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New UK guidance on the use of concrete in aggressive ground

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Abstract

The UK guidance for specification of concrete in aggressive ground has been revised following the discovery of the thaumasite form of sulfate attack in the foundations to highway bridges in England in 1998. Interim advice was issued in the Report of the Thaumasite Expert Group in January 1999. Following consultation with industry, a new BRE Special Digest 1 was published in September 2001 (to replace Digest 363) and parallel amendments to the current BS 5328 were drafted. New concepts are introduced for ground assessment and concrete specification. Allowance is now made for the oxidation of sulfides in the ground and there is a new classification for the aggressive chemical environment. Concrete specification additionally takes into account the required structural performance level, the carbonate content of aggregates, and the need for additional protective measures. Compatible guidance is being put in place for the UK Highways Agency and for BS 8500, the UK complementary standard to the European Standard BS EN 206-1, which will replace BS 5328 in December 2003.

Keywords: Sulfate attack; Thaumasite; Guidance documents; Ground assessment; Concrete specification

1. Introduction

It has long been recognised in the UK that concretes made with Portland cements are vulnerable to attack by sulfates, usually originating in the ground [1]. For many years it was considered that the only components of the cement which were affected were the calcium aluminate phases and calcium hydroxide and that the minerals formed by this attack were ettringite and gypsum. Sulfate-resisting cements with low contents of calcium aluminates were evolved and later the benefits of using cements based on pulverized-fuel ash or ground granulated blastfurnace slag were appreciated. Guidance on designing concretes to resist such aggressive ground was developed, e.g. in a series of BRE Digests, the most recent of which was Digest 363: *Sulfate and acid resistance of concrete in the ground*, the first edition of which was published in 1991 [2].

Over the last decade or so, however, deterioration of concrete 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 structures [3]. These include concrete foundations and floor slabs exposed to sulfate-bearing ground and hardcore, roads and sub-bases, tunnel linings and sewer pipes. Additionally thaumasite has been found at the interface of lime–gypsum plasters with cement-based renders; in lime gypsum plasters with cement clinker or clay impurities; and the mortar and renders of exposed sulfate-bearing brickwork. The full extent of this problem is still unknown.

The distinguishing features of the thaumasite form of sulfate attack (TSA) are that it requires a source of carbonate ions in addition to sulfate ions and that it targets the calcium silicate phases within hardened cement paste. In the 1960s Erlin and Stark [4] were the first to identify and report on the occurrence of thaumasite in cement-based components suffering from sulfate attack in the USA. Since then, a growing number of cases have been identified worldwide, although the majority have been found in the UK.

In the 1990s the Building Research Establishment (BRE) investigated three cases of TSA in the concrete foundations to domestic properties in the Cotswolds area of England [5,6]. In all cases, the TSA-affected concrete contained carbonate-bearing (limestone) aggregates and was exposed to moderately aggressive (Class 3) sulfate conditions in a seasonally cold, wet environment. The concrete encountered in each case satisfied the recommendations of the then-current version

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of Digest 363. It therefore became apparent that the Digest needed to be revised to take account of the risk of TSA occurrence. Accordingly, a new version of Digest 363 [2] was issued in January 1996 which drew attention to the risk of TSA in concretes containing internal calcium carbonate and promised further guidance based on on-going research.

Subsequently, in 1998, several cases of TSA were identified in the foundations to UK motorway overbridges, the worst occurrence resulting in severe concrete deterioration to a depth of up to 70 mm [7]. The high profile of these cases ensured a rapid pan-industry response, culminating with a report by a Thaumasite Expert Group (TEG) [8] set up by the UK Government. This report gave interim guidance on specifications to minimise the risk of TSA in new construction and on the management of existing structures affected by TSA. It also recommended that the appropriate UK guidance documents, principally those issued by BRE, the British Standards Institution (BSI), and the UK Highways Agency (HA), relating to the performance of concrete in sulfate-bearing ground, should be revised to incorporate the interim recommendations of the TEG report.

This revision has now been carried out and in this paper we describe how this has been done and the nature of the resulting guidance in the UK. A detailed review is included of the first two items of guidance to be published, BRE Special Digest 1: *Concrete in Aggressive Ground* (SD1) [9] and Amendments to BS 5328: *Concrete* [10].

