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A comparison of classification systems for aggressive ground with thaumasite sulfate attack measured at highway structures in Gloucestershire, UK

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Abstract

Part one of the BRE Special Digest 1 'Concrete in aggressive ground' (2001) provides UK guidelines on assessing aggressive ground conditions with respect to the specification of concrete and protective measures required for concrete structures in contact with the ground. This supersedes the guidelines of BRE Digest 363 (1996) and the Thaumasite Expert Group Report (1999). All three publications rely in part on classifying the ground based on the chemical composition of the soil, backfill and groundwater at the location of the proposed structure. This paper provides an empirical assessment of the three classification schemes that was made possible following an extensive investigation into the thaumasite form of sulfate attack (TSA) in buried concrete highway structures in Gloucestershire. Ground classifications were made at 21 of the sites. The results of this study confirmed that whenever possible, the sulfate concentration in groundwater should be measured, and that as noted in SD1, the potential sulfate classification can be too conservative. The conclusions are limited geologically to the Lower Lias Clay Formation and to Recent Alluvium. The current classification system needs to be developed further by undertaking and reporting similar case studies from a variety of ground conditions.

Keywords: Thaumasite sulfate; Classification; Lower Lias Clay; Gloucestershire

1. Introduction

In March 1998, the thaumasite form of sulfate attack (TSA) was identified to the reinforced concrete foundations of a road bridge on the M5 Motorway in Gloucestershire, UK. The Highways Agency appointed Halcrow to assess the extent and implications of the problem to their structures in the county. Slater et al. [1] provide a summary of the investigation and its principal findings. By February 1999, when site works had been completed, a total of 28 structures had been investigated, which at most structures included the detailed and extensive description, sampling and testing of concrete and of the adjacent soil and groundwater. The sampling and testing procedures are summarised by Floyd and Wimpenny [2]. TSA was found and quantified at 19 of the structures and a comparison between respective concrete and ground conditions was undertaken at 21 of the structures.

The source of the sulfates for the formation of TSA was considered to be the surrounding natural ground of Jurassic-age Lower Lias Clay, and the associated groundwater, and also the backfill to the structures, which mainly comprised reworked Lower Lias Clay. The ground conditions adjacent to each structure were classified in accordance with BRE Digest 363 [3], which at the time was the current UK guideline on the resistance of concrete to sulfate and acid ground conditions. The Thaumasite Expert Group, which was set up during the investigation, updated the classification scheme by introducing the concept of the 'potential sulfate class' [4]. Subsequently, the two classification schemes were reviewed and tested against the relative amounts of TSA found at each structure. The objective was to assess whether the schemes were sufficiently robust and repeatable to:

- provide an accurate prediction of the degree of TSA (or its absence) to be expected at other existing structures;

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- provide an indication of the risk of TSA to new structures so they may be designed accordingly.

The results of the assessment are reported here and were also made available to the Building Research Establishment to assist in the production in 2001 of the BRE Special Digest 1 (SD1) [5] that supersedes Digest 363 and the Thaumasite Expert Group Report (TEGR). The classification scheme to be followed in accordance with the SD1 is similar to that introduced by the TEGR and is also assessed in this paper.

2. Location, structure type and geology

The structures investigated are located on either the M5 motorway or major trunk roads in the Gloucester and Cheltenham areas in the southwest of England. The structures consist of 20–30-year old reinforced concrete foundations and comprise: 9 overbridges, 3 footbridges and 2 pipe bridges (mainly spread footing foundations with slender columns, occasionally piled foundations); 3 underbridges (spread footings with counterfort abutments); and 4 culverts (box structures).

All the structures investigated are founded either in the Lower Lias Clay Formation or in Recent Alluvium. A typical description of Lower Lias Clay is:

- *Very stiff to stiff, dark blue grey, friable, thinly laminated silty CLAY, and occasionally weak thinly to thickly laminated MUDSTONE. With some calcareous fossil shells and rare pyrite. Thinly bedded, and occasionally interbedded with limestone. Occasionally with orange brown staining along fissures and bedding planes. Weathering to soft to firm olive grey with some brown mottling silty CLAY with rare selenite crystals.*

The excavations to form the foundations were backfilled with a mixture of predominantly Lower Lias Clay and a variable proportion of local superficial deposits (alluvium and terrace gravel). A general description of the backfill is:

