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The occurrence of thaumasite in modern construction – a review

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Abstract

This paper provides a review of the reported cases of deterioration in modern construction, where the formation of the sulfate-bearing mineral thaumasite has been identified. The formation of thaumasite can cause varying degrees of deterioration within a wide variety of building systems including lime–gypsum plasters, exposed sulfate-bearing brickwork, concrete foundations and floor slabs exposed to sulfate-bearing ground, concrete roads and sub-bases, sewer pipes, tunnel linings and old blastfurnace slags used as landfill.

In Spring 1998, the thaumasite form of sulfate attack was found in the foundation concrete of 10 motorway bridges in Gloucestershire, western England. As a result, the UK Government convened the Thaumasite Expert Group (TEG), who were commissioned to prepare a Report 'The thaumasite form of sulfate attack: Risks, diagnosis, remedial works and guidance on new construction' [Thaumasite Expert Group, The thaumasite form of sulfate attack: Risks, diagnosis, remedial works and guidance on new construction, DETR, London, 1999]. This paper was one of the references used in the preparation of the TEG Report, which was published in January 1999.

Deterioration as a result of the formation of thaumasite has become recognised as a separate form of sulfate attack, which has the potential to affect a wide variety of components and a range of building materials. The full extent of the problem is still unknown. There are two distinct ways in which thaumasite can precipitate as a reaction product, especially within concretes and mortars. These have been termed the thaumasite form of sulfate attack (TSA) and thaumasite formation (TF) by the Thaumasite Expert Group. TSA refers to cases where there is significant damage to the matrix of a concrete or mortar as a consequence of replacement of cement hydrates by thaumasite. TF, on the other hand, refers to incidences where thaumasite can be found in pre-existing voids and cracks without necessarily causing deterioration of the host concrete or mortar. In relation to the current paper, it was not always easy to identify retrospectively whether the occurrence of thaumasite in the reported field cases was associated with TSA or TF. Distinctions were therefore only made when it was possible to do so.

The references reviewed in this paper span a time period of over thirty years and some of these, especially the more recent UK cases, prompted the TEG to provide new interim recommendations in order to minimise the effect of TSA in new construction. However, in many of the remaining cases reported in the following paper, deterioration could have been avoided simply by following good practice of the period, either by the use of more suitable materials for given service conditions or by better workmanship on site.

Keywords: Thaumasite; Modern construction; Deterioration

1. Introduction

Sulfate attack in concretes and mortars is a well-known and documented problem. The minerals most commonly seen as a product of sulfate attack are gypsum ($CaSO_4 \cdot 2H_2O$) and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$). For a long time ettringite was regarded as the principal mineral responsible for expansion and deterioration occurring in concretes and mortars suffering from sulfate attack. However, over the last thirty years a third mineral has been increasingly found in cement-based materials which have been exposed to sulfates and this mineral is thaumasite. Thaumasite is a calcium silicate carbonate sulfate hydrate ($CaSiO_3 \cdot CaCO_3 \cdot CaSO_4 \cdot 15H_2O$) and can be found occurring alongside ettringite, gypsum or on its own. Thaumasite is structurally similar to ettringite and because of this, partial solid solution between the two minerals can occur resulting in ettringite/thaumasite mixed crystals. The increase in the number of detected

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cases of thaumasite in recent years is most probably due to the onset of more selective analytical and diagnostic techniques, which can differentiate between ettringite, thaumasite and mixed crystals of both.

The thaumasite form of sulfate attack is different from the conventional form because it is the calcium silicate hydrates (CSH) in the hardened Portland cements which are targeted for reaction and not the calcium aluminate hydrates. CSH is the main binding agent in all Portland cements including sulfate-resisting Portland cements (SRPC). The formation of thaumasite is therefore accompanied by a reduction in the binding ability of the cement in the hardened concrete, resulting in a loss of strength and transformation of the cement paste into a mushy, incohesive mass. The expansive disruption which is normally associated with sulfate attack sometimes accompanies the formation of thaumasite, but is not a characteristic feature.

