ELSEVIER

Cement & Concrete Composites 25 (2003) 1035–1043

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Thaumasite field trial at Shipston on Stour: three-year preliminary assessment of buried concretes

N.J. Crammond [a,*], G.W. Collett [a], T.I. Longworth [b]

[a] *Centre for Concrete Construction, Building Research Establishment Ltd. (BRE), Garston, Watford WD25 9XX, UK*
[b] *Centre for Ground Engineering and Remediation, BRE, Garston, Watford WD25 9XX, UK*

Abstract

A combined field and laboratory trial to investigate the thaumasite form of sulfate attack (TSA) in buried concrete was instigated by BRE in 1998 following the discovery of several cases of TSA in UK below-ground construction. Two identical sets of 98 concrete specimens were buried in sulfate-bearing Lower Lias Clay at a site in Central England. The first set of specimens was excavated in June 2001, after three years. The other set will be excavated after 10 years. A further similar assemblage has been subjected in the laboratory at 5 °C to a sulfate solution which simulates the site groundwater. Each set contains specimens with a range of quality and composition, mixes including combinations of eight binder types and four aggregate types, including limestone and siliceous aggregate.

After three years, identical concretes have generally behaved similarly in the field and laboratory studies, with a range of sulfate attack from none to moderate surface attack, dependent on concrete quality and composition. XRD analysis has shown the dominant form of sulfate attack to be TSA.

Keywords: Concrete; Thaumasite; Sulfate attack; Field trial; Lower Lias Clay; Laboratory study

1. Introduction

During the early 1990s, several investigations by BRE found that cast-in situ concrete foundations had been attacked by sulfates in the ground, despite the apparent use of sulfate-resisting concrete compositions then recommended [1–4]. In each case the principal reaction product was the mineral thaumasite and the coarse and/or the fine aggregate was limestone. Subsequent laboratory tests involving the immersion of concrete cubes in sulfate solutions indicated that, under certain circumstances, concrete with a normally sulfate resistant composition was vulnerable to the thaumasite form of sulfate attack (TSA) when it contained carbonate-bearing aggregate (e.g. limestone or dolomite) [4]. From these tests and the investigations of the failures in the field, the important factors external to the concrete appeared to be low temperature (<15 °C), very wet sites and readily available sulfate in permeable adjacent soil.

A combined field and laboratory trial to further investigate the performance of concretes containing limestone aggregates in sulfate-bearing ground was instigated by BRE in 1998. The trial site was a 9 m wide roadside verge at Shipston on Stour in Central England, adjacent to one of the TSA field cases [5]. The ground comprised Lower Lias Clay with wet, Sulfate Class 3 (1.4–3.0 g/l SO_4) groundwater conditions [1] at a reasonable working depth (2.5 m) for test specimens. The field trial comprised the burial of 196 test specimens in 1998 in two trenches, with half to be excavated for assessment after three years, and the other half to be excavated for assessment after 10 years. A selected number of specimens were also exposed in the laboratory at 5 °C to a sulfate solution that simulated the Shipston groundwater.

In June 2001, three years after their burial, the 98 test specimens in the first trench (hereafter called the three-year trench) were excavated for visual and laboratory assessment.

This paper describes the range of concrete specimens buried at the field trial site in May 1998, including their composition, method of manufacture and installation.

---

[*] Corresponding author. Tel.: +44-1923-664200; fax: +44-1923-664096.
E-mail address: crammondn@bre.co.uk (N.J. Crammond).

0958-9465/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0958-9465(03)00129-X

The exposure conditions, the excavation and provisional visual assessment of the specimens are also presented, together with the results to date from the parallel laboratory study. The three-year test specimens are currently undergoing detailed laboratory analysis at BRE and the findings will be published at a later date.

