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Thaumasite sulfate attack in field and laboratory concretes: implications for specifications

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Abstract

The reported studies made on field elements affected by thaumasite sulfate attack are discussed, together with the reported laboratory performance of concrete and mortars immersed in sulfate solutions maintained at 5 °C. It is concluded that magnesium ions ingressing from groundwater or resulting from dedolomitization of an aggregate containing dolomite play a major role in increasing the risk of thaumasite attack and that attack can also arise from exposure to sulfuric acid bearing groundwaters, or sulfuric acid resulting from oxidation of pyrites within aggregates. Guidance is given on concrete qualities and materials to resist sulfate attack and thaumasite sulfate attack resulting from salts present in groundwater.

Keywords: Calcium hydroxide; Magnesium cation; Sulfuric acid; Calcium carbonate

1. Introduction

Thaumasite sulfate attack, is to the author's knowledge, a rare cause of concrete deterioration. It was first reported by Erlin and Stark in 1965 who observed thaumasite attack in sewer pipes and a concrete pavement [1]. In the UK, the buried elements of 27 30-year old M5 over-bridges in contact with a large volume of pyritic containing clay backfill have deteriorated due to thaumasite sulfate attack [2,3]. In 1999 a UK Expert Group issued a report dealing with thaumasite sulfate attack and gave recommendations for minimizing its occurrence in new construction [3]. In 2001 BRE published a Digest [4], in four parts, giving guidance on the constituents and qualities of concrete required to resist chemical attack, and specifically to resist thaumasite sulfate attack, based on the recommendations of the UK Expert Group. In making their recommendations the UK Expert Group were aware that no data existed on the pH, cation and sulfate ion concentrations in the groundwater within the backfill during the early life of the bridge foundations, and that it had not been established in the laboratory sulfate exposure tests on which their recommendations were largely based, that the deterioration within the laboratory samples was similar to that observed in the affected field elements.

In this paper the observations made on field elements affected by thaumasite sulfate attack are discussed, together with the observed performance of concretes and mortars immersed in sulfate solutions maintained at 5 °C. Guidance is given on concrete qualities and materials to minimize sulfate attack and thaumasite sulfate attack.

2. Field cases

2.1. USA

In 1965, Erlin and Stark [1] reported on the occurrence of thaumasite in two sanitary sewer pipes and at the base of a core taken from an 11-year old pavement. In the affected regions of the sewer pipes thaumasite was associated with calcite, gypsum and brucite. A chemical analysis of material filling a blister, including aggregate, gave 11.3% sulfate. One pipe was severely deteriorated to a depth of about 12 mm beneath which there were deposits of thaumasite, ettringite, gypsum and traces of calcite.

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2.2. Canada

In 1992, Bickley et al. [5] reported on thaumasite sulfate attack in 4-year old concrete in the Polar Continental Shelf Project facilities at Resolute Bay in the Canadian Arctic. The gravel used contained dolomite, calcite and quartz. Columns at the Arctic site were severely distressed at ground level and the authors considered that it was 'likely that the initially placed concrete was not able to cure sufficiently before being subjected to a combination of freezing temperatures at night and aggressive sulfate/carbonate rich water from the partially thawed surrounding terrain'. In a subsequent paper [6] they concluded that the adhering moisture in the soil samples could present the most severe sulfate exposure conditions for concrete. Paste concentrates prepared from severely distressed parts of the columns showed extensive amounts of gypsum, thaumasite, calcite and quartz and an absence of calcium-silicate-hydrate, portlandite and ettringite. The sulfate contents of the paste concentrates were in the range 22.0–26.4% as SO_4 by mass.