For thaumasite to form in building products, all the components to comprise this mineral (sulfate ions, carbonate ions and calcium silicate or calcium silicate hydrate) must either be available in the materials themselves or transported to the reaction site by water. Carbonate ions are an additional ingredient needed to form thaumasite which are not required to form ettringite or gypsum. Carbon dioxide dissolved in the incoming water provides one source of carbonate ions. In recent years, however, the Building Research Establishment (BRE) have shown that a more prominent source of carbonate ions can be derived from limestone present within the building material itself as aggregate or filler. Therefore if a concrete or mortar containing limestone comes into contact with sulfated water, then all the components necessary for thaumasite formation are present and it is possible for deterioration to proceed at a rapid rate. The reaction relies on copious amounts of water and the rate of reaction is greatly increased at cold temperatures below 15 °C.

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Deterioration as a result of the formation of thaumasite has become recognised as a separate form of sulfate attack, which has the potential to affect a wide variety of components and a range of building materials. The full extent of the problem is still unknown. There are two distinct ways in which thaumasite can precipitate as a reaction product, especially within concretes and mortars. These have been termed the thaumasite form of sulfate attack (TSA) and thaumasite formation (TF) by the Thaumasite Expert Group. TSA refers to cases where there is significant damage to the matrix of a concrete or mortar as a consequence of replacement of cement hydrates by thaumasite. TSA-affected concrete turns into a soft, mushy mass with a distinctive white colouration. TF, on the other hand, refers to incidences where thaumasite can be found in pre-existing voids and cracks without necessarily causing deterioration of the host concrete or mortar.

This paper provides a review of the reported cases of deterioration in modern construction due to either TSA or degradation where TF has been identified. In many cases it has proved impossible to say which of the two processes was observed, so a distinction was only made in clear-cut cases. Because thaumasite contains ingredients commonly found in cement-based systems ($CaSiO_3$, $CaSO_4$, $CaCO_3$ and H_2O), its occurrence has been found in a wide variety of building materials, from gypsum-based plasters to structural concrete exposed to sulfate-bearing groundwaters. Thaumasite-related problems have also been encountered in historical buildings [1–5], especially when modern materials have been used for repair purposes, but the details of these have not been included in the following text.

2. First reported field cases of thaumasite in deteriorated building materials

The first workers to identify and report on the occurrence of thaumasite in cement-based components suffering from sulfate attack were Erlin and Stark [6]. Over a two year period in the 1960s they reported four separate cases of thaumasite-related deterioration in different parts of America: an 11-year-old concrete pavement (road), a cement grout taken from a salt mine and two cases of deterioration in sewer pipes. The first sewer pipe was 5 years old and thaumasite had occurred within calcite covered blisters on the inside surface of the pipe. The second sewer pipe was approximately 32 years old, where thaumasite was found together with ettringite, gypsum and traces of calcite. Approximately 10 years later a further case of deterioration as a result of the formation of thaumasite was found in a soil cement sub-base material after exposure to sulfate-rich groundwater [7]. The soil was composed of dolomitic limestone plus minor amounts of quartz and illitic clay.

Between 1971 and 1976, the French workers Lachaud et al. [8] reported 69 cases of expansion/deterioration in building materials and concluded that over half of these were due to the formation of the mineral thaumasite. Unfortunately, it has not been possible to say whether the reported cases occurred in real buildings or laboratory investigations.

3. Thaumasite in gypsum plaster systems

Some building systems seem more susceptible to the formation of thaumasite than others. One such example is the combination of either gypsum plaster with adhering render or lime/gypsum plasters with cement-based impurities. Combine either of these with water penetration and a cool temperature, and the interface between plaster/render or plaster/impurity has the perfect chemical environment for the rapid formation of thaumasite. In 1972, Fleurence [9] of the French Ceramic Society reported extensive thaumasite crystallisation within the interface of gypsum plaster and concrete. A similar finding, also in France, in the 1970s found that the bond failure between glazed wall tiles and underlying render was due to the almost complete conversion to thaumasite of the plaster/mortar adhesive interface [10]. Towards the end of the 1970s, Kollman et al. [11] carried out detailed research on the cause of severe deterioration of some lime–gypsum plasters. He concluded that the formation of ettringite and thaumasite nuclei was the cause of the deterioration.

Further studies by Bensted [12] in the UK showed that if a coat of masonry cement render was improperly covered with a coat of gypsum plaster under cold, wet conditions, blisters containing a mixture of ettringite and thaumasite formed within 8 weeks. Daniels [13] reported on a similar situation, which was investigated by the BRE Advisory Service. In this latter case, angle beading had been fixed to an external wall using gypsum plaster 'dabs'. This area was then rendered. The reaction at the interface between dab and render formed thaumasite and caused severe bulging of the external render at the corner of the property where the angle beading had been used.