2. Design of field trial

2.1. General

The field trial concrete mixes were designed to provide combinations of aggregates and binders previously shown to have given rise to deterioration due to TSA (under laboratory conditions), and also combinations which it was hoped would prove resistant. Most of the trial concretes were specimen cubes 250 × 250 × 200 mm in size, but a number of precast concrete masonry blocks were also included. The two trial trenches (three-year and 10-year) contained identical concrete specimens in the same relative positions under the same exposure conditions, at a depth of 2.3–2.5 m below ground. The exposure conditions for the concrete specimens were designed to include:

- Cast-in situ cubes, with some faces cast directly against the in situ Lower Lias Clay and some against shuttering which was later removed and the face of the concrete covered with back-filled clay. These conditions simulated trench fill and strip foundations respectively.
- Precast cubes, subjected to a 14-day period of air-curing, and then placed so that some faces were in contact with in situ Lower Lias Clay and some against the back-filled clay to ascertain whether an initial air-cure (as would be found, for instance, in precast pile manufacturing) would beneficially affect the concretes in the same way as it does for conventional sulfate attack.

2.2. Concrete mixes

Three sources of limestone aggregate, both coarse and fine fractions were included in the concrete mixes, also one source of flint gravel was included as a control. The geological type and mineralogical compositions of these is given in Table 1.

To avoid confusion between commercial 'cements' and those produced in the mixer from blends of these 'cements' with other cementitious materials, the term 'binder' has been used throughout this paper. Eight types of binder were included: three Portland Cements with tricalcium alumuinate (C_3A) varying from 1% to 10%, and the 10% C_3A PC blended with ground limestone (PLC), ground granulated blast furnace slag (PC/ggbs), pulverised fuel ash (PC/pfa), metakaolin and microsilica. BRECEM (a 50:50 blend of high alumina cement and ggbs) was also included. The compositions and appropriate British and European Standard notations are shown in Table 2.

The four aggregate types were combined with the eight binder types to produce 39 different concrete mixes, comprising 33 main and six outlier mixes, as lis-

Table 1
Aggregate type and composition

Aggregate type	BRE code	Mineralogical composition
Flint gravel	S (Siliceous)	Quartz, minor calcite
Crushed magnesian limestone	M (Magnesian)	Mainly dolomite, trace quartz
Jurassic limestone gravel	J (Jurassic)	Mainly calcite, trace quartz, trace dolomite
Crushed carboniferous limestone	C (Carboniferous)	Mainly calcite, trace quartz, minor dolomite

Table 2
Binder type and composition

BRE code	Binder type	BS number and date	Cement type to BS EN 197-1 2000 [6]
B1	Portland cement (PC): (9.9% C_3A:42.5 N/mm^2)	BS 12:1996	CEM I
B1a	Portland cement (PC): (6.6% C_3A:42.5 N/mm^2)	BS 12:1996	CEM I
B2	Sulfate-resisting PC (SRPC): (1.4% C_3A:42.5 N/mm^2)	BS 4027:1996	CEM I[a]
B3	Combination of 70% PC (B1): cement and 30% pfa	BS 6588:1996	CEM II/B-V
B4	Combination of 60% PC (B1): cement and 40% ggbs	BS 146:1996	CEM III/A
B4a	Combination of 30% PC (B1): cement and 70% ggbs	BS 4246:1996	CEM III/B
B5	Portland limestone cement (PLC) containing 15% limestone	BS 7583:1996	CEM II/A-LL
B6	BRECEM (50% HAC/50% ggbs)	–	–
B7	PC-silica fume (microsilica): (90% B1:10% microsilica)	–	CEM II/A-D
B8	Portland metakaolin cement (75% B1:25% metakaolin)	–	–

[a] Included here as it complies with constituent requirements of BS EN 197-1: 2000 for CEM 1 together with special sulfate resisting properties. It will eventually be covered specifically in a future part of EN197.

