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Laboratory study of the long-term durability of buried concrete exposed to Lower Lias Clay

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HIGHLIGHTS

- The aggressivity of Lower Lias Clay can result in severe concrete deterioration.
- The study affirms the susceptibility of both 25% PFA concrete and SRPC concretes to TSA.
- Bitumen coating was an effective barrier at preventing deterioration in all concretes even when the surface scratched.
- The amount of thaumasite formation was found to decreased significantly with increasing burial depth.

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ABSTRACT

This paper describes a long-term investigation into chemical degradation vulnerability of four different types of concrete that were exposed to pyrite rich clay. In this, four 100 mm square by 1.2 m long concrete columns made from Portland cement (PC), Portland limestone cement (PLC), sulfate resisting Portland cement (SRPC) and Portland cement blended with 25% pulverised fuel ash (PC-PFA) were buried for 9 years in slightly weathered Lower Lias Clay of water soluble sulfate class DS-2. One face of each concrete column was coated with bitumen to test the performance of this method of protection. The temperature was controlled at 4.5 ± 0.5 °C using a cold water circulation system. The performance of the different concretes was assessed by means of visual observation supported by X-ray diffraction (XRD), Infra-red Scanning (IR) and Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDX) to identify the deterioration products.

It was found that deterioration due to the thaumasite form of sulfate attack occurred in all four concretes with PLC concrete being the worst affected. The thickness of thaumasite deterioration into the concretes over the 9-year exposure was as follows: PLC = 47; PC = 33; SRPC = 22 and PC-PFA = 10 mm. The study affirmed the susceptibility to Thaumasite Sulfate Attack (TSA) of both PC-25% PFA replacement and SRPC concretes. It was also found that, the amount of concrete deterioration decreased with increasing burial depth, which was probably due to reduced access to air. The bitumen coating, even if damaged, was an effective barrier at preventing deterioration in all concretes.

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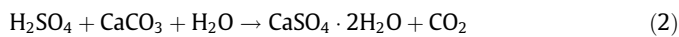
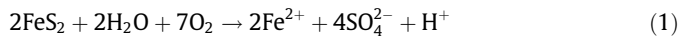
1. Introduction

Problems due to the thaumasite form of sulfate attack (TSA) in buried concretes have been extensively reported during the last 15 years with significant cases identified in the UK, USA, Canada, South Africa, France, Germany, Norway and Slovenia [1]. Due to the impact of sulfate attack on concrete durability and performance, TSA became a major concern in the UK, when in

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March 1998 it was discovered that many M5 motorway bridge substructures in Gloucestershire, UK were seriously compromised [2]. Further cases were reported in buried concrete elsewhere in southern England, including the M4 in Gloucestershire, Somerset and Wiltshire, and in County Durham in the north-east of England [3]. All of the affected concretes were in contact with a large volume of pyritic clay/mudstone backfill. It was postulated that oxidation of pyrite present in excavated material following atmospheric exposure prior to backfilling led to the formation of sulfate and sulfuric acid, which as illustrated by Eqs. (1) and (2) would result in raised acidity and sulfate levels in the ground water [4].



The presence of calcium carbonate (calcite) in the clay provides a means for the acid to be neutralized in Eq. (2), with the sulfate precipitation as gypsum, but the solubility of gypsum is about 1.4 g/l of water so the ground water will remain sulfate rich. Floyd et al. [4] point out that due to reactions with clay minerals, the ground water may also contain aluminum, potassium, magnesium ions, which can result in a range of reaction products as well as the formation of iron hydroxide and carbon dioxide.

In the case of the M5 bridge foundations, the concrete was affected due to the presence in particular of pyrite in the locally sourced Lower Lias Clay that was used as fill around the cast in situ concrete foundations [5]. Longworth [6] and others have reported that reactive forms of pyrite, such as the framboidal form, will oxidize rapidly when given access to oxygen and water.

Thaumasite, which can be represented as $\text{CaSiO}_3 \cdot \text{CaSO}_4 \cdot \text{CaCO}_3 \cdot 15\text{H}_2\text{O}$, requires sources of calcium, sulfate, carbonate, excess water and a temperature of below 15 °C to form [7]. Factors that may affect the initiation of thaumasite formation in buried concrete, in addition to the chemistry of pore water and the permeability of concrete, may include type and quantity of cement used in concrete, change to the ground chemistry and depth and geometry of the buried concrete [2]. TSA has a significant influence on the durability of concrete not least because the formation of thaumasite is usually accompanied by loss of strength and bond between the cement paste and the aggregate particles [8].

Since the late 1990s, there have been many attempts to investigate the performance of different cement binders, such as Portland cement, sulfate resisting Portland cement, and blended cements including silica fume, pulverized fuel ash and ground granulated blast furnace slag [8–16]. It appears that there is uncertainty about the performance of SRPC and PFA blended concrete in this respect, as some researchers [8,17,18] found them to be susceptible to TSA while others [19,20] reported good performance which they attributed to such factors as a reduced Ca:Si ratio in concrete made with PFA. Crammond et al. [17] reported that SRPC cast-in situ concretes containing siliceous aggregates had performed satisfactorily against TSA. The same work reported on field trials at Shipston on Stour in Gloucestershire, UK in which the effects on TSA resistance of water/binder ratio (0.53–0.75) and binder types were investigated. It was found that while concrete deterioration depended particularly on concrete quality, it was also influenced by binder composition with PC blended with ground granulated blast furnace slag mixes showing higher resistances to TSA.