- *Firm locally soft, bluish grey mottled olive brown, silty CLAY with medium gravel to cobble size (up to* 200 *mm) lithorelicts of unweathered Lower Lias Clay. With occasional pockets of orange brown slightly sandy clay, a little fine to medium gravel of limestone, sandstone and mudstone and rare pockets of very soft black fibrous and amorphous organic clay. With rare calcite shells, clusters of selenite crystals up to* 6 *mm and very rare pyrite crystals.*

In situ alluvium was associated with streams that crossed the highways and were diverted through box culverts. This was typically a thin deposit of soft to firm, yellowish brown sandy CLAY with some oolitic limestone gravel. On the River Severn floodplain, the undersides of buried concrete pile caps were in contact with soft, locally very soft greenish grey organic clay, whilst the sides and top were surrounded by backfill of approximately equal quantities of Lower Lias Clay and alluvium, with some inert demolition materials.

3. Procedure for the classification of aggressive ground conditions

3.1. Background

In the classification scheme recommended in Table 1 of BRE Digest 363, there are five possible classes of aggressive ground, based predominantly on the measurement of water-soluble sulfate in the ground, and on the sulfate content of groundwater. The classification system recommended by the TEGR (summarised in Fig. 6.2 of that report) uses the same guidelines as Digest 363 but adds the measurement of total sulfur content of the soil to derive an additional 'potential sulfate' class. This effectively measures the maximum amount of sulfur in the ground in all its forms, and assumes that it is all available to potentially form sulfate. In Part 1 of SD1, the classification procedure is similar to that in the TEGR with one of the main differences being that the total potential sulfate class is limited to being a maximum of two classes higher than the water-soluble sulfate class.

It must be emphasised that this study is not a classification of the whole site but a comparison of the relative merits of three sulfur species classes (water-soluble sulfate, groundwater sulfate and potential sulfate). To determine a classification of the site to Digest 363, TEGR or SD1, requires a compilation of all the results for that site together with a degree of engineering judgement to consider the geology around the structure and the form of the structure. Further modification of the class using Tables 1a–c, 2 or 3 of Digest 363 or applying the ACEC class of Special Digest 1 has not been attempted.

3.2. Soil and groundwater sampling

Soil sampling was undertaken from trial pits, dynamic window sample holes, dry percussive boreholes and rotary core holes. In rotary core holes minimal water was added to the hole by using an air-mist flush. Sample types included jar samples, sealed hand or excavator driven U100 tubes (450 mm long, 100 mm diameter), and sealed clear plastic tubes (up to 1000 mm long, 60–120 mm diameter), driven by percussive boring or window sampler.

Three types of groundwater sample were recovered:

- samples of seepage from trial pit, excavation or borehole walls without on site filtering;
- sealed samples extracted from BAT piezometers with minimal exposure to the atmosphere;
- bailed samples extracted from slotted screen standpipes.

The amount of sampling depended on the type of structure being investigated and the priority given to the site based on structural safety implications and construction or repair programs. Sampling typically consisted of two trial pits or larger excavations, and 4–8 boreholes (all with piezometers or standpipes), and occasionally 4–8 window sample holes. Piezometers and standpipes were sampled after installation, once in January–March 1999 and once in August 1999).

3.3. Soil and groundwater testing

The testing required for the three classification schemes is summarised in Table 1. These tests were undertaken as routine during the project. Testing also included a full suite of chemical and mineralogical analyses and geotechnical classification tests for additional studies. The total number of soil samples tested for sulfate classification was approximately 500, ranging from only 2 or 3 per structure to over 120 at one structure, but was typically 10–20 per structure. Where groundwater was encountered, the number of samples tested for sulfate classification ranged from 1 to 9 per structure, but was typically 2 or 3 per structure. All piezometer test results are used equally in the site assessment process, including multiple samples from the same piezometer.

3.4. Classification procedure

The findings of the study indicate that disturbance of the Lower Lias Clay during backfilling has permitted the oxidation of pyrite to proceed, generating sulfate. As a result, one might expect differences in sulfate levels between the disturbed and undisturbed ground at each structure. Therefore, at each structure, the classification procedure is made twice for:

- The natural (undisturbed) ground and groundwater adjacent to the structure but outside of the footprint of the foundations, to assess 'background' conditions and conditions that might be analogous for new construction.
- The backfill and associated groundwater above and beside concrete that is or was the most readily available source of sulfates for TSA.