Table 3
Concrete mixes

	Aggregate types		Binders (see Table 2)										Free water/ binder ratio
	Coarse	Fine											
33 Main mixes. Binder content = 320 kg/m^3	S	S	B1	B1a	B2	B3	B4	B4a	B5				0.53
	M	M	B1	B1a	B2	B3	B4	B4a	B5	B6	B7	B8	0.55
	M	J	B1	B1a	B2	B3	B4	B4a	B5				0.55
	M	C	B1	B1a	B2	B3	B4	B4a	B5				0.58
	J	J	B1										0.52
	C	C	B1										0.58
6 Outlier mixes. Binder content = 290 kg/m^3	S	S	B1						B5				0.76
	M	M	B1						B5				0.75
	J	J	B1										0.72
	C	C	B1										0.75

ted in Table 3. The main group all had a nominal binder content of 320 kg/m^3 and a slump of 50 ± 20 mm. This binder content was chosen as representative of the levels for various binders given in Table 7a of BS 5328: Part 1 [2] for Class 2/Class 3 boundary sulfate conditions. A small range in associated water/binder ratio (0.53–0.58) was allowed in order to achieve comparable workability for mixes which were so disparate in aggregate and binder properties. The outlier group of six mixes was included in order to obtain data on the effect of sulfate on poor quality concrete. These had a reduced nominal binder content of 290 kg/m^3, an increased slump of 75 ± 20 mm and a range of water/binder ratios between 0.72 and 0.78. All mixes were made in 30 litre batches, which provided sufficient material to cast two cubes for placing on site, one in each of the two trenches.

2.3. Precast concrete masonry blocks

The blocks were supplied in three mix types incorporating Jurassic Oolitic gravel aggregate, Jurassic Oolitic gravel aggregate plus pfa, and siliceous aggregate. After steam-curing, half of each type were air-cured, and the other half were shrink-wrapped. Each block was 440 mm × 215 mm × 100 mm with a nominal strength of 7 N/mm^2.

3. Details of field trial site

3.1. Topography and geology of the site

The site lies in a broad vale of Lower Lias Clay (of Jurassic age) which lies to the north-west of uplands formed by the Cotswold Hills. The site is located on gently sloping flanks of a low hill in the Lower Lias Clay, which is capped by glacial Till some 500 m uphill of the site.

The geological profile determined from site investigation boreholes and examination of the three-year sample trench typically comprises:

0–0.5 m: Fill material comprising mostly clay with gravel. Contains no significant sulfates.
0.5–0.7 m: Buried former top-soil.
0.7–1.3 m: Colluvial (hill-slope) deposit comprising soft structureless clay with occasional gravel and cobbles of flint, limestone and sandstone. Contains no significant sulfates.
1.3–2.0: Weathered Lower Lias Clay, soft, mostly structureless, mottled grey–brown/yellow–brown. Continuous but small groundwater seepage from some fissures below 1.75 m. Contains no significant sulfates due to disturbance and leaching.
2.0–2.7 m: Blocky weathered orange–brown colour Lower Lias Clay with clearly defined bedding plane fissures, with fissure separation increasing from 10 mm at the top of this section to 30 mm at the bottom. Many of the fissure surfaces have light blue–grey gleying, characteristic of anaerobic conditions beneath the water table. Continuous but small groundwater seepage from some fissures. Abundant clumps/sheets of gypsum crystals below 2.3 m.

3.2. Hydrology of site

The site has a high natural groundwater level and a mobile groundwater condition resulting from downslope drainage of rainwater from the hill slopes above. Groundwater levels have been monitored by piezometers installed (with sand back-fill and near-surface bentonite seal) in two boreholes drilled to 3 m depth and one drilled to 6 m depth. The groundwater levels are fairly consistent across the site, the seasonal range being from 0.3 to 1.0 m below ground level and the average depth being about 0.7 m.

3.3. Chemistry of site

The chemistry of the site has been investigated by analysing soil samples and groundwater taken at various depths in boreholes, piezometers and the three-year trial trench. Determinations on groundwater have typically included dissolved sulfate (as SO_4), cations Mg, Ca, Na, K, and pH. Those on soil have included total sulfur, acid-soluble sulfate, and SO_4, Mg, Ca, Na, K in a 2:1 water/soil extract.