In another BRE Advisory investigation, TSA was diagnosed as causing the formation of large blisters on a sports hall floor [14]. The reason for this was that thaumasite had formed at the interface of the anhydrite (calcium sulfate) screed and cement-based levelling compound, causing a loss of bond. The source of the moisture required to catalyse the reaction was attributed to the screed itself.

Problems encountered with thaumasite-related deterioration in plaster systems have largely been overcome in recent years. This has been accomplished by improving workmanship, reducing contamination of lime–gypsum plasters with silicate impurities and keeping conditions dry.

4. Thaumasite in brickwork

Another building system in which thaumasite has been shown to readily form is brickwork made from sulfate-bearing clay bricks (defined as 'N' category in BS 3921:1985 [15]).

Problems of spalling and cracking have recently been found by BRE [16] in exposed, rendered parapet walls on top of three prestigious buildings in the southeast of England. In all three cases, the walls had been constructed using 'N' category bricks and problems of drying shrinkage within the render coats had caused very small cracks to open up allowing water to penetrate to the brickwork substrate and to become trapped. Such wet conditions were ideal for sulfate attack. Within five years of application of the render, the walls had severely cracked and deteriorated as a result of TSA at the back of the render and within adjoining bedding mortar between the bricks. Similar problems had previously been identified by Crammond [17] in exposed buildings in South Wales.

A further case study investigated by BRE involved the deterioration of bedding mortar in 500 mm thick masonry retaining walls to underground garages supporting a housing estate in the southeast of England [18]. The retaining walls had been constructed using sulfate-bearing bricks and only started showing signs of distress 10 years after construction when the surrounding land drains became blocked and surface water was redirected through the walls instead. This water had drawn soluble sulfate salts to the surface of the walls where efflorescence and crypto-efflorescence had become a serious problem. Furthermore some of the soluble sulfates had reacted with the cement paste within some of the bedding mortar causing pockets of thaumasite-rich, soft, mushy material to form within the body of the walls. TSA had occurred in these pockets as the cement paste matrix had been completely replaced by thaumasite. There were two sources of carbonate ions available to form thaumasite and these were the small quantities of carbonate material within the mortar sand and carbon dioxide dissolved in the surface run-off water. As a result of the deterioration induced by sulfates, the damaged brickwork had to be replaced with concrete at a cost of three million pounds to the local housing authority.

TSA is not only associated with external exposure conditions, it has also been identified by BRE in the tiled, internal cubicle walls of a one-storey shower block, again in the southeast of England [16]. The walls to the shower cubicles had been constructed using sulfate-bearing bricks and had originally been plastered with gypsum plaster. At a later date, this plaster was removed and replaced with a 12 mm thick cement/sand render onto which ceramic tiles were laid. Over the 4–6 years after refurbishment, the render had become detached from the brickwork resulting in severe spalling of the tiled walls. Removal of the tiles and render revealed the presence of white mushy material, later identified as thaumasite, coating the back of the render, at the intersection with underlying brickwork. Water from the showers had slowly penetrated through fine cracks in the render and had fuelled the TSA. The deterioration process had been greatly accelerated in this case because the original gypsum plaster had not been thoroughly removed prior to renovation of the shower block.

Damage to brickwork as a result of TSA can be avoided by:

- Not using sulfate-bearing clay bricks in exposed or severely wet environments;
- Making sure that any external render coat is sufficiently waterproof;
- Making sure that any residual plaster is removed before re-rendering internal walls with sand/cement mortar.

In the UK, the above three recommendations are already included in current specification and best practice documents relating to masonry construction [19–21]. Future TSA problems relating to brickwork can therefore be avoided by following guidance, which is already in place.

5. Thaumasite in limestone aggregate concrete foundations

5.1. TSA in SRPC piles below a UK housing estate

In 1990, BRE investigated the cause of severe deterioration caused by TSA in in situ concrete foundation piles below a 4-year-old UK housing estate [22]. The piles had been exposed to the Lower Lias Clay and the groundwater flowing on the site was Class 3 (as defined in BRE Digest 363 [23]). Excessive amounts of this water had percolated through the tops of the piles, which had transformed into a white, pulpy mass. Analysis of the sound core of one of the piles showed it to comprise a good quality SRPC concrete containing oolitic limestone coarse and fine aggregate. The cement content was found to be in excess of 400 kg/m^3 and the w/c (water/cement) ratio was in the range 0.3–0.5. Examination of the deteriorated concrete showed that most of the hydrated cement paste and the finer limestone aggregate fraction had completely transformed into thaumasite. This was the first recorded case where deterioration due to sulfate attack had occurred in concrete foundations specifically designed to provide good sulfate resistance and, as a result, in 1996, a warning was included in a revised edition of Digest 363 [23].

