DETAILS OF SPECIMENS AND FIELD TRIAL

General

The field trial concrete mixtures 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. The trial concretes studied here were specimen cubes 250 x 250 x 250mm in size. The two trial trenches (3-year and 10-year) contained identical concrete specimens in the same relative positions under the same exposure conditions, at a depth of 2.3 – 2.5m 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.

Concrete mixtures

Three sources of limestone aggregate (Magnesian/dolomitic limestone, Carboniferous limestone and Jurassic oolitic limestone), both coarse and fine fractions, were included in the concrete mixtures. Also one source of flint gravel was included as a control. The geological type and mineralogical compositions of these are given in Table 1 of [4].

Eight types of binder were included: three portland cements (PC) with tricalcium aluminate (C_3A) varying from 1 to 10%, and the 10% C_3A PC blended with ground limestone (PLC with 15% ground limestone), ground granulated blast furnace slag (70% ggbs/30% PC and 40% ggbs/60% PC), pulverised fuel ash (30% fly ash/70% PC), metakaolin (25% metakaolin/75% PC) and microsilica (10% microsilica/90% PC). 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 of [4].

The four aggregate types were combined with the 8 binder types to produce 39 different concrete mixtures, comprising 33 main and 6 outlier mixtures, as listed in Table 3 of [4]. The main group all had a nominal binder content of 320 kg/m^3, a slump of 50 ± 20 mm and a range of water/binder ratios between 0.52 and 0.58. The outlier group of 6 mixtures 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 mixtures 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.

Summary of ground conditions on field trial site

The details of the field trial site including topography, geology, ground chemistry and temperature have been dealt with in[4]. Additional relevant information has however become available since December 2001, arising from the recent installation of three more piezometers on the Shipston site. The results of the chemical analyses of the soil samples taken from the piezometer bore holes and groundwater collected from the piezometers are summarised as follows.

- Groundwater conditions on the Shipston site throughout the field trial have been wet (below groundwater table) and Mobile at the 2.5 m depth of the concrete specimens.
- The pH of the ground and groundwater at all levels has been consistently neutral, at about 7.5.
- During the period May 1998 to June 2001, sulfate concentrations in the 3-year trench at the level of the concrete specimens were at the lower-half of Sulfate Class 3[3]. New UK specifications are now in place, which classify sulfate conditions in terms of an Aggressive Chemical (AC) Class (Building Research Establishment [[15]5]). The AC Class at the 2.5 m depth of the concrete specimens works out as AC-3 on the basis of a Design Sulfate Class of 3, a natural soil site, a neutral pH of 7.5 and a Mobile groundwater condition.
- The sulfate ions in the groundwater are associated primarily with calcium (Ca^{++}), magnesium (Mg^{++}) and sodium (Na^{+}) cations. The groundwater is near-saturated with respect to gypsum ($CaSO_4{\cdot}2H_2O$). Analyses of bicarbonate in groundwater from the new piezometers installed at concrete specimen level has indicated an amount of carbonate present of 0.24 to 0.29 g/l CO_3, equivalent to 0.41 to 0.48 g/l expressed as $CaCO_3$.
- Ground temperatures have varied seasonally between about 10°C and 13°C at the 2.5 m depth of the concrete specimens. This is within the temperature range which encourages the occurrence of TSA in susceptible concrete.
- Though pyrite is probably present at depths approaching 5m, no contribution to the chemistry of the groundwater at the 2.5 m depth of the concrete specimens would appear to have been made from the (recent) oxidation of pyrite.

ASSESSMENT OF THREE-YEAR SPECIMENS

General

A number of techniques were employed in order to ascertain the type and degree of sulfate attack encountered in the field trial test specimens after three years exposure to AC Class 3 sulfate conditions. These are as follows.

An initial visual assessment of the 86 concrete cubes was made as they were excavated from the trench and this has been presented in [4]. After transportation back to BRE, each test specimen was subjected to a visual and physical inspection in the laboratory. Photographs were taken of the two side faces, exposed to either in-situ clay or backfill clay whilst buried. Samples were scraped from the surfaces of selected specimens and these were analysed using X-ray diffraction. Nineteen of the cast-in-situ test specimens then underwent further sample preparation enabling their surfaces and centres to be examined in more detail using chemical analysis, optical microscopy and scanning electron microscopy.