As might be expected from the varying materials noted in the ground profile (Section 3.2) the ground chemistry varies significantly with depth, the ground and groundwater down to 2 m depth having no significant sulfate content, while below this relatively large amounts are found in weathered Lower Lias Clay down to depths of at least 5 m. The analyses which are considered to best represent the aggressive ground conditions at the location of concrete specimens are groundwater samples taken at a depth of 2.5 m directly after re-excavation of the three-year trench. These gave:

- Sulfate content of about 1.5–1.8 g/l SO_4, equivalent to the lower-half of Sulfate Class 3.
- Calcium ion (Ca^{2+}) content of 0.5 g/l, indicating the groundwater is near-saturated with respect to gypsum.
- Magnesium ion (Mg^{2+}) content of 0.7 g/l, i.e. well below the 1.2 g/l threshold which leads to m-suffix Design Sulfate Classes DS-4 m and DS-5 m in BRE SD1 [7].
- Sodium ion (Na^+) content of 0.04 g/l.
- Potassium ion (K^+) content of 0.01 g/l.
- pH of about 7.5.

Together with the assessed mobile groundwater condition, the natural-ground status of the site, and the neutral pH, this leads to an Aggressive Chemical Environment for Concrete (ACEC) Class of AC-3 [7].

Ionic balance calculations for the above results indicate a significant ionic imbalance, with a greater combined cation content (Ca, Mg, Na and K) than required for the SO_4 anion concentration. This indicates the presence of other anionic groups in solution such as bicarbonate, which could provide an additional source of carbonate ions for the TSA reaction.

The above characterisation of ground conditions at concrete specimen depth based on groundwater samples contrasts with that based on soil samples. Analyses of 2:1 water/soil extracts on soil samples from 2.5 m depth consistently gave a sulfate ion content of about 1.7 g/l SO_4, i.e. near the middle of Sulfate Class 2 using the class limits of BRE SD1 [7]. This discrepancy accords with other reported investigations of Lower Lias Clay sites and indicates a fundamental inadequacy in the 2:1 water/soil extract classification procedure.

3.4. Ground temperatures

Ground temperatures have been monitored with thermister probes positioned at 2.5 m depth near to the cubes in the three-year trench. Temperatures have ranged from 9.5 to 12.5 °C.

4. Installation of concrete specimens

4.1. Excavation and ground conditions during installation

The two 2.5 m deep trenches were excavated in May 1998. Soil from 0 to 1.5 m depth was stored separately from soil from 1.5 to 2.5 m depth, so that during backfilling clay containing a high level of sulfate could be placed around the test specimens. However, this was only partially achieved as most of the ground excavated from 1.5–2.0 m is virtually devoid of sulfate. The intermixed presence of this fraction will have reduced the sulfate content of the back-fill below the amounts found in the in situ Lower Lias Clay at 2.3–2.5 m.

4.2. Placing of concrete specimens

The precast concrete specimens arrived on site marked with Mix number/Specimen number. On the first day of sample installation, they were placed into their allocated positions along both sides of the trench bottoms (Fig. 1). On the subsequent days, the cast-in situ concrete specimens were mixed (to standard procedures [8]) and placed in numerical order between the precast cubes. The moulds for the cast-in situ specimens comprised timber shuttering at the front, and thin sheets of transparent plastic to either side, to prevent direct

Fig. 1. Precast concrete specimens placed at 2.5 m depth in trial trench, awaiting casting of intermediate cast-in situ cubes in May 1998.

contact with the precast specimens. Any groundwater that had collected was meticulously removed to ensure the planned water-binder ratio of the fresh concrete was maintained. The mix was poker-vibrated after half-filling the mould and again when it was full. Finally the 24 precast concrete masonry blocks were positioned at each end of each trench. The trench was back-filled on the day following the placing of the last specimens.

5. Retrieval and visual assessment of three-year field specimens

5.1. Procedure

The 86 concrete cube and 12 concrete block specimens in the three-year trench were excavated 18–21 June 2001. The surfaces of some samples had been attacked to a substantial degree and it was difficult to remove excess clay from these without damaging/removing some of the deteriorated material (Fig. 2). Any material that had obviously become detached from a particular sample was also collected and kept with the bulk specimen. Each block/cube was visually examined and photographed on reaching the surface before being sealed in a polythene bag for transfer back to BRE, where in-depth characterisation of the type and extent of attack is currently being carried out. At the time of writing, only preliminary X-ray diffraction (XRD) analyses, reported below, have been undertaken.