Stratigraphic, material type and weathering variations were noted at and between structures and were considered for other aspects of the project, but for the purposes of this study, differentiation is not required. The view is taken that all materials surrounding the concrete are relevant to the classification.

On receipt of soil and groundwater test results from the testing houses, the results were entered into the

Table 1
Principal soil and water tests used for classifying aggressive ground conditions

Parameter	Test method	Objective	Relevant classification scheme
Acid soluble sulfate	BS1377: 1990 (but with in-house ICP–AES instead of gravimetric measurement)	To determine the requirement for additional water-soluble sulfate tests or class 1 condition	Trigger level for Digest 363, TEGR ('result 1') and SD-1
Water-soluble sulfate (2:1 extract)		To determine concentrations of the mobile sulfate compounds. Used to classify soil	Classify as 1–5 Digest 363, TEGR ('result 2') and SD1
Groundwater sulfate	BS1377: 1990 Ion chromatography	Preferred method of classification for the site	Classify as 1–5 Digest 363, TEGR ('result 3') and SD1
Total sulfur	IR detection LECO analyser	Provides an indication of the 'Potential Sulfate' of disturbed ground, designed to include sulfides that may oxidise to sulfate in the future	Classify as 1–5 TEGR ('result 4') and SD-1
pH	BS1377: 1990	To determine acidic conditions for Digest 363 and SD1	Table 2 of Digest 363 Table 2 of SD 1 (suffix z) Note: all results were above threshold values—no further assessment required
Water-soluble magnesium/ groundwater magnesium	BRE279 ICP–AES	To determine if the sulfate is present in large quantities in the more soluble and destructive form of $MgSO_4$	Table 1 of Digest 363 Table 2 of SD 1 (suffix m) Note: all results were below threshold values—no further assessment required

project database. A computerised routine was then applied to each sample, and ultimately to the backfill and natural ground at each structure, to provide aggressive ground classifications to the requirements of Digest 363, TEGR and SD1. For soil results, the classification at each structure was based on the mean of the top 20% of results (for less than 10 samples this is the highest of the 10) in accordance with Digest 363. For groundwater results, the classification was based on the highest value at the site.

In addition to sulfate and total sulfur tests, soil and groundwater pH and magnesium tests were undertaken in accordance with Digest 363 and SD1. The majority of pH results were greater than 7.0 and none were below the threshold value of 5.5. Therefore pH results do not affect the classification procedure in this study. Likewise, magnesium results were not greater than threshold levels and do not affect the classification procedure.

4. Semi-quantitative classification of TSA

The amount of TSA present in the concrete of each structure was measured where concrete was exposed, and a relative classification of the degree of TSA was devised [2]. Each pier or structural element investigated is assigned an attack grade based on the grading scheme shown in Table 2. To obtain an attack grade for the structure as a whole, the mean of the values for each pier or structural element is taken. Thaumasite sulfate attack is variable at all the structures and a degree of engineering judgement is required in all cases, therefore the grading scheme is semi-quantitative.

5. Results

5.1. Variability of data affecting classification

The large volume of samples tested and classified allowed a valid statistical distribution of classifications in the Lower Lias Clay and backfill to be observed. Fig. 1 shows histograms of the distribution of water-soluble sulfate class applied to each sample tested, for backfill and Lower Lias Clay. A wide spread of results was determined for the water-soluble sulfate and total sulfur values for soil within a single site and for the area as a whole. For example, at the Tredington Ashchurch Road Bridge northbound pier, water-soluble sulfate results in natural ground were classified as: class 1 (3 no.), class 2 (7 no.), class 3 (2 no.). Based on all 12 results the site is classified as class 3 ground conditions, but with fewer tests, there is an increasing chance that the site would be classified as class 2. This emphasises that in a material such as Lower Lias Clay, where sulfides and sulfates may be concentrated in particular clusters, zones or horizons, the number and spacing of tests is important.