Visual and physical inspection

The surfaces of each test specimen were examined visually and the photographs taken of the in-situ clay and backfill clay side faces are archived at BRE. For each specimen, the physical robustness of the four cube faces, which had been exposed to sulfates in the ground, was determined with the aid of a metal spatula. In the cases where sulfate attack had occurred, the surface concrete was soft and crumbly and could be easily dislodged with the spatula. In the cases where sulfate attack had not occurred, the concrete surface was sound and impenetrable to the spatula. The scraping technique using a spatula was also employed to ascertain a very approximate 'depth of attack' in the cubes, which showed significant signs of degradation. Depth of attack measurements (mean and maximum) were taken for the two side faces, the top face and the bottom face and these are presented in Table 1.

The measured values of depths of attack are not very accurate and can only be used as a guideline. They are inaccurate because:

- The depth of attack varied over the surface area of an exposed face and was often concentrated at corners, along edges and in blisters.
- The surface of the in-situ clay side face of the cast-in-situ cubes can be particularly irregular, which makes reading off a definitive depth measurement difficult.
- During excavation, soft surface material from many of the badly attacked cubes remained behind in the walls and floor of the 3-year trench. This would mean that the depth of attack is underestimated in some specimens.
- The onset of TSA is probably accompanied by expansion of the degraded surface layers. This could lead to an overestimated depth of attack as the measurement would not have been made from the original external surface.
- The deteriorated outer surface of a TSA-affected concrete will shrink in volume as it dries out.
- For cast-in-situ cubes, the initial front to back dimension was not accurately known, so this could not be used in the calculation of depth of attack.

X-ray diffraction analysis

X-ray diffraction (XRD) was carried out on 49 samples scraped from the surfaces of selected test specimens. The samples comprised deteriorated surface concrete, which had been ground to less than 53 microns prior to analysis. An automated Siemens D500 with a copper Kα X-ray tube (400kV, 300mA) was the equipment used. The scanning range was between 5° and 50° 2θ, the step size was 0.05° 2θ and the step count was four seconds.

The reaction products detected using XRD are listed in Table 1 and these mainly comprised sulfate-bearing minerals such as thaumasite, ettringite and gypsum. Gypsum would be the only sulfate mineral likely to be detected in any adhering clay.

XRD is particularly useful in differentiating between thaumasite, ettringite and mixed crystals of both [1]. This can be done by studying the position and number of peaks formed in the 15.7 to 16.0° 2θ region of the XRD trace. Four such traces are shown in Fig. 1. These were used to investigate the effect of aggregate type on reaction product composition and will be discussed in a later section.

Calcite is the only non-sulfate mineral listed in Table 1. It can form as a reaction product of carbonation or popcorn calcite deposition (see later) but its presence can also be attributed to carbonate grains within either aggregate or clay.

Coring of selective specimens for chemical and microscopical analysis

On their return to BRE, the 19 cast-in-situ cubes selected for chemical analysis and microscopical examination were cored using a 100mm diameter cutting tube. The concrete cores were taken horizontally through the centres of the 250x250x250mm specimens. The two exposed faces on the cores represented the two side faces, which had been exposed to either the in-situ clay or backfill clay on site. Due to the highly friable nature of some of these surfaces, selected samples were resin-impregnated prior to the coring in order to keep all the friable concrete and clay materials intact.

On receipt of the cores in the BRE Microscopy Unit, they were dried at 40°C for 24 hours. The cores were then placed on their sides within containers and the lower halves were impregnated with a low viscosity epoxy resin containing a blue dye. The half-impregnated core samples were then cut along their length so that the impregnated and non-impregnated halves were separated. The non-impregnated halves were further cut into a series of 7mm thick slices running parallel to the outer surfaces of the core and these were analysed for total sulfate content.

The resin-impregnated halves of the cores were lapped to produce flat surfaces, which incorporated the two original outer side faces of the cubes and any attached materials. These lapped surfaces were then made into standard 30 micron thin sections covered with temporary glass slips. The specimens were then ready for examination in transmitted light using a polarizing microscope and, if required, by the scanning electron microscope (SEM) at a later stage.