2. The new guidance

2.1. Evolution of guidance on TSA

Following the identification of TSA in concrete of below-ground structural elements of a number of M5 bridges in 1998, the UK Minister for Construction established the TEG under the chairmanship of Les Clark, Professor of Structural Engineering, University of Birmingham. It was asked to report on the nature and threat of TSA and to provide interim guidance on its avoidance. BRE provided the Secretariat for the Group and some BRE staff served as members of the Group and others as supporting technical experts. The TEG identified the primary risk factors necessary for the occurrence of TSA in buried concrete as

- sulfates and/or sulfides in the ground;
- mobile groundwater;
- carbonate, generally in the aggregate;
- low temperature (generally below 15 °C).

They also identified a number of secondary factors that can influence the occurrence, severity and effects of TSA:

- type and quantity of cement in the concrete;
- quality of the concrete;
- changes to ground chemistry and water regime resulting from construction;
- type, depth and geometry of the buried concrete.

For the M5 bridges, the following combination of factors proved critical:

- the use of limestone in coarse and fine aggregates;
- groundwater where sulfate concentrations were higher than predicted by the original ground investigation owing to oxidation of pyrite (iron sulfide) in backfill derived from unweathered Lower Lias Clay;
- ponding of groundwater within a sump formed by the original construction excavation.

Based on its findings, the TEG developed interim guidance and recommendations for new works. Following the publication of the TEG report in January 1999, much work has gone into preparation of new national guidance including:

- BRE Special Digest 1 (SD1) [9];
- Amendment to the British Standard for concrete, BS 5328 [10];
- Amendment to the British Standard for aggregates, BS 882 [11];
- BS 8500: Complementary British Standard to the new BSEN206-1 [12];
- Highways Agency Manual of Contract Documents for Highway Works [13].

SD1 and the Amendments to BS 5328 were prepared in tandem. SD1 was published in September 2001 and the BS 5328 Amendments issued for public comment in October 2001. To ensure close collaboration between the BSI Committee for Concrete and BRE, a working party, chaired by Philip Nixon, BRE, and including several TEG members, was established to oversee parallel production of the two documents. It was decided that the advice in BS 5328 would be restricted to concrete quality requirements. All other aspects including ground investigation, classification and any measures in addition to the concrete quality which were necessary to achieve the structure's service life would be included in SD1. The guiding principle in the preparation of both SD1 and the Amendments to BS 5328 has been to follow the direction of the TEG report and in particular to accept, until new research evidence is available, the decisions of the TEG on concrete mix design limits. A key concern in formulating the new guidance has been to consult with the many stakeholders to make the guidance as applicable and user-friendly as possible. This has resulted in a BRE guidance document with a wider scope than its predecessors.

2.2. BRE special digest 1: concrete in aggressive ground

2.2.1. New concepts in the guidance

The guidance for concrete in aggressive ground has been radically revised as compared to Digest 363 [2]. Key changes have been:

- clarification of modifications to initial ground sulfate classification that takes account of factors such as acidity, groundwater mobility and type of site;
- allowance for enhanced aggressiveness in pyrite-bearing ground;
- provision of measures to combat the occurrence of TSA;
- an interface with emerging European Standards for cement and concrete.

Owing to its greater length and complexity, SD1 has been published in four parts as the first in a new series of BRE Special Digests. The layout and inter-relationships of SD1 are illustrated in Fig. 1.

A number of new concepts are introduced in SD1:

Part 1 - Assessing the Aggressive Chemical Environment
- Site investigation and testing → ACEC classification

Part 2 - Specifying concrete and Additional Protective Measures
- ACEC class + Structural Performance Level → DC class + number of APM
- DC class → concrete quality
- Choice of APM

Part 3 - Design Guides for common application

Part 4 - Design Guides for specific precast concrete products

Fig. 1. Layout of Special Digest 1.

Ground assessment

- Allowance for increase in sulfate from oxidation of pyrite by introduction into sulfate classification the consideration of total potential sulfate.
- Aggressive chemical environment for concrete (ACEC) classification. This new designation reflects the wider scope of the ground investigation which, in addition to the sulfate levels, now specifically includes acidity, ground water mobility and whether the site is natural or brownfield.