It seems that there are very few published investigations concerned with the interaction between pyritic ground and concrete [4,17,21]. Most reported investigations into the performance of different binders were conducted by exposing samples to sulfate solutions, rather than to pyritic ground conditions. In fact no studies in which the long-term performance of different binders exposed to pyrite bearing soils were found despite an extensive literature review being performed. The study described in this paper was designed to address this deficiency, by assessing the performance over a 9-year period of concrete columns made with four types of binder that were designed to comply with BRE SD-1, 2001 [22] recommendations in terms of water to cement ratio and binder type. Such concretes might be designed for exposure to water soluble sulfate DS-2 Lower Lias Clay conditions. The influence of bitumen coating to prevent concrete deterioration was also investigated. The performance of the concretes was assessed by means of visual observations and measurements of the distance to which deterioration advanced into the concrete the thickness

of concrete deterioration, together with X-ray Diffraction (XRD), Infra-red Scanning (IR) and Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDX) to identify the deterioration products.

2. Experimental work

2.1. Cementitious binders and concrete mixes

Concrete mixes were prepared using Portland cement (PC), Portland limestone cement containing 20% limestone filler (PLC), sulfate resisting Portland cement (SRPC) and PC blended with 25% PFA (PC-PFA). A water/binder ratio of 0.45 was used in all mixes and siliceous aggregates were used for both the coarse and fine fractions.

2.2. Lower Lias Clay

Partly weathered Lower Lias Clay obtained in May 2002 from Moreton Valence, Gloucestershire, UK was used to simulate the ground conditions. The clay contained 1.00% sulfur and its sulfate class conformed to DS-4 according to the current BRE SD1 [23] classification. The amounts of water and acid soluble sulfate and total sulfur prior to interaction with concretes are listed in Table 1 together with the BRE specification for sulfate design class. The water soluble cations and anions together with the carbonate content and pH are shown in Table 2.

2.3. Specimen preparation and exposure

Four separate 100 mm square by 1.2 m long prisms were cast using the four mixes mentioned above. These were removed from the casting moulds after 18 h, and then placed in a mist room at 95% RH and 21 °C for 28 days to cure. After curing, one face of each was coated with one layer of bitumen as shown in Fig. 1(a and b). The prisms were assembled to form a column that was then buried in the slightly weathered Lower Lias Clay. Thus each concrete specimen exposed two faces to clay one of which was bitumen coated.

To simulate damage that might occur during construction, in some places the bitumen coating was scratched with a blade to expose the underlying concrete. The initial moisture content of the clay was between 20% and 35% and it was compacted in layers to a density of approximately 1960 kg/m³. Open ended 2 mm diameter piezometer tubes were placed at various depths in the clay, as illustrated in Fig. 1(c). These were later used to extract samples of the pore water from within the body of the clay sample.

The clay, together with the concrete columns were confined in a permeable cylindrical jacket as shown in Fig. 1(c), and the whole assembly was placed in a tank containing water to the same height of the clay and maintained at a temperature of 4.5 ± 0.5 °C. This temperature was chosen to create optimum conditions for the formation of thaumasite to accelerate the deterioration processes. It should mention that the clay was probably not fully saturated as some pores in the clay would have contained air.

2.4. Concrete testing

During the initial 12 months of the experiment, the top 200 mm of the specimens were examined and photographed after removing 100 mm layer of clay at 6 months and a further 100 mm at 12 months [24]. The experiment was run for a further 8 years when it was entirely dismantled and the observations and testing described below were carried out. The results of visual assessment and chemical changes in the clay at 12 months were reported by Byars et al. [24].

2.4.1. Visual and physical observations

Specimen deterioration was visually assessed for signs of blistering, cracking, softening, spalling, loss of corners or edges, loss of aggregate and the presence of any precipitated minerals. Evidence of damage, discolouration or loosened or weakened concrete was photographed at different burial depths, namely burial depth 1 (200–300 mm), burial depth 2 (300–600 mm) and burial depth 3 (600–900 mm). The thickness of deteriorated material was measured using a modified hand-held penetrometer which, as shown in Fig. 2, was equipped with a thick rigid steel needle attached to the plunger. Measurements were taken immediately after the concrete specimens had been removed from the clay, before any loss of moisture. A force equivalent to a pressure reading of 3 kPa on the penetrometer scale was found to be sufficient to enable penetration of the probe through the full thickness of softened and deteriorated material without piercing the underlying sound concrete. The measurements were the average of a minimum of 5 measurements in each 100 mm length of column at different burial depths for all columns. The deterioration thickness reported here refers to the thickness of deterioration into the concrete from the original specimen surface. The un-attacked edge of the prism was used as a reference.

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