Total sulfate determinations

The five sub-samples for each of the 19 specimens comprised:

- the outer 0 to 7mm portion of concrete adjacent to the in-situ clay side face
- the adjoining portion of concrete 7 to 14mm from the in-situ clay side face
- the outer 0 to 7mm portion of concrete adjacent to the backfill clay side face
- the adjoining portion of concrete 7 to 14mm from the backfill clay side face
- a central portion of concrete equidistant from the two side faces

This technique was chosen in order to assess how much sulfate had penetrated into the surfaces of the concretes over the three-year period they were exposed to sulfate-bearing groundwater. The methods used will be discussed in more detail in a later section.

Sulfate level determinations have always been the traditional method used by engineers/practitioners to establish whether or not a concrete or mortar is undergoing sulfate attack. Levels significantly greater than 4% SO_3 (4.8% SO_4^{2-}) by weight of binder have often been used to indicate the presence of potential sulfate attack. In the present study, the amount of sulfate in each binder type is already known and it ranges from 3.2% SO_3 (3.8% SO_4^{2-}) downwards. It can therefore be stated that if the sulfate level increases significantly above 3.8% SO_4^{2-} by weight of cement in the specimens examined (say > 6%), then sulfate attack can be diagnosed, providing there is also physical signs of deterioration.

Optical microscopy examinations

Optical or petrographic microscopy is a very valuable tool in the study of degradation processes such as the thaumasite form of sulfate attack (TSA) as it does not destroy the fabric of the concrete under examination. This means that as well as identifying reaction products formed, the technique can also record their mode and location of deposition within the degraded concrete. The observations made during the thin section examinations are presented in Table 1 and are discussed in the next section. The main degradation process identified in the current study is the thaumasite form of sulfate attack (TSA). An accompanying reaction, known as popcorn calcite deposition (PCD), which as yet is not fully understood, has also been identified.

a) TSA

Four distinct zones of TSA have been well documented in the literature [1,6]. These range from innocuous Zone 1 TSA, in which thaumasite occupies areas of pre-existing voidage to Zone 4, in which the cement paste matrix is completely transformed into thaumasite mush. In addition, three main types of thaumasite were identified under the microscope, a colourless, low birefringence variety, a yellow, higher birefringence variety and a variety somewhere between the two. Whilst examining the thin sections, it became apparent that the more yellow colouration was found in thaumasite deposition closest to the clay interface.

b) PCD

An increasing amount of 'Popcorn Calcite Deposition' (PCD) has been identified in deteriorated concretes over the last few years [7]. It comprises coarse crystals of calcite and, like thaumasite, it does not possess any binding properties. It forms under wet conditions in areas of a deteriorated concrete previously occupied by cement paste. It can be regarded as the final degradation process associated with TSA. PCD occurs as the pH of the cement pore fluid drops from around 10.5 towards 7 and it has also been linked to the presence of available bicarbonate ions in surrounding groundwater.

Scanning Electron Microscopy (SEM)

A CamScan scanning electron microscope (15kV beam energy, $5x10^{-10}$ amp beam current) and its microanalytical capability Energy Dispersive X-ray Spectroscopy (EDX) was used for two purposes:

- To establish the level of sulfates in the surface layers of six selected concrete specimens
- To obtain the chemical composition of the sulfate-bearing phases present within the surfaces of two selected concrete specimens.

More analytical details are provided in a later section.

DISCUSSION OF THREE-YEAR ASSESSMENT

Cast-in-situ versus precast - same composition

When a particular concrete mixture exhibited TSA, the air-cured faces of the precast cubes invariably performed better than their cast-in-situ counterparts. This confirms that an initial air-cure is beneficial in protecting buried concrete from any form of sulfate attack.

Cast-in-situ concrete cubes made with portland cement

a) PC concretes containing all-in siliceous aggregate

Deleterious TSA was not found in the faces of the siliceous aggregate concretes containing either PC (7% C_3A) or SRPC. It was found up to a depth of 1mm on the side faces of the PC (10% C_3A) main mixture and was definitely found up to a depth of 8mm on the top corner of this specimen. In fact, TSA was more prevalent along cube corners and edges. The faces, corners and edges of the two outlier specimens also showed evidence of deleterious TSA.