Sound samples of the foundation concrete were exposed to various laboratory-prepared sulfate solutions at 5 °C and the deterioration was so extreme that after three years exposure, several of the samples had converted into a sludge which could literally be poured out of the sample container. These laboratory studies provided conclusive evidence that the carbonate ions needed for the formation of thaumasite were derived from the concrete itself.

5.2. TSA in foundations to Arctic buildings in Canada

In the early 1990s Bickley et al. [24] discovered severe deterioration caused by TSA in the reinforced concrete foundations of two buildings in the Canadian arctic. Expansion and premature loss of structural integrity had occurred to such an extent that some of the columns had to be replaced after a two-year service period. The concretes were exposed to the severe cold of the arctic and stood in ponded meltwater for two months of the year. The columns and slab were attacked by high levels of sulfates in the groundwater, resulting in the formation of thaumasite and gypsum. Ettringite was not found. The concrete contained dolomite and calcite as fine aggregate, which was considered by the authors to be the source of carbonate ions rather than atmospheric CO_2.

Repairs to the piers supporting one of the buildings was successfully carried out by jacketing them with steel-encased silica-fume grout [25]. The repair to the second building, involving polymer concrete, was unsuccessful at the first attempt and had to be repeated under stricter quality control.

5.3. TSA in strip foundations to domestic house in central England

A third foundation failure, the second in the UK, was investigated by BRE in 1994. This manifested itself in the form of a large subsidence crack in the garage wall to a 12-year-old detached house [26]. Trial pits were excavated below the defective garage wall exposing the strip foundations. The exposed concrete was found to be in a particularly poor condition throughout its whole profile and it was easily crumbled by hand. Examination of the foundations showed that they contained a Carboniferous limestone (dolomite and calcite) coarse aggregate and a Jurassic oolitic limestone fine aggregate. The concrete had been supplied ready-mixed on site and had been made using Portland cement (PC). The site had often become very wet. Tests on samples of the in situ Lower Lias Clay taken from the vicinity of the strip foundation indicated that the sulfate conditions were Class 2. Analysis of the groundwater, however, showed it to contain Class 3 sulfate levels. As groundwater determinations are considered more accurate, the sulfate ground conditions were classified as Class 3. A staged deterioration process was identified in the concrete foundations collected from below the garage wall and from foundations elsewhere around the property. Sulfates from the surrounding groundwater had penetrated the concrete, resulting initially in the formation of ettringite within empty pores within the concrete. This ettringite was gradually replaced by the growth of thaumasite. Thaumasite crystals not only occupied the pores but their growth spread into the surrounding cement paste matrix where they could eventually be found loosely cementing the sand grains together (TSA).

The serious subsidence cracking, which had led to the investigation, was caused by a combination of shrinkable clay on site and the very weak condition of the TSA-affected strip foundations.

5.4. TSA in the foundations to M5 motorway bridges in the west of England

In 1998, TSA was found by the engineering consultants, Halcrow Group, to be causing severe surface deterioration and expansion in the buried concrete foundations to several bridges on the M5 motorway in the Gloucestershire region of the west of England [1,27].

The bridges had been exposed to re-worked unweathered Lower Lias Clay for over 30 years. Excavation and stock piling of the sulfide-bearing unweathered clay prior to construction had resulted in rapid oxidation of pyrite (FeS_2). This generated sulfuric acid, which reacted with contained $CaCO_3$ to form sulfate-bearing compounds such as gypsum [1,28]. After construction, the newly oxidised clay was used as backfill around foundations to depths of up to 5 m. Much of the backfill was also below the level of motorway drainage and was therefore very wet. Consequently, the buried concrete, which had not necessarily been designed to be sulfate resistant, was exposed to clay and groundwater, now enriched in sulfates. Hobbs and Taylor [29] are of the opinion that it was primarily the action of sulfuric acid on the concrete, which initiated TSA at the ground/concrete interface. However, no evidence of acid ground or groundwater conditions has been found in oxidised clay backfill during extensive investigations at the M5 bridges [30].