5.2. Summary of classification results

The results of the soil and TSA classifications at each structure are summarised in Table 3. At some sites not all the necessary sulfur species tests could be undertaken and therefore not all three ground classifications can be

Table 2
The TSA classification scheme adopted

Grade	Name	Description
1	None	
2	Slight	Less than 15% of buried surface area surveyed is softened and max. depth of attack is less than 15 mm
3	Moderate	At least 15% of buried surface area surveyed is softened or max. depth of attack exceeds 15 mm
4	Severe	At least 25% of the buried surface area surveyed is softened and max. depth of attack exceeds 25 mm

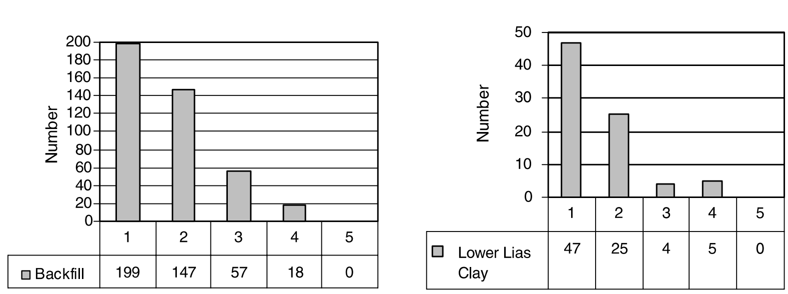


Fig. 1. Histograms of the BRE Digest 363 classifications for backfill and Lower Lias Clay using water-soluble sulfate content.

Table 3
The sulfate class and TSA grade measured at each buried concrete structure

Structure number	Type[a]	Backfill			Natural ground			Severity of thaumasite sulfate attack (overall structure rating)
		Water-soluble sulfate BRE Digest Class	Groundwater sulfate BRE Digest Class	TEGR and (SD1) Potential Sulfate Class[b]	Water-soluble sulfate BRE Digest Class	Groundwater sulfate BRE Digest Class	TEGR and (SD1) Potential Sulfate Class [b]	
M5_72.50	O	4	4	5	3	3	5	4
M5_81.00	C				2		5(4)	1
M5_81.20	U	2	3		2	2		3
M5_82.30	O	2	2	5(4)	2	2	5(4)	2
M5_82.60	O	2	2	5(4)	1	2	5(3)	2.5
M5_85.60	F	3	3	5	2	2	5(4)	3
M5_86.80	U	3	3	5	2	3	5(4)	3.5
M5_90.30	U	3	3	5	3	4	5	3
M5_90.90	F	3	2	4	2	1	4	2.5
M5_95.00	P	1		5(3)				3
M5_97.00	O	3	2	5				2.25
M5_97.20	O	3	4	5	2	4	5(4)	3
M5_101.50	O	3	4	5	2	3	5(4)	3
M5_110.10	P	1		4(3)				1.5
A40_159.90	C	1		3	1		5(3)	1
A40_161.50	O	2			1			3.5
A40_161.60	O	2	3	5(4)	1	2	5(3)	3.25
A40_163.80	F	1			2		5(4)	1
A40_166.90	C				1		1	1
A40_171.40	O	3	2	5	1		2	1
A417_83.90	C	1		5(3)				1

[a] Structure type: O = overbridge, U = underbridge, F = footbridge, P = pipe bridge, C = culvert.
[b] Values in brackets are SD1 Class, limiting potential sulfate class to a maximum of two classes above water-soluble sulfate class.

assigned. Where no classification is assigned care is taken to ensure that null results are not included in the correlation and plots that are subsequently derived. There is a maximum of six classifications at each site, three for natural ground and three for backfill.

In summary:

- There are 21 structures where soil classifications have been obtained and 13 structures where groundwater classifications have been obtained.
- Water-soluble sulfate classifications in backfill are available for 19 structures. The results vary between class 1 and 4 and are usually class 2 or 3. Only one site is class 4, and this is where the most extensive TSA was encountered.
- Water-soluble sulfate classifications in natural ground are available for 17 structures. The results are usually class 1 or 2; only two sites are class 3.
- Groundwater classifications in backfill are available for 13 structures. The results vary from class 1 to 4. Groundwater classifications in natural ground are available for 11 structures and similarly vary from class 1 to 4.
- Potential sulfate classifications (to TEGR) in backfill are available for 16 structures and are predominantly class 5; the lowest result is class 3. Potential sulfate classifications in natural ground are available for 15 structures and again are predominantly class 5; one site is class 1 (alluvium), one site is class 2 (alluvium) and one site is class 4, the rest are all class 5.

