfate class to cater for the type of site, groundwater mobility and acidity were in given Digest 363, however, these were used inconsistently and were difficult to handle in project documents. ACEC classification was introduced to provide a ground classification structure that catered for these recommended adjustments in demonstrably clear way.

needs to be specified such that it will withstand the high sulfate levels potentially resulting from pyrite oxidation. Recommendations for appropriate mixes of concrete are given in BRE SD1 [30]. In addition to an appropriate concrete specification, the following additional protective construction measures can be taken to minimise the risk of TSA when the potential sulfate content is particularly high and/or high performance structures need to be safeguarded:

- *Design construction works so that disturbance (e.g. cut and fill) of the ground is minimised.* As well as providing an opportunity for sulfides in unweathered clays to become oxidised, such disturbance can also increase ground permeability and increase hydraulic gradients, making sulfate-bearing groundwater more mobile.
- *Design excavations within a clay stratum such that they do not act as sumps with high concentrations of sulfate-rich groundwater.* Specifically avoid backfilling excavations with sulfide-bearing clay. Other backfills should be well-compacted to minimise the creation of voids and drainage paths.
- *The use of construction such as piled or trenchfill foundations that avoid excavation and backfilling may be appropriate.*
- *Design ground drainage* such that any drains which can channel water to below-ground structures are avoided and any flows of mobile ground water which might be coming from a sulfate source are intercepted.
- *Apply a protective coating* of a material such as rubberised bitumen emulsion or epoxy resin.

6. Conclusion

Historically, the potential for sulfate concentration to be increased as a result of disturbance of pyrite-bearing ground during construction has not been taken into account in UK guidance documents for concrete design. Following the finding in 1998 that such a mechanism had contributed to the incidence of TSA in the foundations of numerous motorway bridges, new guidance has been issued in BRE Special Digest 1 which recommends that sites possibly containing pyrite be investigated to determine the amount present. If the quantity is substantial and the ground will be disturbed, then it is additionally recommended that the site be classified for sulfate class on the basis of the determined TPS.

This procedure is very conservative and may lead to a high sulfate class (often Class 5 for Lower Lias Clay). Further research is needed on sulfate conditions developed in a range of pyritic strata affected by construction to enable the present empirical correlations with sulfate class to be relaxed to more representative levels.

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