On the whole, the bridge foundations had been built using high quality concrete with a low porosity and good compaction. Two detailed examples are as follows:

5.4.1. Tredington/Ashchurch bridge (south of junction 9 of M5)

TSA was found to be more advanced in the foundations to the three piers of this bridge than to any of the others investigated. These piers each comprised three slender columns, which extended 5 m below ground level to a supporting base slab. The concrete from the foundations comprised Portland cement (C_3A 11%) with a cement content of 370 kg/m^3 and a w/c ratio about 0.5. Good quality dolomitic coarse aggregate had been used along with oolitic limestone and quartz fine aggregate. The estimated cube strength of the unattacked concrete was found to be in excess of 60 MPa. TSA occurred in the lower parts of the slender foundation columns at a depth of to 5 m below ground, where the presence of mobile groundwater had ensured that conditions remained wet for long periods. Softening of the concrete as a result of TSA had started at the concrete/ground interface and had penetrated up to 50 mm into the body of the concrete. The softening was also accompanied by significant expansion. Four different stages of TSA were identified as follows with Zone 1 adjacent to unaffected concrete and Zone 4 at the concrete/clay interface:

Zone 1: No visual evidence of attack; occasional voids are lined with either ettringite or thaumasite.
Zone 2: Thin cracks lined with thaumasite appear running sub-parallel to the concrete surface. Little portlandite is observed in the paste and calcium carbonate sometimes lines cracks.
Zone 3: Sub-parallel, thaumasite-filled cracks become wider and the amount of unattacked cement paste is greatly reduced. Haloes of pure white thaumasite are observed around aggregate pieces. Little portlandite is observed in the paste and calcium carbonate sometimes lines cracks.
Zone 4: Transformation of cement paste to thaumasite is complete, all that remains is aggregate particles embedded in extremely soft white mush. Localised anaerobic corrosion occurred in isolated chloride-rich areas, where the depth of attack had penetrated through the concrete cover to the steel.

The three slender columns of each pier were completely removed during refurbishment of the bridge and were replaced with a more robust construction comprising much thicker sections of TSA-resisting concrete. Re-worked Lower Lias Clay was not used in the reconstruction.

5.4.2. Golden valley interchange (Junction 11 of M5)

In this second example, the damage to concrete was found to be more patchy in character, typically taking on the form of blisters approximately 100 mm across and extending to a maximum depth of 40 mm. The foundation concrete comprised sulfate-resisting Portland cement with a cement content of 370 kg/m^3 and a w/c ratio of about 0.5. Good quality limestone (mostly calcium carbonate with minor dolomite) coarse aggregate had been used along with quartz sand as the fine aggregate. The estimated cube strength of the unattacked concrete was approximately 60 MPa. The amount of deleterious TSA was found to be significantly reduced in this structure compared with that observed in the Tredington/Ashchurch Bridge. Apart from finding the above four zones, thaumasite was also observed forming in close association with gypsum. At the base of the foundations, the concrete was honeycombed and secondary crystals of ettringite were found lining most of the entrapped air voids.

The damaged TSA-affected surface concrete was removed and after patching, the columns were not reburied but were left exposed to the atmosphere.

6. Thaumasite in non-limestone aggregate concrete foundations

Over the last decade or so, six cases of surface deterioration of buried concretes containing aggregate, which had little or no carbonate component, have been identified in the UK by Geomaterials Research Services [31]. These cases include two concrete foundations and a road base exposed to sulfate-bearing London Clay, two instances of surface deterioration of concrete piles in the northwest of England and a bridge foundation in central England. Softening of the concrete surface to a depth of greater than 20 mm in places was accompanied by the formation of abundant thaumasite within voids and cracks and along aggregate surfaces. Thaumasite was also found replacing the cement paste in places (TSA). Precipitation of very coarsely crystalline secondary calcite on the surface and within the relict paste was also observed. The carbonate ions needed to form thaumasite and secondary calcite probably originated from a source other than the aggregate and the suggested source is the flowing groundwater containing carbonate or bi-carbonate ions. All the above cases appear to involve an excess of sodium and sulfate ions (for example in the form of de-icing salts). The precipitation of thaumasite followed by coarsely crystalline secondary calcite has been found in laboratory-stored cement-based samples exposed to alkali sulfates [32].