5.3. Backfill classifications

Fig. 2 compares the results per structure for the three classification types (water-soluble sulfate, groundwater sulfate and potential sulfate) in backfill. This shows:

- The backfill classification based on groundwater is the same as the soil water-soluble sulfate class at six sites, one class lower at three sites and one class higher at four sites. At the sites where the groundwater sulfate class is lower, this may be attributed to very wet ground conditions where the groundwater might be expected to be highly mobile (e.g. the River Severn floodplain); or to surface run-off seepage into a shallow trial pit.
- The potential sulfate class (to TEGR) is between 1 and 4 classes higher than the water-soluble sulfate class and between 1 and 3 classes higher than the groundwater class.

5.4. Natural ground classifications

Fig. 3 compares the results per structure for the three classification types (water-soluble sulfate, groundwater

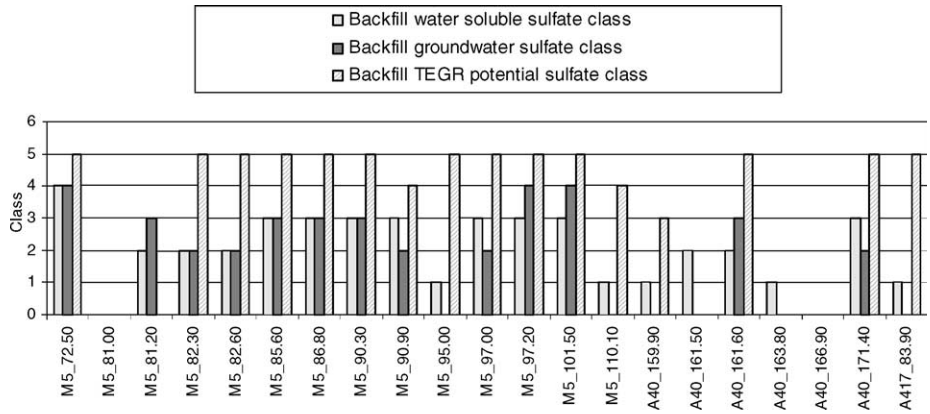


Fig. 2. BRE Digest 363 and TEGR classifications for backfill at all sites.

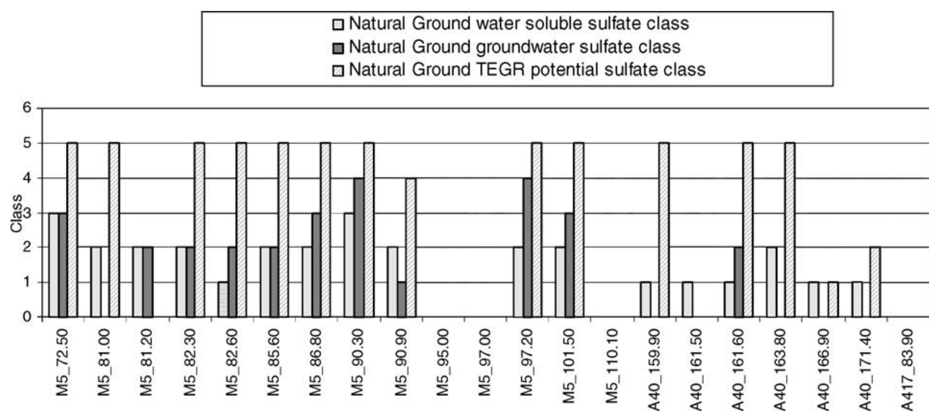


Fig. 3. BRE Digest 363 and TEGR classifications for natural ground at all sites.

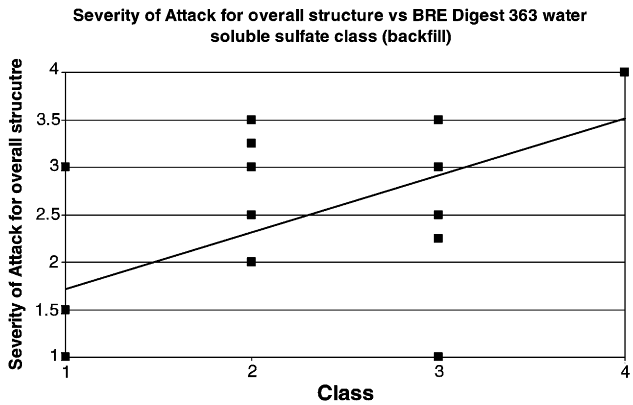
sulfate and potential sulfate) in natural ground. This shows:

- The groundwater class is usually the same or up to 2 classes higher than the water-soluble sulfate class.
- The potential sulfate class (to TEGR) is usually between 2 and 4 classes higher than the water-soluble sulfate class and between 1 and 4 classes higher than the groundwater sulfate class.