2.3. South Africa

In 1983, Oberholster et al. [7] reported on the occurrence of thaumasite in concrete blocks containing a black carbonaceous shale within which there was a high content of disseminated fine pyrrhotite, pyrite and chalcopyrite giving a sulfur content of 1.44% by mass and a potential SO_4 of 4.3% by mass. Extensive random cracking was apparent in the rendering of external walls. Wide vertical cracks in the lower portions of the external walls were attributed to expansion of the floor slabs, which also contained black shale as aggregate. Thaumasite was observed around the aggregate particles and throughout the mortar. The authors attributed the thaumasite attack to the oxidation of pyrites with the sulfuric acid formed reacting with calcite in the aggregate and the cement hydration products to form gypsum. The gypsum then reacts with calcite and calcium silicate hydrates to form thaumasite [6].

2.4. Italy

In 1987 Berra and Baronio [8] reported on the occurrence of thaumasite in a 40-year old concrete lining affected, in their view, by compounds resulting from oxidation of pyrites in the surrounding rock. The groundwater was not particularly aggressive—about 260 mg SO_4/l, 10 mg Mg/l, 63 mg CO_2/l and pH 6.5. It is believed that the excavated rock was used as the aggregate [8], so oxidation of pyrites within the aggregate could have been a major contributor to the thaumasite attack. Tests on the sound concrete gave a MgO content of 1.82% by mass of concrete indicating that dolomite was present. The authors note [8] that 'The concrete lining was badly damaged over wide areas', 'with the concrete reduced to a white plastic mass with pieces as thick as the whole concrete lining (300 mm)'. In the affected regions, tests showed that thaumasite and calcite were present and that ettringite was absent. Since no comment is made regarding the presence of portlandite it can possibly be assumed that it was absent. The SO_4 content of the plastic concrete was determined to be about 3.3% by mass, namely about 20–25% by mass of the cement.

2.5. United Kingdom

In the UK, approximately 30 cases of deterioration to concrete associated with thaumasite formation have been reported. The concretes were designed for Class 2 or Class 1 sulfate exposure. All but three of the cases were 30-year old sub-structures in contact with large volumes of Lower Lias clay backfill which had a pyrites content of about 5% by mass. In the case of one of the exceptions, a 9-year old concrete foundation to a detached garage on sloping ground [9], the pyritic Lower Lias clay in contact with the foundation was disturbed as a consequence of wetting and drying and the presence nearby of a 3.5 m high hawthorn hedge and a 10 m high ash tree (National House Building Council, private communication). In the case of one of the two remaining exceptions, the affected concrete was in contact with a 300 mm thick layer of burnt colliery shale which continued to a higher level where it formed the sub-base to the pavement [10]. The third exception was the top of in-situ concrete piles placed in Lower Lias clay [11]. In two of the '30' cases an SRPC was used and in the worst example a PC with a C_3A content of 11.0% by mass, together with a dolomitic coarse aggregate and a fine aggregate consisting of a mixture of siliceous sand and oolitic limestone. Petrographic examination of thin sections, taken from the most severely affected bridge elements, broadly indicated the following [3]:

- A zone at the concrete/clay backfill interface, where transformation of cement paste to thaumasite was complete (about 5–10 mm in thickness, possibly resulting from the expansion of less than 3 mm thickness of the original sound concrete). The SO_4 level was approximately 40% by mass of the cement.
- A second zone where cracks filled or lined with thaumasite were present parallel to the concrete element's surface (generally 10–15 mm in thickness, possibly resulting from the expansion of less than 5–8 mm in thickness of sound concrete) and in which haloes of white thaumasite could be seen around the coarse and fine aggregate particles including the siliceous sand particles. In this zone there was an absence of other sulfate minerals, little portlandite,

calcium carbonate was occasionally precipitated into cracks and voids (W J French, Geomaterials Research Services Limited, personal communication, September 1998) and the expansion of the original concrete was approximately 100%. The SO_4 level ranged from 13% to 37% by mass of cement.

- A third, deeper zone with no visual evidence of deterioration, but with voids occasionally lined with ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) and thaumasite (approximately 5 mm in thickness).