5.2. Condition of precast concrete masonry blocks

The blocks containing siliceous aggregate and those containing pfa were in good condition with no visible evidence of sulfate attack. Those containing the Jurassic Oolitic gravel aggregate had been attacked to varying degrees, and had a soft, white reaction product on the surfaces and corners. The worst attack appeared to be on the block subjected to seal-cure (i.e. shrink wrapped after steam-cure) although the air-cured block had also been attacked. XRD of the white material scrapped from the surface of the seal-cured block detected the presence of calcite (from the aggregate) and thaumasite.

Fig. 2. Removal of concrete specimens from three-year trench in June 2001. White TSA reaction product is clearly visible.

5.3. Condition of precast and cast-in situ concrete cubes

5.3.1. General

The following points should be noted in respect of the visual assessment:

- The experimental design introduced several variables to give the concrete cubes a range of resistance to TSA (see Section 2). These parameters included: choice of aggregates, choice and amount of binders, water/binder ratio, precast or cast-in situ. A correlation of cube performance with these parameters was looked for when the cubes were examined.
- When a cube had been attacked, the resultant reaction product was soft and white and appeared to be typical of TSA. XRD results (see Table 4) have confirmed this. The amount of attack and its position varied from cube to cube but tended to be more extreme on the top edges and corners of the attacked cubes.

5.3.2. Cast-in situ versus precast cubes—same composition

When a particular composition exhibited TSA, the precast cubes invariably performed better than their cast-in situ counterparts, except for the bottom face. This was particularly so in the outlier mixes but also occurred with the PLC main mixes, where for many of the cubes, the bottom face, consisting mainly of soft white material, detached itself from the base of the cube.

5.3.3. Back-fill clay face versus in situ clay face—same composition

Where a particular cube had been attacked, comparisons were made between the side face in contact with the back-fill clay and the side face in contact with the virgin clay. It was considered on site that the side face in contact with the virgin clay exhibited the greatest attack, but this needs verification in the laboratory. A reason for this could be partly due to the lower concentrations of sulfate ions in the back-fill clay (see Section 4.1). However, the top face (struck face), also in contact with back-fill clay, often appeared worse than either of the two side faces.

Table 4
Minerals formed (from XRD) during sulfate attack in specimens shown in Fig. 3

Aggregate		Binder	Minerals formed during sulfate attack			
Coarse	Fine		Thaumasite (T)	Ettringite (E) or Mixed T/E	Gypsum	Calcite
S	S	B1	P	m	m	P
M	M	B1	P	m	t	P
S	S	B1a	m	m	P	P
M	M	B1a	P	m	m	P
S	S	B2	m	m	m	P
M	M	B2	P	m	m	m

Key: Aggregate—see Table 1; Binder—see Table 2. Minerals present: P—predominant; m—minor; t—trace.

5.3.4. Concrete cubes made with Portland cement (main mixes)

Cubes made with sulfate resistant and ordinary Portland cement will be considered as one group.

(a) *Variable C_3A content in PC and variable aggregate composition:* For the four aggregate types used, cubes were produced with PC C_3A contents of 1%, 7% and 10%, with a nominal cement content of 320 kg/m^3. Fig. 3 shows comparative photographs between cast-in situ cubes made with either all-in magnesian limestone aggregate or siliceous aggregate. The accompanying XRD results for these six selected specimens, showing the relative amounts of surface reaction products formed during sulfate attack, are presented in Table 4. This table includes a column pertaining to secondary calcite. As large quantities of calcite were not present in any of the six original concrete mixes, calcite deposition must have accompanied the TSA. The key observations are:

- The cast-in situ cubes made with all four aggregate types and 10% C_3A have all been attacked: the siliceous aggregate cubes show the least, but still significant, amount of surface deterioration. Table 4 shows TSA to be the main mechanism behind this surface deterioration, even in the siliceous aggregate concretes containing low amounts of carbonate. Tests are now underway at BRE to measure the carbonate/bicarbonate ion content of the adjacent groundwater (see Section 3.3) as this could have provided the additional supply of carbonate ions. With C_3A content reduced to 7% of PC, the amount of visible surface attack remained similar in the concretes containing carbonate aggregate (thaumasite main reaction product found), but had significantly lessened in the cube containing siliceous aggregate (gypsum main reaction product found).
- The SRPC concrete cubes (1% C_3A) made with carbonate aggregate appeared to have performed slightly better than the equivalent PC concretes, but still showed significant signs of surface TSA. The SRPC cube made with siliceous aggregate showed no visible signs of attack.