Concrete mix design

- Aggregate carbonate range (ACR) classification. The introduction of ACR follows one of the most important recommendations in the TEG report. Because of the role of the carbonate molecule in the formation of thaumasite, aggregates are classified according to their carbonate content into ranges A, B and C, where A has the greatest potential for contributing to TSA. Fig. 2 shows a chart which can be used in deriving ACR.
- Design chemical class (DC class). Again, this new designation reflects the wider scope of the guidance with, for example, a separate DC class for acid conditions.

Additional protective measures (APM)

This concept had been included in the BRE guidance previously in the form of surface protection to be used in the most severe sulfate environments. However, the TEG extended the use of APM to compensate for the fact that not enough was known about the ability of

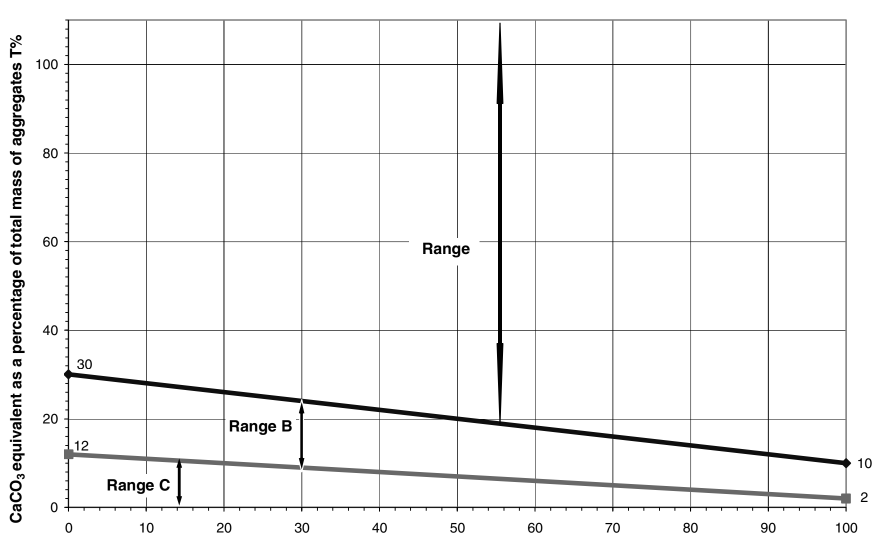

Fig. 2. Chart used to determine aggregate carbonate range from the carbonate content (expressed as $CaCO_3$ equivalent) in the coarse and fine aggregate.

concrete mix designs to resist TSA. In SD1 the use of APM has been further extended and rationalised. The APM recommended comprise:

- APM1—enhanced concrete quality, ie. use of a concrete appropriate to a higher DC class.
- APM2—use of controlled permeability formwork. This produces a dense, low permeability surface zone which resists the ingress of aggressive chemicals.
- APM3—provide surface protection, e.g. by use of coatings or water-resisting barriers.
- APM4—provide a sacrificial layer of concrete which can be attacked without compromising the safety of the structure.
- APM5—address the drainage of the site to keep aggressive groundwater away from the concrete.

Design guides for:

- Common applications. These design guides do much of the work for the engineer and provide a direct route from the ACEC class to the DC class and appropriate APM.
- Specific precast products. Some precast products, such as precast concrete pipes and tunnel lining segments have a resistance to aggressive chemicals is particularly good, such that they do not fit well into the general guidance. They have therefore been given their own set of design guides. The justification for this is that these products are specified (e.g. pipes in accordance with BS 5911) to be of very high quality concrete and also have a high degree of manufacturing control. Concrete blocks, which are more resistant than their low cement contents would suggest, are also covered by a designated design guide.

2.2.2. Layout of SD1

Part 1 deals with assessing the chemical aggressiveness of the ground. It shows how to derive the ACEC class of a site by determining soluble sulfate and magnesium, potential sulfate (from oxidation of any pyrite), the pH and mobility of groundwater. It also takes into account whether the site is natural ground or brownfield.

Part 2 describes how the ACEC class is considered together with the proposed use and section width of the concrete, resulting in a specification for the concrete construction.

Concrete used is considered in terms of structural performance level (SPL), classified as low, normal or high according to the required service life, criticality of use and vulnerability of structural details. As sulfate attack progresses in from the surface of the concrete, three divisions of section width are taken into consideration when deciding the necessary protection measures. However, it is important to realise that this approach implicitly accepts that some attack on the concrete surface can be tolerated for thicker sections. There are situations, such as the sides of friction piles, where this is not acceptable: in such cases, the design guides should be followed.