The depths to which thaumasite sulfate attack occurred in concretes in contact with 'disturbed' Lower Lias clay, reported by BRE, are:

- Up to 40 mm at 4 years (possibly resulting from the expansion of up to 20 mm of the original sound concrete) SRPC in-situ pile [11].
- Up to 50 mm at 9 years (<25 mm of sound concrete) PC strip foundation [9] w/c ~ 0.55.
- Up to 40 mm at 29 years (<20 mm of sound concrete) PC motorway foundation [3], w/c ~ 0.50.

No data exists on the groundwater aggressivity during the early life of the concrete elements, consequently it is not known to what extent the attack is due to sulfuric acid, neutral sulfates or some combination of the two. Recent tests carried out by BRE [12] on groundwater samples taken from relatively undisturbed pyritic clay, close to the affected PC strip foundation, gave

Mg^{2+} 260 mg/l; Na^{+} 277 mg/l; K^{+} 21 mg/l;
Ca^{2+} 483 mg/l; SO_4^{2-} 2.37 g/l

indicating a sulfate class of 3 with approximately 35% and 40% of the SO_4 ions being associated with magnesium and calcium respectively. In the case of the affected 4-year old SRPC in-situ pile, the attack occurred to an even greater depth than that observed in laboratory tests where concrete cubes of w/c 0.50–0.55 were immersed in a 18 g SO_4/l magnesium sulfate solution (sulfate class 5), replenished every 3 months [11]. So it follows that the affected elements were almost certainly subject to groundwater that was particularly aggressive during the early life of the elements.

Hobbs and Taylor [14] have speculated that as a consequence of pyrites oxidation within Lower Lias clay backfill, the aggressivity of the groundwater to concrete could have been greatly enhanced by the formation of sulfuric acid. The acid formed could lower the pH of the groundwater and neutralization reactions with the carbonate compounds within the clay could result in the formation of sulfates of calcium, magnesium, sodium and potassium. The latter three sulfates are highly soluble and their more rapid formation in the clay backfill could produce high groundwater sulfate levels during the early life of the affected substructures.

2.6. Inferences from the field observations

A number of tentative conclusions can be reached regarding the conditions conducive to thaumasite attack in field conditions:

- a low temperature;
- wet conditions;
- exposure to sulfates, particularly those associated with the magnesium cation;
- exposure to sulfuric acid;
- the prior formation of ettringite;
- the depletion of portlandite indicating that a pH below that of a saturated calcium hydroxide solution accelerates thaumasite formation. This depletion could arise from exposure to sulfuric acid, magnesium sulfate, sodium sulfate or from leaching. Subsequent formation of brucite or the continuing presence of sulfuric acid would reduce the pH further making the C–S–H more susceptible to attack. The magnesium ions required could enter the concrete from the groundwater or result from attack on dolomite within an aggregate. Alternatively sulfuric acid could enter the concrete from the groundwater or result from oxidation of pyrites within the concrete aggregate;
- the inclusion within the concrete of at least 10–25% calcium carbonate by mass of the cement. This is because the SO_4 levels in regions affected by thaumasite attack range from 13% to 37% by mass of the cement.

Conditions which appear not to be conducive to thaumasite attack are:

- 'neutral' groundwaters containing sulfate ions derived primarily from gypsum, except in the surface regions of the concrete where calcium hydroxide is depleted by leaching;
- 'neutral' groundwaters containing zero or low concentrations of magnesium ions.

3. Laboratory studies

Apart from work at the UK Building Research Establishments [13,15–18] and Sheffield University [19,20], only very limited laboratory testing has been carried out to study thaumasite attack [8,21]. All of the test work has been carried out in 'neutral' sulfate solutions.

3.1. NBRI, South Africa

Van Aardt and Visser [21] immersed autoclaved and non-autoclaved dolomitic aggregate mortars in a 5%

sodium sulfate solution maintained at either 5 or 25 °C. After 1300 days the autoclaved mortars stored at 5 °C disintegrated into a soft pulpy mass containing considerable thaumasite. The non-autoclaved mortars did not disintegrate and contained considerable ettringite, together with a little thaumasite. At 25 °C the autoclaved mortars performed well and the non-autoclaved mortars deteriorated rapidly with large quantities of ettringite being detected.