5.5. Comparison between sulfate class and TSA attack grade

Figs. 4 (for backfill) and 5 (for natural ground) plot the three classifications assigned to each structure against the attack grade assigned to the same structure. As points overwrite one-another on the plot, the number of points is shown in the matrix beside each plot. None of the best-fit lines are forced through the origin. The figures show the following:

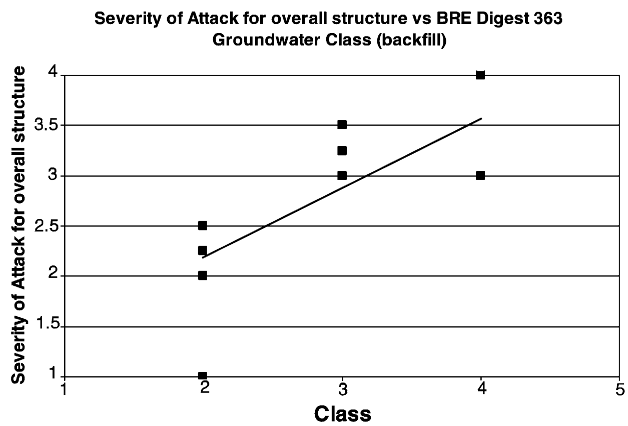
- A reasonable correlation (>0.7) is apparent between the overall attack grade and the classification of the backfill at each site when using groundwater data.
    - Based on this plot it may be possible to predict the degree of TSA that has already occurred at structures approximately 30 years old buried in backfill of Lower Lias Clay.
    - Whether this relationship exists for younger structures or structures in other materials needs to be tested.
    - This relationship applies to groundwater extracted from 30-years old backfill and therefore may not be a good predictive tool for the risk of attack to new structures in backfill because the groundwater chemistry may have changed over the years.
    - In additional studies, an apparent relationship was found between the degree of TSA and the maximum and minimum groundwater levels [1], indicating the importance of a full assessment of groundwater characteristics at a site.
- There is no significant correlation using the water-soluble sulfate results in the backfill.
- The potential sulfate class (to TEGR) of backfill cannot be used to determine the degree of attack that has already occurred at a structure, because in the Lower Lias Clay fill nearly all the sites have the maximum TEGR class.



Number of results

Attack Grade					
4				1	
3.5		1	1		
3.25		1			
3	1	1	4		
2.5		1	1		
2.25			1		
2		1			
1.5	1				
1	3		1		
Class	1	2	3	4	5

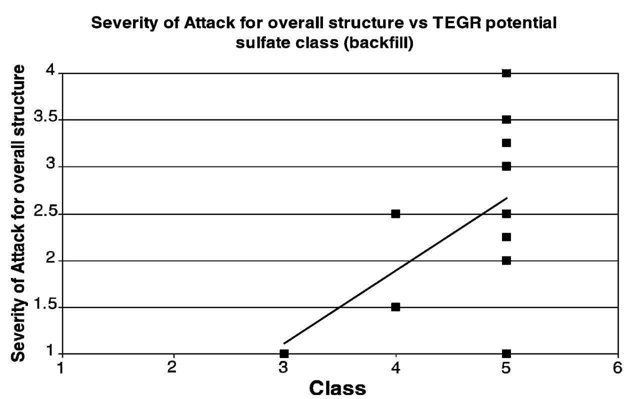
Correlation = 0.5812



Number of results

Attack Grade					
4				1	
3.5			1		
3.25			1		
3			3	2	
2.5		2			
2.25		1			
2		1			
1.5					
1		1			
Class	1	2	3	4	5

Correlation = 0.7376



Number of results

Attack Grade					
4					1
3.5					1
3.25					1
3					5
2.5				1	1
2.25					1
2					1
1.5				1	
1			1		2
Class	1	2	3	4	5

Correlation = 0.4786

Fig. 4. Plots of site classification (BRE Digest 363 and TEGR) against severity of attack grade for backfill.