XRD analysis identified an ettringite/thaumasite mixed crystal as being the main reaction product present. This can be seen from the positions of the XRD peaks depicted in blue in Fig. 1, which are equidistant from the 15.78º 2θ reflection for ettringite and the 16.00º 2θ reflection for thaumasite. Under the microscope, the ettringite/thaumasite mixed phase is indistinguishable from thaumasite; it does not resemble ettringite in any way. The mixed crystal can be seen gradually replacing the cement paste matrix and TSA progression through Zone 1 to Zone 4 can be clearly seen. Conventional sulfate attack has not been observed. The ettringite/thaumasite mixed crystal preferentially forms around carbonate particles in the fine aggregate indicating that these particles contribute in part to the supply of carbonate ions needed to form thaumasite. Interestingly, this halo thaumasite (Fig. 2) is a higher birefringence variety compared with that which precipitates in microcracks and elsewhere in the paste. Why two seemingly different types of thaumasite should be observed under the optical microscope when only one distinct phase has been identified using XRD remains unresolved.

Substantial gypsum and minor amounts of ettringite have also been observed lining surface air voids and adhesion cracks. Popcorn Calcite Deposition (PCD) was identified in most of the siliceous aggregate PC concretes. The initial impression gained was that it appeared to be associated with areas of significant thaumasite deposition but on closer inspection, it was found to occur in areas where only Zone 1 TSA had been detected.

b) PC concretes containing all-in Magnesian limestone aggregate

Deleterious TSA was identified in the exposed surfaces of all five PC concretes containing a Magnesian coarse and fine aggregate. There is definitely more 'face' attack than in the siliceous aggregate PC concretes and the depth of attack was greater in all cases (see Table 1). The depth of attack in the SRPC concretes were comparable with that observed in the other two PC concretes with higher C_3A contents.

Under the microscope, the two distinct birefringence colours of thaumasite are again noticeable. Also, the yellow colouration of the thaumasite under plane polarised light deepens towards the concrete/clay interface. Typical consumption of the cement paste and Magnesian limestone aggregate particles have been observed, in which thaumasite is mostly present as Zone 2 to Zone 4 deposition with little evidence of Zone 1. A single phase of thaumasite was identified by XRD. Its crystalline structure is very close to that of pure thaumasite as shown in Fig. 1.

Cast-in-situ concrete cubes made with PLC and all aggregate types

Deleterious TSA was identified in the exposed surfaces of all eight PLC concretes irrespective of aggregate type and concrete quality. Zones 1 and 4 were more prevalent than Zones 2 and 3. Optical microscopy studies have shown there to be a sharp degradation front between the attacked and the sound concrete. Neither ettringite nor gypsum have been identified as void-fill. Out of all the cubes investigated during this field trial, the outlier specimen comprising PLC and Magnesian limestone aggregate was the most severely attacked (Table 1) and Fig. 4.

XRD analysis has shown that two reaction products tend to form in concretes containing PLC and these are a thaumasite-like phase and lesser quantities of an ettringite-like phase. PCD was identified within some Zone 4 TSA locations but only in the concretes containing siliceous aggregate.

Cast-in-situ concrete cubes made with 30%fly ash/70%PC and all aggregate types

None of the concretes made with 30% fly ash/70% PC show any evidence of deterioration. However, the level of sulfates in the surface layers is much higher than in the bulk of the specimens. This phenomenon was found in other unattacked concretes and is discussed in more detail in a later section.

Under the microscope, some minor Zone 1 TSA was identified but this was insignificant in terms of deleterious TSA. Some secondary ettringite was also found precipitating in voids. PCD was identified in the concrete specimens containing siliceous aggregate. This points to the fact that PCD can form in the absence of TSA.

Cast-in-situ concrete cubes made with 70%ggbs/30%PC and all aggregate types

A small amount of attack (up to 1mm deep in places on three faces) was identified in the 70%ggbs concrete containing a mixed aggregate of Magnesian limestone and Carboniferous limestone. XRD analysis found that this was due to the presence of gypsum and not thaumasite. Thaumasite was found in the surface of some of the cubes but only as a non-deleterious void filling (Zone 1). Secondary ettringite was also observed in some of the surface air voids. Small pockets of PCD were observed in the surface of the 70%ggbs cube containing siliceous aggregate. This has occurred in the absence of deleterious TSA.

Cast-in-situ concrete cubes made with remaining binders and Magnesian limestone aggregate

There is no evidence of deleterious TSA occurring in any of these three concrete specimens although a significant build-up of sulfates was discovered in the outermost surfaces of the concretes made with BRECEM and microsilica (see later section). Minor amounts of thaumasite were observed under the microscope but only as Zone 1 TSA. A few air voids and adhesion cracks were also lined with gypsum and ettringite.