3.2. Technical University of Milan, Italy [8]

Mortars made with quartz sand with added calcium sulfate of 7% by mass of the cement were immersed in water at 5 and 20 °C for 3 months and then immersed for 2 months in a solution containing 1 mole of each of the following: calcium hydroxide, calcium carbonate, amorphous silica and calcium sulfate with a pH of about 5.5. Thaumasite attack was not observed, but minor thaumasite formation occurred in mortars stored at 5 °C.

3.3. University of Sheffield, UK [19,20]

In one series of tests small cylinders of cement paste (10 mm diameter × 10 mm in height) made with 0%, 5%, 15% and 35% limestone powder additions were cured in water for 28 days and then immersed in various solutions at 5 °C for up to 420 days [19]. The water/solids ratio was 0.5 giving an increasing water/pc ratio with increasing limestone addition. The storage solutions were boiled tap water, distilled water, 0.4% Na_2SO_4, 0.4% $MgSO_4$, 1.8% Na_2SO_4, 1.8% $MgSO_4$, 0.4% $MgSO_4$ + 0.4% Na_2SO_4 and 1.8% $MgSO_4$ + 1.8% Na_2SO_4. The relative aggressiveness of the solutions, in order of increasing aggressiveness were—(1) tap water/distilled water; (2) 0.4% Na_2SO_4; (3) 1.8% Na_2SO_4; (4) 0.4% $MgSO_4$/(0.4% $MgSO_4$ + 0.4% Na_2SO_4) and (5) (1.8% $MgSO_4$ + 1.8% Na_2SO_4)/1.8% $MgSO_4$.

In the cement pastes with 5% and 15% limestone additions stored in the stronger magnesium solutions, small amounts of thaumasite were detected by XRD accompanied by ettringite, gypsum, portlandite and calcite. The spalled material taken from the cylinder containing 35% limestone stored in the 1.8% $MgSO_4$ solution contained thaumasite, brucite, calcite and negligible portlandite. The remaining part of the cylinder, which was still strong, contained ettringite, gypsum, portlandite and calcite. It was concluded that Mg^{2+} ions played a major role in the 'sulfate attack' of cements and concretes.

In a second series of tests, non-destructive and destructive tests were used to identify and examine the interaction of the changes in mechanical properties of small mortar specimens, 40×40×160 mm in size, with the onset of sulfate attack. The water to cement plus limestone powder ratio was 0.5. The limestone powder additions were 0%, 5%, 15% and 35% by mass of cement and the test samples were immersed in a 1.8% $MgSO_4$ solution maintained at 5 and 20 °C. The prolonged exposure to $MgSO_4$ solution produced similar 1-year compressive strengths at 0% and 5% limestone content, a strength loss of 10–15% at 15% limestone content and strength losses of 40% and 75% at 35% limestone content for test samples immersed at 20 and 5 °C respectively. The authors concluded [20] that 'at the 35% limestone content level, structural members loaded in compression could suffer serious strength loss and lack of safety if they are exposed to aggressive sulfate conditions of about 5 °C'. As the test samples were only 40×40×160 mm in size such a sweeping conclusion is not justified. For example, thaumasite sulfate attack to a depth of 20 mm into a concrete element of 300×300 mm section could result in a reduction of compressive strength of at most 13%.

3.4. Building Research Establishment, UK

An extensive series of tests in which 100 mm concrete cubes containing siliceous and limestone aggregates were immersed in sulfate solutions maintained at 5 and 20 °C has been carried out at the Building Research Establishment [13,16,17]. In these tests the various sulfate solutions were replenished every 3months. Deterioration of the cubes was assessed by wear rating which is given by

$$\frac{\sum(\text{wear on 8 corners of each of } 3 \times 100 \text{ mm cubes})}{6}$$