Deterioration has recently been found in the concrete foundations to a housing development in Southern California, USA [33,34]. The houses, which were approaching 10 years old, were built, into hillsides, so their foundations comprised retaining walls, foundation piers and stem walls. The adjacent hillside soils were derived from an ancient seabed, which contained significant quantities of sodium chloride, sodium sulfate and magnesium sulfate. The concrete had been made with USA-defined Type V cement (SRPC) but had a water/cement ratio of 0.65–0.70, resulting in an elevated paste porosity. A wide variety of efflorescence salts were routinely observed on the evaporating surface of the foundation concretes. However, the damage was not just superficial as many reaction products, in particular magnesium silicate hydrate, brucite ($Mg(OH)_2$), Friedel's salt ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$), sodium carbonate and thaumasite were found at depth within the concrete. Much of the cement paste had lost its integrity, mainly as a result of the removal of portlandite, de-calcification of the calcium silicate phases and the ultimate replacement of calcium with magnesium in many of the cementitious compounds. Thaumasite was observed as a minor constituent up to a depth of 40 mm and was present as small accumulations (order of 10 μm across) within the cement paste. It was also occasionally found in bands and thick deposits near the soil interface [34].

7. Thaumasite in tunnel systems

In 1975 Lukas [35] reported on the damage observed in a concrete tunnel lining (location and use not stated) due to sulfate attack. Destruction in some areas had turned the concrete into a plastic mass. Analysis by X-ray diffraction confirmed the end product to be thaumasite. In this case it was shown that thaumasite formation arose through a conversion process via ettringite. Ettringite was first formed from the reaction between sulfate-rich water and the calcium aluminates within the cement paste, and then converted to thaumasite by the addition of CaO, CO_2 and SiO_2. More recently Deloye et al. [36] identified sulfate attack in the jointing mortar of an old sandstone block-built railway tunnel in France where gypsum, ettringite and thaumasite were found. Also, Schwander and Stern [37] found thaumasite in the gunite lining to the Dettenberg rail tunnel in Switzerland. Between the years 1982 and 1986, concrete deterioration caused by the formation of thaumasite had been reported in many concrete structures in the northeast of Italy [38]. Four tunnels and one bridge had been severely damaged with the concrete cracking or transforming into a pulpy mass. In some of these cases, the sulfate and carbonate sources necessary to produce thaumasite had been found to be the concrete aggregate which was composed of dolomite contaminated with gypsum and/or anhydrite.

Another case of deterioration of a tunnel lining was reported by Baronio and Berra [39]. The concrete lining was in direct contact with the surrounding ground rock and the purpose of the tunnel was to carry a smaller diameter metal pipeline full of water from a dam in the Novara province of Italy to the local power station. The pipeline and the surrounding tunnel had been laid in the 1930s and in 1986, advanced deterioration was noticed in the concrete, with pieces as thick as the whole 300 mm lining breaking off. The deterioration seen was most probably a result of TSA and it was so severe that large areas had been transformed into a plastic mass. They found that pyrite in the rock surrounding the tunnel lining had oxidised forming water-soluble sulfates. These sulfates were then transported to the concrete lining by groundwater, which also contained large quantities of dissolved carbonate ions. The surrounding country rock was used as the concreting aggregate and it contained calcareous schists, another possible source of carbonate ions. The conclusion was that thaumasite had formed due to the low temperatures, very high humidity and presence of CO_3^{2-} and SO_4^{2-} ions dissolved in the groundwater. The absence of ettringite in the deteriorated concrete was due to it having been completely transformed to thaumasite.

A similar case was recently discovered in a stretch of the London Underground Northern Line near to Old Street Station [16,40]. Oxidation of iron pyrite in the surrounding sandy ground had generated very acidic, highly sulfate-bearing groundwaters. As there was insufficient calcium carbonate present in the ground to neutralise it, the acidic groundwater attacked the 90 year-old cement grout behind the cast iron tunnel linings. In some areas, the cast iron had been severely attacked and eroded by sulfuric acid. In other areas, where the grout layer was thicker, formation of thaumasite and gypsum within the grout had caused expansion and cracking of the cast iron tunnel linings. Limestone filler present within the cement grout had provided the source of carbonate ions required to form the thaumasite. London Underground Limited have since stripped out and replaced the defective tunnel linings.