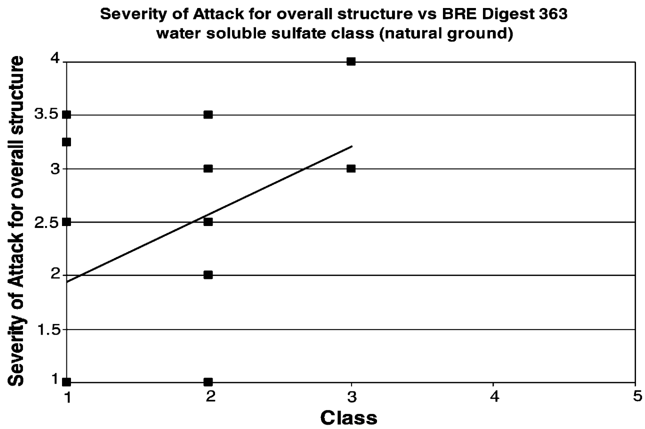
- In Fig. 5 there is no correlation between each sulfate class in the natural ground and TSA, although the plot of groundwater sulfate class against TSA rating has the narrowest scatter and most consistent trend.

Figs. 6 (for backfill) and 7 (for natural ground) show plots of the potential sulfate class modified by SD1 (to be limited to a maximum two class higher than water-soluble sulfate) against the attack grade assigned to the same structure. These plots can be compared with the bottom plots of Figs. 4 and 5. The figures show that the modification of TEGR by SD1 improves the correlation between potential sulfate class and measured TSA attack, particularly in undisturbed ground.

6. Conclusions

The study indicates that:

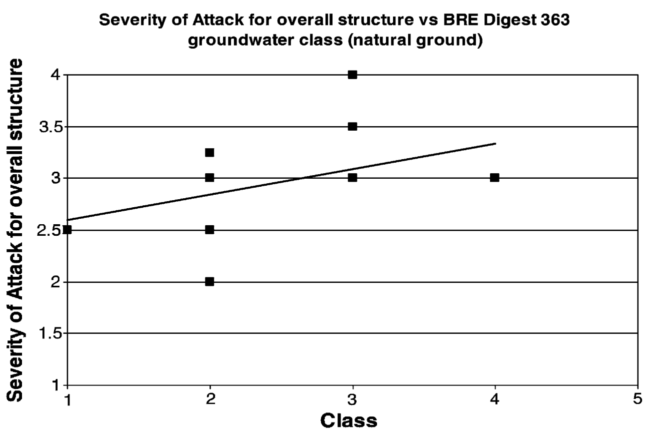
- There is large variation in sulfate class in the Lower Lias Clay and it is important to adhere to or increase the testing frequency described in SD1.



Number of results

Attack Grade	Class 1	Class 2	Class 3	Class 4	Class 5
4			1		
3.5	1	1			
3.25	1				
3		4	1		
2.5	1	1			
2.25					
2		1			
1.5					
1	3	2			

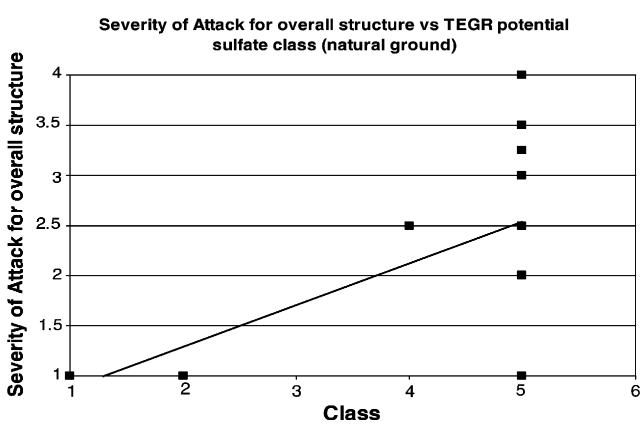
Correlation = 0.4012



Number of results

Attack Grade	Class 1	Class 2	Class 3	Class 4	Class 5
4			1		
3.5			1		
3.25		1			
3		2	1	2	
2.5	1	1			
2.25					
2		1			
1.5					
1					