The criterion of assessment used for tests carried out at 20 °C was that the sulfate resistance of concrete is good when the wear rating at 3 or 5 years is less than 15 or 21 mm respectively [22–24]. Hobbs and Matthews [25] used a further criterion, namely that the sulfate resistance of concrete subject to sulfate class 4 or 4 m exposure is high when the wear rating after 3 or 5 years exposure to 18 g SO_4/l as sodium sulfate and 18 g SO_4/l as magnesium sulfate is less than 40 and 60 mm respectively. Based on these criteria Tables 1 and 2 list concretes giving similar good sulfate resistance after 3 or 5 years immersion in sulfate solutions of various aggressivities. Three-year data on PC/fly ash concretes have yet to become available, but 1-year data on low w/c PC/fly ash concretes have shown good performance (N.J. Crammond, Building Research Establishment, UK—personal communication, 2000). Three important points to note from Tables 1 and 2 are:

- a reduced performance for SRPC concretes at 5 °C compared to 20 °C;
- in the absence of magnesium ions, a performance for SRPC concretes and PC/70% slag concretes at 5 °C which is independent of aggregate type;

Table 1
Concretes of similar sulfate resistance—BRE 3- and 5-year wear ratings less than about 40 and 60 mm respectively

Cation ($18\ g\ SO_4/l$)	Temperature (°C)	Aggregate (Lst = limestone)	Cement or combination	Water–binder ratio	Binder content (kg/m^3)
Sodium	20	All	SRPC	1.08	180
	20	All	8.8% C_3APC	0.6	300
	20	Siliceous	10.3% C_3APC/25% Lst	0.59	300
	20	All	14% C_3APC/30% fly ash	0.5	300
	20	All	14% C_3APC/70% slag (Al_2O_3 11.5%)	0.45	380
	20	All	10% C_3APC/70% slag (Al_2O_3 14.7%)	0.45	380
Magnesium	20	All	SRPC	0.97	200
	20	Siliceous	5.3% C_3APC/25% Lst	0.59	300
	20	All	8.5% C_3APC	0.55	300
	20	All	14% C_3APC/70% slag (Al_2O_3 7.5%)	0.45	380
Sodium	5	Siliceous	SRPC	0.5–0.55	350
	5	Siliceous	7.2% C_3APC/70% slag (Al_2O_3 11.8%)	0.5–0.55	350
	5	Siliceous	PC/fly ash; PC/Lst	Not tested	
Magnesium	5	Siliceous	SRPC	0.5–0.55	340
Sodium	5	Lst coarse and/or Lst fine	SRPC	0.5[a]	340
	5	Lst coarse and/or Lst fine	7.2% C_3APC/70% slag (Al_2O_3 17.0%)	0.5[a]	340
	5	Lst coarse and/or Lst fine	PC/fly ash; PC/Lst	Not tested	–
Magnesium	5	Lst coarse and/or Lst fine	SRPC	0.4[b]	400
	5	Lst coarse and/or Lst fine	7.2% C_3APC/70% slag (Al_2O_3 17.0%)	0.5–0.55[a]	340

[a] Lower water–binder ratios are necessary to give similar sulfate resistance when high absorption limestone aggregates are used [13].

[b] By extrapolation from results obtained at higher water–cement ratios. For a 0.50–0.55 w/c ratio carboniferous fines concrete the 3-year rating was 48 mm [13].

Table 2
Concretes of similar sulfate resistance—4.2 g SO_4/l, 1.05 g Mg/l, 5 °C—BRE 3-year wear ratings less than 15 mm

Aggregate (Lst = Limestone)	Cement or combination	Water–binder ratio	Binder content
Siliceous	SRPC	0.55	300
Siliceous	7.2% C_3APC/70% slag (Al_2O_3 11.8%)	0.45[a]	380
Siliceous	PC/fly ash; PC/Lst	Not tested	–
Lst coarse and/or Lst fine	SRPC	0.45[b]	380
Lst coarse and/or Lst fine	7.2% C_3APC/70% slag (Al_2O_3 17.0%)	0.45[b]	380
Lst coarse and/or Lst fine	PC/fly ash; PC/Lst	Not tested	

[a] By extrapolation. Wear rating 44 mm at a free w/c ratio of 0.50–0.55 [13].