The defining factors of ACEC class, SPL and concrete section widths are brought together in Table 7 in SD1 (Fig. 3) to define the recommended DC class and number of APM required. The first column shows ACEC classes up to the AC-4 family. These are broadly equivalent to sulfate classes 1–4 in Digest 363. Suffix 's' indicates that the AC class derives from a 'Static' groundwater condition; suffix 'z' indicates acid ground conditions, and suffix 'm' relates to ground with high magnesium content. Footnotes to the Table (shown in SD1) indicate other available options or restrictions on use.

As with its precursors, SD1 recommends in Table 6 (see extract in Fig. 4) the minimum cement content and maximum free water/cement ratio for each DC class. There are now eight basic classes between DC-1 and DC-4m (column 1) instead of the former five, because acid conditions, indicated by suffix 'z', now have separate classifications. Column 2 shows the ACR that may be used in each DC class. The choice of cement groups (column 3) follows the classification system adopted by the TEG report rather than those of Digest 363.

The concept of starred DC classes has been introduced in Table 6 to take advantage of the greater resistance to TSA provided by range B and C aggregates when used in mixes with higher cement contents and lower free water/cement ratio than those specified for equivalent basic DC classes. Use of these single- and double-starred DC classes is equivalent to adoption of one or two APM respectively.

The number of APM to be applied is determined by the aggressiveness of the ground, as indicated by ACEC class, section width of the concrete and partly by the required purpose and durability of the structure as specified by the designated SPL. In general, no APM are required when the aggressivity of the ground is less than AC-3 or when the groundwater is static.

Parts 3 and 4 of the Special Digest give design guides for specifying concrete which lead the reader directly from the ACEC class to the appropriate DC class and to the relevant number of APM. From this point, the required concrete quality can be specified and the specific APM selected.

Part 3, *Design guides for common applications*, contains the following:

- Series 1: for non-domestic buildings;
- Series 2: for low-rise domestic buildings;
- Series 3: for transport structures.

Each design guide is limited to a particular type of concrete construction and hydrostatic and carbonation

Table 7. Concrete quality and Number of Additional Protective Measures recommended for the general use of in-situ and precast concrete								
Design Chemical (DC) Class / Number of Additional Protective Measures (APM) [1],[2]								
	Low Structural Performance Level			Normal Structural Performance Level			High Structural Performance Level [3]	
Section thickness / ACEC class	< 140 mm	140 - 450 mm	> 450 mm [4]	< 140 mm	140 - 450 mm	> 450 mm [4]	140 - 450 mm	> 450 mm [4]
AC-1	DC-2/ 0	DC-1/ 0	DC-1/ 0	DC-2/ 0	DC-1/ 0	DC-1/ 0	DC-1/ 0	DC-1/ 0
AC-1s	DC-2/ 0	DC-1/ 0	DC-1/ 0	DC-2/ 0	DC-1/ 0	DC-1/ 0	DC-1/ 0	DC-1/ 0
AC-2	DC-3/ 0	DC-2/ 0	DC-1/ 0	DC-3/ 0	DC-2/ 0	DC-1/ 0	DC-2/ 0	DC-1/ 0
AC-2s	DC-3/ 0	DC-2/ 0	DC-1/ 0	DC-3/ 0	DC-2/ 0	DC-1/ 0	DC-2/ 0	DC-1/ 0
AC-2z	DC-3z/ 0	DC-2z/ 0	DC-1/ 0	DC-3z/ 0	DC-2z/ 0	DC-1/ 0	DC-2z/ 0	DC-1/ 0
AC-3	DC-3/ 2 [5] [6]	DC-3/ 1 [5]	DC-2/ 1	DC-3/ 3 [5]	DC-3/ 2 [5]	DC-2/ 2	DC-3/ 3 [5]	DC-2/ 3
AC-3s	DC-4/ 0	DC-3/ 0	DC-2/ 0	DC-4/ 0	DC-3/ 0	DC-2/ 0	DC-3/ 0	DC-2/ 0
AC-3z	DC-4z/ 0	DC-3z/ 0	DC-2z/ 0	DC-4z/ 0	DC-3z/ 0	DC-2z/ 0	DC-3z/ 0	DC-2z/ 0
AC-4	DC-4/ 2 [5] [6]	DC-4/ 1 [5]	DC-3/ 1 [5]	DC-4/ 3 [5]	DC-4/ 2 [5]	DC-3/2 [5]	DC-4/ 3 [5]	DC-3/ 3 [5]
AC-4s	DC-4/ 0	DC-4/ 0	DC-3/ 0	DC-4/ 0	DC-4/ 0	DC-3/ 0	DC-4/ 0	DC-3/ 0
AC-4z	DC-4z/ 1 [7]	DC-4z/ 0	DC-3z/ 0	DC-4z/ 1 [7]	DC-4z/ 0	DC-3z/ 0	DC-4z/ 0	DC-3z/ 0
AC-4m	DC-4m/ 2 [5] [6]	DC-4m/ 1 [5]	DC-4m/ 0	DC-4m/ 3 [5]	DC-4m/ 2 [5]	DC-4m/ 1 [5]	DC-4m/ 3 [5]	DC-4m/ 2 [5]
AC-4ms	DC-4m/ 0	DC-4m/ 0	DC-3/ 0	DC-4m/ 0	DC-4m/ 0	DC-3/ 0	DC-4m/ 0	DC-3/ 0