Correlation = 0.4316



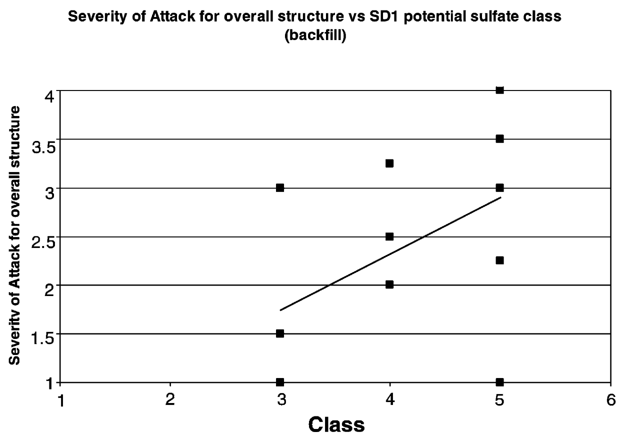
Number of results

Attack Grade	Class 1	Class 2	Class 3	Class 4	Class 5
4					1
3.5					1
3.25					1
3					4
2.5				1	1
2.25					
2					1
1.5					
1	1	1			3

Correlation = 0.4874

Fig. 5. Plots of site classification (BRE Digest 363 and TEGR) against severity of attack grade for natural ground.

- In undisturbed Lower Lias Clay, the groundwater sulfate class is often higher than the water-soluble sulfate class. Efforts should be made to obtain at least two groundwater samples per site during the ground investigation. As noted in SD1, care must be taken that samples in trial pits are not percolating surface run-off.
- Groundwater sulfate content appears to offer the best correlation to TSA, particularly in backfill at existing structures and may be one of the best methods of assessing the risk of TSA at existing structures without exposing the concrete. A larger sample group is required for correlation to be statistically significant.
- Total potential sulfate class, used in the TEGR for assessing pyritic clays, generally indicates class 5 (maximum class) conditions in the Lower Lias Clay. The total potential sulfate class therefore provides a robust indication of a potential risk but no correlation to measured TSA. SD1 recognises that potential sulfate class may be over-conservative and limits the design sulfate class to not more than two classes above the water-soluble sulfate class. This produces

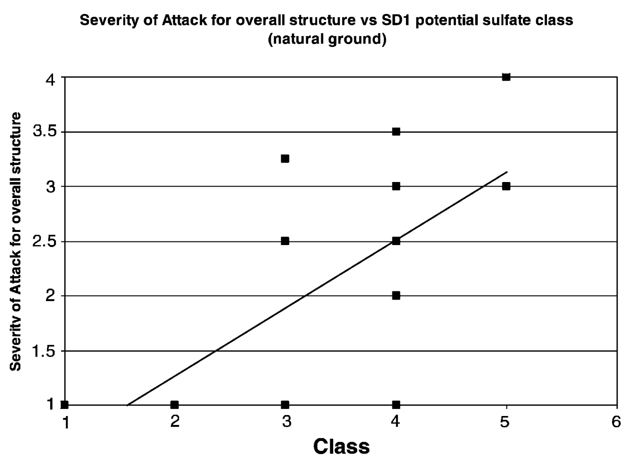


Number of results

Attack Grade	1	2	3	4	5
4					1
3.5					1
3.25				1	
3			1		4
2.5				2	
2.25					1
2				1	
1.5			1		
1			2		1
	Class				

Correlation = 0.5309

Fig. 6. Plot of total potential sulfate class (from BRE SD1) against severity of attack grade for backfill.



Number of results

Attack Grade	1	2	3	4	5
4					1
3.5				1	
3.25			1		
3				3	1
2.5			1	1	
2.25					
2				1	
1.5					
1	1	1	2	2	
	Class				

Correlation = 0.5934

Fig. 7. Plot of total potential sulfate class (from BRE SD1) against severity of attack grade for natural ground.

an improved correlation to TSA at the structures investigated.

The conclusions are limited by the lack of understanding of the rate of TSA and the assumption that the sulfate ground conditions measured in 1998–1999 at variable distance from concrete are representative of the ongoing process of TSA. Work for this project has indicated that several other variables affect the distribution and extent of TSA [1]. The results are also confined geologically to the Lower Lias Clay Formation.

The classification schemes of aggressive ground conditions have developed from a combination of theory and empirical data. The current scheme in SD1 should continue to be developed and refined from case histories taken from a variety of ground conditions so that parity can be achieved between water-soluble sulfate class, groundwater sulfate class and total potential sulfate class, and better correlation can be achieved with field measurements of TSA or other sulfate related concrete attack.

Acknowledgement

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