[b] By extrapolation. For a 0.50–0.55 w/c ratio carboniferous fines concrete the wear rating was 32 mm [13]. Lower water–binder ratios are necessary to give similar sulfate resistance when high absorption limestone aggregates are used.

- in the presence of magnesium ions and carbonate aggregate, a reduced performance for SRPC concretes at 5 °C and an enhanced performance for PC/70% slag concretes at 5 °C.

In another series of tests, small mortar samples were immersed at 5 °C in a range of sulfate solutions maintained at 5 °C. The deterioration was found to be strongly dependent upon the C_3A level of the cement [15]. Examination by X-ray diffraction and scanning electron microscopy showed conventional sulfate attack products, gypsum and ettringite, ahead of the thaumasite front [15]. In the case of companion mortars stored at 20 °C, visual deterioration due to thaumasite attack was not observed [13].

In a further series of tests [18], PC mortars and Portland limestone mortars were, after 28 days storage in water at 20 °C immersed for 1 year in either a 4.2 g SO_4/l and 2.0 g Na/l or a 4.2 g SO_4/l and 1.05 g Mg/l solution, maintained at 5 °C, with and without air bubbling. Greater deterioration was observed in the magnesium sulfate solution. Qualitative X-ray diffraction data obtained on material removed from deteriorated Portland limestone prisms with a w/c ratio of 0.75

showed the formation of ettringite and thaumasite for prisms exposed to both sulfate solutions with and without air being bubbled through the solutions. It was concluded that CO_2 resulting from the air did not participate in thaumasite formation.

The deteriorated PC prisms with a w/c ratio of 0.75 showed the formation of ettringite for prisms exposed to these solutions.

3.5. *Inferences from laboratory studies*

The laboratory observations indicate that the following combination of conditions are conducive to thaumasite attack:

- a low temperature;
- wet conditions;
- exposure to sulfates associated with the magnesium cation;
- the prior formation of conventional sulfate attack products;
- the presence of at least between 15% and 35% of calcium carbonate by mass of the cement.

4. Concrete qualities and materials to resist sulfate and thaumasite attack

It is clear from the observations made on the performance of concrete both in the field and the laboratory, that its resistance to chemical attack is dependent upon both sulfate ion concentration and magnesium ion concentration. Current specifications, however, do not adequately take into account the possible adverse effects of magnesium ions in groundwater [4].

Based on the published literature it is proposed that the minimum concrete qualities given in Table 3 will provide satisfactory resistance to sulfate attack and thaumasite sulfate attack. The groundwater sulfates and magnesium levels quoted relate to the groundwater in contact with the concrete, namely the measured levels in the undisturbed ground, disturbed ground or the backfill in contact with the concrete. The approach adopted is simpler than that in the BRE Special Digest [4], with the aggregates being split into two carbonate ranges, low and high, rather than three carbonate ranges and with only one additional protection measure being required for concretes of high structural performance subject to the two most aggressive groundwater exposures (Tables 3–5).

Table 4
Aggregate carbonate ranges (% $CaCO_3$ equivalent)

	Range H, high	Range L, low
All carbonate in coarse fraction	15–108	0–15
All carbonate in fine fraction	5–108	0–5
Carbonate in both fractions	(5–15) to 108	0 to (5–15)

5. Conclusions

1. Field observations indicate that the following combination of conditions are conducive to thaumasite attack:
   (i) a low temperature
   (ii) wet conditions
   (iii) exposure to sulfates, particularly those associated with the magnesium cation and/or exposure to sulfuric acid
   (iv) the prior formation of ettringite
   (v) the depletion of calcium hydroxide
   (vi) the inclusion within the concrete of at least 10% to 25% calcium carbonate by mass of the cement.