Fig. 3. Extract from Table 7 from Part 2 of SD1 showing the relationship between concrete quality and the number of APM recommended for the general use of in situ and precast concrete. (References relate to footnotes in the complete Table in SD1.)

Table 6: Concrete qualities to resist chemical attack for the general use of in-situ and precast concrete				
Design Chemical Class [5]	Aggregate Carbonate Range	Cement or combination group [1]	Dense fully compacted concrete made with aggregate conforming to BS 882 or BS 1047	
			Minimum cement content kg/m^3	Maximum free water/ cement ratio
DC-1	No restriction	1, 2, 3	-	-
DC-2	A[4], B, C	1 [2]	340	0.50
	A[4], B, C	2, 3	300	0.55
DC-2z [3]	No restriction	1[2], 2, 3	300	0.55
DC-3	A	2a	400	0.40
	A	2b, 3	380	0.45
	B, C	2, 3	340	0.50
DC-3* [7]	B	2, 3	380	0.45
DC-3** [8]	C	2, 3	380	0.45
DC-3z [3]	No restriction	1[2], 2, 3	340	0.50

Fig. 4. Extract from Table 6 from Part 2 of SD1 showing the concrete qualities required to resist chemical attack. (References relate to footnotes in the complete Table in SD1.)

conditions. In addition to recommending the appropriate DC class and APM, the design guides carry specific design notes based on expert experience. Fig. 5 shows an extract from Series 1 design guide 1d. This guide assumes a normal structural performance level.

Part 4, *Design guides for specific precast products*, covers:

- pipeline systems;
- precast linings for tunnels and shafts;

Design guide 1d: Cast-in-situ concrete greater than 140mm and less than 450mm thick used as a basement or retaining wall, with a hydrostatic head greater than five times the wall thickness. Concrete well compacted.

ACEC Class (From Table 2)	Design Chemical Class for Table 6	Number of Additional Protective Measures to be selected from the Options given in Table 8	
AC-1, AC-1s	DC-1	1	Apply APM5 if practical, otherwise apply APM1 or APM3.
AC-2, AC-2s	DC-2	1	
AC-2z	DC-2z	1	
AC-3	DC-3	3	To include APM5 if practical, otherwise include APM1 or APM3.
	DC-3*	2	
	DC-3**	1	Apply APM5 if practical, otherwise apply APM1 or APM3.
AC-3s	DC-3	1	
AC-3z	DC-3z	1	
AC-4	DC-4	3	To include APM5 if practical, otherwise include APM3.
	DC-4*	2	
	DC-4**	1	Apply APM5 if practical, otherwise apply APM3.

Fig. 5. Extract from design guide 1d from Part 3 of SD1 relating to cast-in situ concrete greater than 140 mm and less than 450 mm thick used as a basement or retaining wall, with a hydrostatic head greater than five times the wall thickness where the concrete is well-compacted.

- precast box culverts;
- precast concrete masonry blocks.

Products are grouped into a separate part of SD1 as their manufacture, combined with tight quality control and surface carbonation before use, typically gives them greater resistance to chemical attack. The guidance, therefore, differs from that for in situ concrete. As they are made to be suitable for use in mobile groundwater conditions, they need only to be specified to meet particular sulfate and acidity conditions, rather than comply with ground assessments in terms of ACEC class.