Finally, the formation of thaumasite was found to varying degrees throughout the mortar in 100 year-old brickwork ‘cut and cover’ walls and floors to the Waterloo and City underground station and depot at Waterloo, London [41]. Precipitation of a layer of mixed crystals of thaumasite and ettringite (up to 3 mm thick) was identified along brick/mortar interfaces. The cement paste within the mortar adjacent to these zones contained pure white areas in which most of the unhydrated cement grains and all the hydrated cement had been replaced by thaumasite. Normally, this form of attack would be called TSA and this would have drastically decreased the strength of the brickwork walls and floors. However, in this case, the thaumasite-bearing mortar joints were found to be still reasonably robust and the compressive strengths of the masonry samples were satisfactory. This is the first identified case study, where TSA has not resulted in the disintegration of the affected building material, although the reason is still unclear.

8. Thaumasite in concrete floor slabs

Over the last 10 years, BRE has identified TSA in three domestic properties as the cause of damage to limestone aggregate concrete floor slabs resting on sulfate-bearing hardcore. The lack of an effective damp proof membrane enabled sulfate-bearing water to be drawn through the overlying slab by capillary action as water evaporated from its upper surface. The TSA typically caused expansion of the floor slab concrete. Due to edge restraint, this, in turn, caused the floor to heave and the walls to be pushed outwards.

In the first case study, a vertical crack was first noticed 20 years after construction on the outside of a gable wall to a 1965 semi-detached house in central England. Subsequent cracking of the gable wall occurred along with slight bulging. Cracking also occurred parallel to the gable wall across the whole width of the living room floor. It was found that the damage was due to expansion and heave of the concrete floor slab. This had been constructed on cinder and ash hardcore containing 1.2% sulfur as SO_4 (Class 2). Thaumasite and minor amounts of gypsum were detected by XRD within the severely deteriorated lower part of the floor slab. The poor concrete quality (PC cement content 6.7%) and leakage of water from a broken drainage pipe had encouraged the occurrence of TSA.

The second case study was a 22 year-old timber framed bungalow in the east of England. The expansion of the floor slab, constructed over sulfate-bearing furnace bottom ash, manifested itself as a 3% sideways bulging of the external brickwork base walls above ground below the damp proof course (dpc). The concrete comprising the lower portion of the floor slab had become severely de-laminated and friable. It contained thaumasite and lesser amounts of ettringite mixed as two distinct phases. TSA was diagnosed. The cement was a PC (cement content 9.4%), which contained 15.2% SO_4 by weight of cement and the coarse and fine aggregates were both oolitic limestone.

The third case study concerned a 1940s pre-fab Arcon steel framed bungalow in southwest England, which had been constructed on hardcore comprising sulfate-bearing cinders and bricks. A 50 mm vertical differential movement was discovered as a result of TSA in the severely cracked foundation raft. The top 40 mm of the raft was found to be still relatively sound between the cracks but the remaining 110 mm was extremely friable. Sodium sulfate was found precipitating as efflorescence on the top surface of the raft and copious amounts of both thaumasite and gypsum were discovered within the lower friable zone. The cement type was PC and its content was in the region 10–11%.

All three of these problems due to floor/raft heave could probably have been avoided through the application of an effective moisture barrier between hardcore and overlying concrete. Recent revisions of UK recommendations [23,42,43] have both advised against the use of high sulfate (Class 3 and above) hardcore, and stipulated the inclusion of such a barrier with hardcore of sulfate Class 2 and above, thereby effectively eliminating the threat of TSA-related heave problems in ground floor slabs.

9. Thaumasite in concretes affected by ASR or DEF

Thaumasite has been found, usually co-existing with secondary ettringite, within concretes damaged as a result of the alkali-silica reaction (ASR) [44]. Another example of thaumasite associated with ASR-affected concrete was found in the Les Cedras dam in Canada [45]. In this case thaumasite precipitation occurred along the interface between dolomitic aggregate and cement paste.

The occurrence of thaumasite has also been found in concretes suffering from delayed ettringite formation (DEF). This discovery was made by Sylla in Germany [46], whilst examining heat-treated precast concrete components such as steps, cooling tower supports, floor slabs, concrete piles and prestressed beams, which had cracked during service. Microanalysis of acicular crystals found in cracks and around aggregate particles revealed them to comprise either ettringite, thaumasite or mixed crystals of both. It was concluded that precipitation of such crystals had led to expansion within microcracks as well as to loss of strength of concrete due to decomposition of the strength-forming hydration products.