Table 3
Concrete qualities and materials to resist sulfate attack—minimum section size >140 mm, mobile groundwater

Concentration in groundwater		Aggregate/carbonate range (see Table 4)	Cement group (see Table 5)	Minimum cement (kg/m^3)	Maximum free w–c ratio
SO_4 (g/l)	Mg (g/l)				
<0.4	–	L, H	1, 2, 3	–	–
0.4–1.4	–	L, H	1, 2, 3	300	0.55
1.5–3.0	<0.35	L, H[a]	2, 3	300	0.55
3.0–6.0	<0.35	L, H[a]	2[b], 3	340	0.50
1.5–3.0	>0.35	H	2b[b], 3	380	0.45 (APM[c])
		L	2	380	0.45
		L	3	340	0.50
3.0–6.0	>0.35	H	2b[b], 3	400	0.40 (APM[c])
		L	3	340	0.50

[a] Non-dolomitic, for dolomitic aggregates assume Mg > 0.35 g/l.

[b] Alumina content of slag <12% by mass.

[c] For high structural performance, one additional protection measure (APM) is recommended—surface protection, a 30 mm thick sacrificial layer or drainage.

Table 5
Cement groups for use in Table 3

Group	Description
1a	BS EN 197-1; CEM I BS 12; Portland cement
1b	BS EN 197-1; CEM II and OEM III/A BS 146:1996; Portland blastfurnace cements BS 146:1996; 200X:blastfurnace cement
1c	BS EN 197-1: CEM III/B and CEM/III/C BS 146:200X and BS 4246:1996; high slag blastfurnace cement
1d	BS EN 197-1; CEM II/V BS 6588; Portland pulverized-fuel ash cements
1e	BS EN 197-1: CEM IV/B BS 6610: pozzolanic pulverized-fuel ash cements
1f	BS EN 197-1; CEM II/A-LL BS 7583; Portland limestone cement
1g	Combinations; CEM I to BS EN 197-1, or Portland cement to BS 12, each with ggbs to BS 6699
1h	Combinations; CEM I to BS EN 197-1, or Portland cement to BS 12, each with pulverised-fuel ash to BS 3892:Part 1
2a	BS EN 197-1; CEM II/B-V BS 6588; Portland pulverized-fuel ash cement containing not less than 26% of pfa by mass of the nucleus[a]
2a	Combinations; CEM I to BS EN 197-1, or Portland cement to BS 12, each with pfa to BS 3892: Part 1, where there is not less than 25% pfa and not more than 40% pfa by mass of the combination
2b	BS EN 197-1; CEM III/B high slag cement
2b	BS 146 200X, BIIIB high slag, low early strength cement
2b	Combinations; CEM I to BS EN 197-1, or Portland cement to BS 12, each with ggbs to BS 6699, where there is not less than 65% ggbs and not more than 79% ggbs by mass of the combination
3	Sulfate-resisting Portland cement to BS 4027

[a] The nucleus is the total mass of the cement constituents excluding calcium sulfate and any additives such as grinding aids.

2. Field observations indicate that the following conditions are not conducive to thaumasite attack:
   (i) 'neutral' groundwaters containing sulfate ions derived primarily from gypsum, in the surface layers of a concrete where calcium hydroxide is depleted by leaching
   (ii) 'neutral' groundwaters containing zero or low concentrations of magnesium ions.
3. Laboratory tests show:
   (i) a reduced performance for SRPC concretes at 5 °C compared to 20 °C
   (ii) in the absence of magnesium ions, a performance for SRPC concretes and PC/70% slag concretes at 5 °C which is independent of aggregate type
   (iii) in the presence of magnesium ions and carbonate aggregate, a reduced performance for SRPC concretes at 5 °C and an enhanced performance for PC/70% slag concretes at 5 °C.
4. Laboratory observations indicate that the following combination of conditions are conducive to thaumasite attack—a low temperature, wet conditions, exposure to sulfates associated with the magnesium cation, the prior formation of conventional sulfate attack products and the presence of at least between 15% and 35% of calcium carbonate by mass of the cement. Thus where comparisons are possible, the deductions from field and laboratory observations are in agreement.

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