(b) *Fixed C_3A content, variable cement content and aggregate composition:* A range of aggregates were incorporated into concretes containing 10% C_3A at two

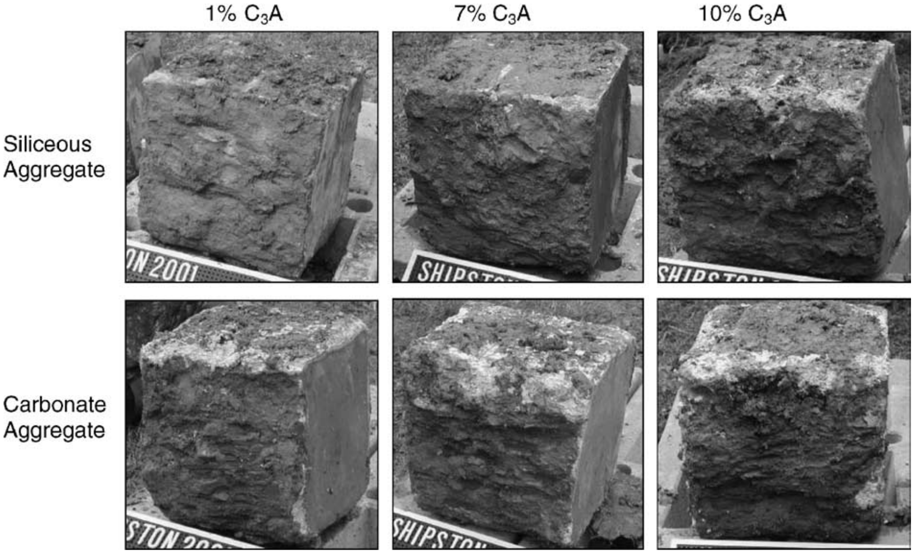

Fig. 3. Comparison of siliceous and carbonate (magnesian) aggregate in Portland cements at different C_3A levels.

different cement contents: nominally 320 kg/m^3 (main mixes) and 290 kg/m^3 (outlier mixes). The key visual observation is that, at this C_3A level, all the main mixes have shown signs of surface attack, independent of aggregate type, but it appeared that the outlier mixes exhibited slightly greater attack.

5.3.5. *Concrete cubes made with Portland limestone cement*

Portland limestone cement (PC + 15% limestone filler) was used with a range of aggregates at different cement contents. The key visual observations are:

- All mixes have been attacked to varying degrees.
- As with the PC, the mixes containing siliceous aggregate have performed slightly better than the equivalent mixes containing carbonate aggregates, but have still been attacked.
- All the limestone aggregate mixes have been badly attacked, although the outlier mixes with lower cement content have performed the worst.

5.3.6. *Concrete cubes made with other binders*

(a) *Partial replacement of PC with other cementitious materials:* In these mixes some of the PC binder is replaced with either pfa (30%), ggbs (40% and 70%), microsilica (10%) or metakaolin (25%). All cubes in this category have performed well irrespective of aggregate type.

It should be noted that the PC binder used contained 10% C_3A and when used alone with Magnesian limestone aggregate was heavily attacked.

(b) *BRECEM cement:* BRECEM, which is not commercially available, comprises 50% calcium aluminate cement and 50% ggbs and all the cubes made with this cement were in good condition irrespective of aggregate type.