2.3. Amendments to BS 5328: concrete

BS 5328, comprising four parts [10], is currently the standard used for most below-ground concrete in the UK. Amendments to the standard that have been drafted to align it with BRE SD1 comprise: Amendment 2 to Part 1, Amendment 3 to Part 2 and Amendment 5 to Part 3. Since BS 5328 is scheduled to be withdrawn in December 2003, when BS 8500 [12] takes precedence, the amendments are limited to giving the requirements to meet the specified DC class and are applicable only to 'Designed' and 'Designated' concrete mixes ('Prescribed' and 'Standard' mixes remain unchanged). Guidance on selecting the DC class and the number of APM is not given. For these the reader is referred to BRE SD1.

2.4. BS8500: concrete—complementary british standard to BSEN206-1

BS 8500, comprising two parts [12], has been prepared for use alongside the new European Standard for concrete, BS EN 206-1 [14] to cater for UK requirements, including a fuller range of ground (exposure) conditions and provision for constituent materials used in the UK. Cements and combinations are, however, designated according to BS EN 197-1: 2000 [15], the European Standard for cements, displacing the traditional UK system.

BS 8500 gives more information on specification for use in aggressive ground than does BS 5328, but it is still necessary for the user to be familiar with BRE SD1. As BS 8500 is a concrete standard, no guidance is provided on how to classify the chemical aggressivity of the site. The starting point is information on ACEC class from the site survey. It is anticipated that experienced users will be able to take the site information provided and use Part 1 of BS8500 to select the DC class/designated concrete and the number of APM for many in situ applications. Less experienced users will need to check their conclusions using the Design guides in BRE SD1: Part 3. Unlike SD1, BS 8500-1 does not provide guidance on selecting the DC class and number of APM for precast concrete products.

When a DC class or designated concrete is specified, the producer has to comply with the comprehensive specifications given in Part 2 of BS8500. These define the constituent materials and limiting values that are permitted and, in the case of designated concrete, the characteristic strength. The limiting values are identical to the recommendations in BRE SD1.

2.5. BS 882: 1992. Specification for aggregates from natural sources for concrete. Amendment No. 1:2000

The British Standard Specification for Aggregates, BS 882, has been amended (2002) such that if required the aggregate producer shall provide information on the carbonate content of the aggregate expressed as the equivalent calcium carbonate content in accordance with SD1.

2.6. Highways agency manual of contract documents for highway works

Clauses to the Highways Agency Manual of Contract Documents for Highway Works have been updated to encompass the recommendations of SD1. These amendments are applicable to Series 1700 *Structural Concrete* of Volume 1: *Specification for Highway Works* and to Series NG 1700 of Volume 2 *Notes for Guidance on the Specification for Highway Works*. The amendments start from the point at which the ACEC class is determined and guide the reader through to the specification of a DC class to the concrete producer. Reference is made to the simplification of the process attainable from the Design guides in Parts 3 and 4 of SD1, but these are not reproduced in the specification. The amendments also incorporate cement designations according to BS EN 197-1. The amendments were implemented in the May 2002 version of the *Specification for Highway Works*.

3. Communicating the message

SD1 was published in September 2001, BS 8500 was published in spring 2002, and the revised version of BS 5328 incorporating the thaumasite Amendment was published in mid 2002. Since there is much new information in these documents for users to understand and apply, their launch has been supported by a series of seminars, sponsored by the UK Department of Trade and Industry (DTI). As well as one at BRE in November 2001, seminars have been organised around the country under the auspices of the Concrete Society's Regions and Clubs network, and local branches of the Institution of Civil Engineers (ICE), Institution of Structural Engineers (IStructE) and local Geotechnical Societies. These have given engineers, concrete producers and others the opportunity to hear about and discuss the guidance directly with specialists. Feedback from the seminars will feed into future revisions of the Special Digest.

4. Conclusion

The UK guidance on concrete in aggressive ground has been comprehensively revised in a series of publications to build on the interim guidance of the report of the Thaumasite Expert Group. New research, which will be coming to fruition over the next few years, will add to the knowledge base on which the guidance rests. If necessary, a further revision will be undertaken to incorporate these new results as they become available.

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