10. Thaumasite in old blastfurnace slags and sulfide-bearing aggregates

The sulfate ions required for sulfate attack can be generated through the oxidation of sulfides within aggregate sources or landfill. Wilson [47] reported on the composition of an old sulfur-rich slag heap in South Wales which had produced so much thaumasite through weathering that it was named the white tip. Crammond [16] also found a similar degradation process in which an old sulfide-bearing blastfurnace slag had weathered to form thaumasite. However, in this case the process occurred in the fill below a UK housing estate and had caused problems of severe heave in the overlying properties. Another incident involving sulfides, was investigated by Oberholster [48] who found that the use of a carbonaceous, sulfide-bearing slate aggregate in concrete floor slabs and in cement bricks was responsible for producing serious cracking in several two-year-old houses in South Africa. Oxidation of the sulfides had formed sulfates which were mobilised by groundwaters. Work carried out by Oberholster revealed the presence of a white, powdery deposit of thaumasite and calcite around aggregate grains.

Thaumasite-related problems caused by the use of aggregates or fill contaminated with sulfides or sulfates can generally be avoided in new construction by excluding the use of such material as imported fill and removing or isolating concrete from existing fill.

11. Thaumasite in roads and road sub-bases

Two examples of deterioration as a result of the formation of thaumasite in roads and road sub-bases have already been mentioned in Section 2 [6,7]. More recently, thaumasite was found filling air voids (TF) in parts of a 33-year-old concrete road in Ont., Canada [49]. Areas where thaumasite had formed were irregular and the cement paste in these areas had a light-coloured appearance. Although the source of sulfate ions is still unclear, the source of carbonate ions was most probably the dolomitic limestone coarse aggregate. A puzzling feature of this case was that an adjacent concrete road, built two years later with the same materials was apparently unaffected by the formation of thaumasite. Differing groundwater/drainage conditions could have been the explanation for this.

In 1989, lime stabilisation had been used during the construction of the sub-base to part of the M40 motorway near Banbury in central England [50]. The combination of lime, Lower Lias Clay containing up to 7.7% pyrite and groundwater caused the formation of, firstly ettringite, followed by thaumasite and gypsum. The resultant expansion of the ground produced up to 150 mm heave over one winter season. In the places where heave had occurred, the clay contained up to 2.8% gypsum, along with calcite and dolomite but no trace of pyrite was found.

12. Implications of finding thaumasite in modern construction

The identification of thaumasite in a deteriorated cement-based building material has to be carefully scrutinised before a proper diagnosis of the degradation mechanisms involved can be made.

Before a case of full-blown TSA can be diagnosed in a concrete or mortar, the cement paste matrix should have been transformed into a white mush composed of thaumasite, which loosely holds the surrounding aggregate particles together. Other visual signs include sub-parallel cracks filled with thaumasite and white haloes of thaumasite occurring around aggregate pieces.

The presence of thaumasite within a deteriorated concrete or mortar does not necessarily mean that it has played a role, major or otherwise, in the degradation process. Thaumasite can be found in concretes already damaged by another deterioration mechanism such as ASR, where it can occur in a non-destructive way (TF) by lining pre-existing pores and cracks.

Therefore, once thaumasite has been detected in a deteriorated cement-based building material, a decision has to be made about its overall role in the deterioration process. This will depend, among other things, on the quantity of thaumasite formed and the location of its crystallisation.

The thaumasite form of sulfate attack or TSA is by far the most damaging mechanism involving the occurrence of thaumasite in modern construction. It has been identified in good quality, buried limestone aggregate concretes exposed to sulfate-bearing groundwaters. The most prominent examples are the recent UK cases discussed in Section 5 of this paper. The fact that most of these buried concretes should have proved sulfate resistant, prompted the UK Government's Thaumasite Expert Group to provide new recommendations in order to minimise the effect of TSA in new construction [1]. The information contained in this paper also helped the TEG to come to the conclusion that 'overall, the number of UK structures potentially at risk of TSA is small and the structural consequences for properly maintained structures will rarely be of serious concern in respect of public safety'.

Many of the problems relating to finding thaumasite in sulfate-bearing brickwork, gypsum plaster systems, concretes or fills contaminated with sulfides or sulfates and ground floor slabs could have been avoided altogether. Deterioration would not have occurred had the good practice of the period been properly followed either by the use of more suitable materials for given service conditions, avoidance of water penetration through cementitious components or by better workmanship on site.

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