6. Parallel laboratory studies

6.1. *Mixes studied in the parallel laboratory study*

Twenty-four concrete mixes were selected for a parallel laboratory study. Thirteen were chosen from the 33 main field trial specimen mixes and four out of the six outlier mixes were also selected. In addition five new concrete mixes containing all-in Carboniferous limestone aggregate were specially made for the laboratory study. Two separate sets of 100 mm concrete cubes (Set 1 and Set 2) were cast for the parallel laboratory study using these 24 mixes:

Set 1: The Set 1 100 mm concrete cubes were made in March 1998, at the same time as the precast Shipston site specimens. Four concrete cubes were prepared from each mix and subjected to different curing conditions before immersion in sulfate solution. This included, after demoulding, two cubes air-cured for 13 days at 20 °C followed by immersion in laboratory-prepared sulfate solution at 5 °C. The remaining two cubes per mix were water-cured at 20 °C for 27 days after demoulding, after which they were placed in sulfate solution at 5 °C. Both air-cured and water-cured cubes were stacked one on top of the other during curing, implying that the 'stuck' or 'contact' face effect described previously [9–12] could be repeated in this trial.

Set 2: The Set 2 100 mm cubes were prepared in July 1998, four months after the Set 1 cubes and the field trial precast specimens, from 18 concrete mixes, 13 of which had equivalent field trial mixes. Set 2 cubes were cured significantly differently from those in Set 1. Four cubes were made from each concrete mix. Cubes 1 and 2 were water-cured at 20 °C for 27 days after demoulding, whereas cubes 3 and 4 were wrapped in cling film and put inside a polythene bag immediately after demoulding and were left to 'seal-cure' in the laboratory at 20 °C for 27 days. Instead of the water-cured cubes being stacked one on top of the other, they were separated by 12 mm thick, 50 mm diameter circular plastic spacers. This was done so that any 'stuck' or 'contact' face effect would be restricted to the area within the circular impression.

6.2. *Exposure conditions used in the parallel laboratory study*

The four cubes from each of the 24 mixes were stored together in one 305 mm × 305 mm × 152 mm sealed plastic container in order to eliminate cross-contamination between cubes containing different aggregate/binder types. The composition of the sulfate solution simulates the Class 3 sulfate waters present at the Shipston field trial site, with a composition: 1.53 g/l $CaSO_4 \cdot 2H_20$, 2.56 g/l $MgSO_4 \cdot 7H_20$, 0.77 g/l Na_2SO_4, 0.05 g/l K_2SO_4 and 0.37 g/l carbonate concentration. The solution was renewed every three months. The storage temperature was maintained at 5 °C throughout the experiment.

6.3. *Results of the parallel laboratory study after two years*

The main findings are:

- TSA has occurred in many of the compositions used, as detailed below. This has been verified using XRD and optical microscopy.
- Seal-curing the concrete cubes has made them more reactive and the resultant mode of attack was found to be similar to the 'contact' face effect found previously.

- The seal-cured surfaces of all the PC and PLC concretes have been attacked irrespective of aggregate type.
- This study now provides laboratory evidence to support previous observations [4] that a TSA-related form of deterioration can occur in PC concretes in the field, which contain little or no carbonate (limestone) aggregate.
- None of the concretes made with 30% PC and 70% ggbs have shown any signs of attack after two years, despite the fact that the PC contained 10% C_3A.
- Concretes made with SRPC were only slightly attacked after two years but concretes containing 60% PC/40% ggbs and 70% PC/30% pfa did not perform well.
- Concretes made with Portland microsilica cement, Portland metakaolin cement and BRECEM were not investigated under laboratory conditions.

7. Conclusions from the preliminary three-year field trial assessment

The findings to date have indicated that a timescale of three years in a field trial is sufficient to differentiate between TSA-resistant concrete mixes and those which are susceptible to TSA. The visual results also correlate well with those of the parallel laboratory study, except for concretes containing pfa and 40% ggbs. A more detailed analytical programme is now underway at BRE using X-ray diffraction, scanning electron microscopy and petrography. It will not be possible to draw definitive conclusions on the three-year findings until this work is carried out, but the conclusions obtained from the field trial so far are as follows:

1. Even after the relatively short period of exposure to Class 3 sulfate-bearing groundwater (1.4–3.0 g/l SO_4) on site, the surfaces of many of the test specimens were covered with a white-coloured reaction product which has been shown by X-ray diffraction analysis to be predominantly thaumasite.
2. The precast concrete masonry blocks containing either siliceous aggregate or pfa were in good condition, but those containing Jurassic Oolitic limestone aggregate were coated with a white reaction product identified as thaumasite.
3. The precast concrete cubes had performed much better than their cast-in situ counterparts.
4. The poorer quality outlier concrete mixes showed more evidence of surface deterioration compared with their equivalent main mixes.
5. In the TSA-affected cubes, the cast-in situ side faces in contact with undisturbed/in situ clay appeared to have been attacked to a greater extent compared with the side faces exposed to back-fill clay. However, the worst attack was found on the corners and edges of the top struck face, which had been in contact with the back-fill clay.
6. All cast-in situ concrete cubes made with either PC or PLC have shown significant signs of surface attack irrespective of aggregate type.
7. The SRPC cast-in situ concretes containing siliceous aggregate had performed satisfactorily whereas those made with carbonate aggregates have shown significant signs of attack.
8. All concretes made with blended cements containing pfa, ggbs (including BRECEM), microsilica and metakaolin performed more or less satisfactorily irrespective of aggregate type.

Acknowledgements

The authors would like to thank the UK Governments' Construction Research Directorate for funding the BRE field trial at Shipston on Stour and the Quarry Products Association (QPA), the British Cement Association (BCA), the Cementitious Slag Makers Association (CSMA) and the UK Quality Ash Association (UKQAA) for providing support, including provision of materials. They would also like to thank numerous colleagues at BRE who assisted in the field and laboratory trials and Warwickshire County Council who own the land and assisted in the burial of the specimens in 1998 and their retrieval in 2001.

References

[1] BRE Digest 363. Sulfate and acid resistance of concrete in the ground. London: CRC; 1991 (Revised 1996).

[2] BS 5328. Concrete, Part 1: 1997 guide to specifying concrete. Part 2: 1997 methods for specifying concrete mixes.

[3] Crammond NJ, Nixon PJ. Deterioration of concrete foundation piles as a result of thaumasite formation. In: 6th International Conference on Durability of Building Materials, Japan, 1993. p. 295–305.

[4] Department of the Environment, Transport and the Regions. The thaumasite form of sulfate attack: risks, diagnosis, remedial works and guidance on new construction. Report of the Thaumasite Expert Group, DETR, London, January 1999.

[5] Crammond NJ, Halliwell MA. The thaumasite form of sulfate attack in concretes containing a source of carbonate ions. In: 2nd Symposium Advances in Concrete Technology. ACI, P154-19, 1995. p. 357–80.

[6] BS EN 197-1:2000. Cement—Part 1: composition, specifications and conformity criteria for common cements. London: British Standards Institution; 2000.

[7] BRE Special Digest 1. Concrete in aggressive ground. London: CRC: 2001. Part 1: assessing the aggressive chemical environment.

[8] BS 1881. Testing concrete. Part 125:1986 methods for mixing and sampling fresh concrete in the laboratory.

[9] Halliwell MA, Crammond NJ. Avoiding the thaumasite form of sulfate attack: two-year report. Building Research Establishment

Laboratory Report BR385. Watford, UK: Construction Research Communications Ltd.; 2000.

[10] Halliwell MA, Crammond NJ. Avoiding the thaumasite form of sulfate attack. In: Proceedings of the 8th Durability of Building Materials Conference. Vancouver; 1999.

[11] Crammond NJ, Halliwell MA, Higgins DD. The use of ground blastfurnace slag to avoid the thaumasite form of sulfate attack: four year results. In: Proceedings of the Conference on Sustainable Construction into the next Millennium: Environmentally Friendly and Innovative Cement-Based Materials, Brazil, 2000. p. 660–70.

[12] Higgins DD, Crammond NJ. Resistance of concrete containing ggbs to the thaumasite form of sulfate attack. In: Proceedings of the First International Conference on Thaumasite in Cementitious Materials, Watford, UK, June 2002.