Other trends found in concretes, which have undergone TSA

Overall, the outlier mixtures with a binder content of 290 kg/m^3 and water/binder ratio of 0.75 did not perform as well as equivalent main mixtures with 320 kg/m^3 binder content and 0.55 water/binder ratio. Where attack occurred, the side face in contact with in-situ clay either showed a greater depth of attack than the backfill clay side face or the amount of attack between the two faces was similar. This was contrary to what had originally been expected as it had been thought that the freer movement of groundwater associated with less well-compacted backfilled clay would have increased the rate of attack. The principle reasons for this not being the case are probably a) the lesser average amount of sulfate in the clay used to backfill around the concrete specimens and b) the fact that the in-situ clay at concrete specimen level had a blocky open-fissured structure that provided relatively free movement to groundwater.

Results from total sulfate determinations

Total sulfate determinations were carried out on 19 selected specimens. The results from these chemical analyses have been puzzling. Table 1 contains two lists of results:

- The average level of sulfate by weight of binder found in the first 7mm of surface material for each specimen type investigated
- The background level of sulfate found within the bulk of the same concretes.

It can be seen that in all cases the level of sulfate is higher in the surface of the concretes than in the central part of the specimens. This is irrespective of whether or not the concrete has deteriorated as a result of sulfate attack.

The initial analyses were carried out using a LECO carbon/sulfur analyser. After the discovery of high sulfates in unattacked specimens, sulfate determinations were repeated using a gravimetric technique based on the BS1881 method [8]. This confirmed the original findings and further corroboration was obtained on six selected samples using the microanalytical capability of the Scanning Electron Microscope. Table 1 shows that there are two concrete types which contain lower, almost normal levels of sulfates in their surface layers and these contain either 70%ggbs/30%PC or a metakaolin cement. In these two cases the concretes must have been impermeable enough to prevent the penetration of significant external sulfates. However, in the other visually unattacked concretes made with SRPC (with siliceous aggregate), 30%fly ash/70%PC, 40%ggbs/60%PC, BRECEM and microsilica cement, sulfates must have penetrated but have not reacted detrimentally with the cement paste phases. Work was carried out to identify the sulfate-bearing species within the surface cement paste and the subsequent results are discussed in the following section.

Investigations to identify the sulfate-bearing phases present in the unattacked concrete surfaces

In order to identify the sulfate-bearing phase or phases present within the surfaces of the unattacked concretes, two of the field trial specimens (one physically attacked, one not) were investigated further using a combination of SEM and XRD. The two cast-in-situ cubes selected were:

- 'Main' mixture concrete containing 30%fly ash/70%PC and a Magnesian limestone aggregate with a 320 kg/m^3 binder content and a free water/binder ratio of about 0.55. Only the side face, which had been exposed to backfill clay whilst buried was examined. The condition of the surface of the concrete was sound after three years exposure to Class 3 sulfates as shown in Fig. 3. However, there is a build-up of sulfates in the surface 7mm of the concrete, corresponding to 11.1% SO_4^{2-} by weight of binder as shown in Table 1.
- 'Outlier' mixture concrete containing PLC and a Magnesian limestone aggregate with a 290 kg/m^3 binder content and a free water/binder ratio of about 0.75. Only the side face, which had been exposed to in-situ clay whilst buried was examined. The surface of the concrete had deteriorated as a result of TSA up to a maximum depth of 20mm as shown in Fig. 4. The level of sulfates in the outermost 7mm of the concrete material was determined to be 16.3% SO_4^{2-} by weight of binder as shown in Table 1.

The thin sections already made and examined under the optical microscope were polished further, coated with carbon and re-examined using SEM and EDX. A back scattered electron image was taken for each of the samples examined and these are shown in Figs. 5 and 6. Ten separate spot analyses for CaO, SiO_2, Al_2O_3, SO_4, Na_2O, K_2O, MgO and total iron as Fe_2O_3 were then collected at depths of 0.2, 1, 2, 6, 10 and 20mm in from the concrete surfaces of each specimen. Only the concentrations of CaO, Al_2O_3, SiO_2, and SO_4^{2-} are reported in this paper; the values for Na_2O and K_2O being consistently below 0.5%, for Fe_2O_3 below 5% and for MgO varying depending on closeness to aggregate fragments. Accurate quantitative analysis of CO_2 and H_2O is not possible using this technique. Three distinct sulfate-bearing phases were identified; one in the 30%fly ash/70%PC concrete (Fig. 5,A) and two in the PLC concrete (Fig. 6, B and C). The phase in the fly ash concrete can easily be seen forming as high relief, cracked features evenly distributed throughout the cement paste. A high relief, cracked phase has also been identified in the PLC concrete but it is less abundant with sulfates tending to be in the low relief, highly porous background material.

An average composition was determined for these three phases and these are shown in Table 2. It can be seen from this table that the percentage total counts collected by the SEM detector varies enormously from 18% for the low relief background material up to 78% for the high relief phase seen in the fly ash concrete. There could be a number of reasons for this difference but optical microscopy studies suggest that the high capillary porosity seen in the background material could be a major factor resulting in the low detection rates.

The oxide compositions for ettringite, thaumasite and gypsum are shown in Table 3 and as both ettringite and thaumasite contain roughly 27% CaO, a third table (Table 4) has been constructed, in which the oxide concentrations from Table 2 have been normalised to 27% CaO. It can be seen from Table 4 that the high relief, cracked areas found in both specimens contain more Al_2O_3 than SiO_2 and an approximate sulfate content of 17 -18%, which is closer to that of ettringite than thaumasite. On the other hand, the non-cracked background material in the PLC concrete contains more SiO_2 than Al_2O_3 and has a lower sulfate content of 14.4%, more indicative of thaumasite.

In order to find out more about these phases, a representative sample from the outermost 7mm of both concretes was analysed using XRD and the resultant traces are shown in Fig. 7. It can be clearly seen that the high relief, cracked phase found in the surface of the fly ash concrete is in fact amorphous, as signified by the absence of sulfate-bearing mineral diffraction peaks. Under the optical microscope, these amorphous inclusions are indistinguishable from the general isotropic cement paste phases. It may follow that the similarly cracked areas in the PLC concrete may also be amorphous but the background material certainly is not. Both XRD (Fig. 8) and optical microscopy studies have identified the background phase to be a highly porous and expansive mesh of thaumasite-like crystals with a structure, and to a lesser extent composition, closer to that of pure thaumasite than pure ettringite.

The values with depth for weight % SO_3^{2-} of total counts are presented in Table 5. It can be seen that there is a high concentration of sulfate in the outer 4mm of the fly ash specimen, which drops to the background level at a depth of about 6mm. Sulfates have penetrated farther in the case of the PLC cube, reaching a depth of over 10mm before achieving background levels.

It is very interesting that the build-up of sulfates in one concrete within clusters of amorphous material has been non-destructive whereas a comparable degree of sulfate build-up forming thaumasite has lead to severe deterioration in the other. Similar findings were found in 1992 during the chemical analysis of field trial specimens excavated from Northwick Park, when it was quoted by Harrison [9] that "It would follow that when the analysis of a concrete reveals a high sulfate content this does not necessarily indicate any deterioration although conversely, loss of strength or visible deterioration accompanied by a high sulfate content would be evidence of sulfate attack." These unusual findings must cast doubt on the use of sulfate determinations as the principle technique for diagnosing sulfate attack in the field. In order to diagnose sulfate attack correctly, the concrete in question must show physical signs of damage in addition to a high sulfate content. This may work well in many instances but problems will arise when:

- the condition of the concrete is not adequately recorded on site
- the concrete is sent to a materials analyst who has had no input into the site investigation or sample collection

CONCLUSIONS

The BRE Shipston field trial has proven to be very successful. The findings to date have indicated that a timescale of three years is sufficient to differentiate between TSA-resistant concrete mixtures and mixtures, which are susceptible. Unfortunately, the concrete mixture proportions do not comply with the new UK recommendations [5] but they probably relate to a significant percentage of the foundation concrete currently buried in the ground. The conclusions from the physical, chemical and mineralogical assessments of the field trial specimens, which have been exposed to Class 3 sulfate conditions for three years are summarised below.

- Even after the relatively short period of exposure to Class 3 sulfates on site, the surfaces of many of the test specimens were covered with a white-coloured reaction product. X-ray diffraction analysis and microscopic studies have shown this reaction