Part A: Introduction

A1. The problem of chemical attack
Chemical agents that are destructive to concrete may be found in the ground. In the UK, sulfates and acids, naturally occurring in soil and groundwater, are the agents most likely to attack concrete. The effects can be serious (see Figure A1) resulting in expansion and softening of the concrete to a mush. A substantial number of other substances are known to be aggressive, most resulting from activities of man, but collectively these are a lesser problem as they are encountered only rarely by concrete in the ground.

It has been standard practice in the UK for at least six decades to design concrete for installation in the ground to be resistant to attack from commonly found chemicals, including sulfates and acids. BRE have underpinned this approach by issuing a series of guidance notes and Digests, dating back to 1939, on the causes of chemical attack and how to specify chemically resistant concrete.

Consequently, the large majority of concrete installed in the ground has performed entirely satisfactorily and is expected to do so for its required working life. Occasionally, however, cases of chemical attack have come to light and have been subject to research by BRE and others. Some of these cases have been attributed to rarely occurring chemicals not specifically covered by BRE Digests; some to natural ground conditions for which there was insufficient guidance, such as occurrence of pyrite; and some to the emergence of previously unrecognised attack mechanisms, such as the thaumasite form of sulfate attack (TSA), which has been extensively reported in the last decade. [1]

Guidance in BRE Digests has necessarily evolved to cater for successive adverse field findings, but also to take advantage of the emergence of new concrete constituents and construction methods, and maintain harmony with newly published standards, latterly European ones. In order to be both comprehensive and flexible, Digests have tended to become longer and more complex. One objective of this third edition of Special Digest 1 (SD1) is to simplify the guidance. Other aims and changes are discussed later.

A2. Scope and structure
A2.1 Types of site and chemical agent covered
SD1 provides guidance on the specification of concrete for installation in natural ground and brownfield locations. The definition of a brownfield location adopted here is one that has been subject to industrial development, storage of chemicals, or deposition of waste, and which may contain aggressive chemicals in residual surface materials or in ground penetrated by leachates. The procedures given for ground assessment and concrete specification cover the fairly common occurrence of sulfates, sulfides and acids. They also cover the more rarely occurring aggressive carbon dioxide found in some ground and surface waters.
While SD1 discusses several aggressive agents, such as ammonium salts and phenols, occasionally found in heavily contaminated ground, no specific procedures are included for dealing with these. Specialist advice should be sought if they are encountered.

**A2.2 Readership**
SD1 provides practical guidance to ground specialists on the assessment of ground in respect of aggressiveness to concrete, and to concrete designers, contractors, specifiers and producers on the specification of concrete to resist chemical attack.

**A2.3 Structure of the guidance**
Guidance is given in Parts B to F as follows:

**Part B** describes modes of chemical attack and discusses the mechanisms of the principal types, including sulfate and acid attack, and the action of aggressive carbon dioxide.

**Part C** deals with assessment of the chemical aggressiveness of the ground. It gives procedures for the determination of Design Sulfate Class from soluble sulfate and magnesium and from the potential sulfate (eg from oxidation of pyrite). It shows how the Design Sulfate Class together with pH and mobility of groundwater may collectively be taken into account for natural ground and brownfield sites to classify a location in terms of Aggressive Chemical Environment for Concrete (ACEC) class.

**Part D** gives recommendations for the specification of concrete for general cast-in-situ use in the ground. It explains how to derive an appropriate quality of concrete, termed the Design Chemical Class (DC Class), from a consideration of the ACEC class together with the hydraulic gradient due to groundwater, the type and thickness of the concrete element, and its Intended Working Life. In some cases, where conditions are highly aggressive, Additional Protective Measures (APM) are recommended.

Part D follows this with guidance on the constituents of concrete required to achieve the identified DC Class. Specification is in terms of maximum free water/cement ratio, minimum cement content and type of cement.

**Part E** gives recommendations for specifying surface-carbonated precast concrete for general use in the ground. An essential requirement for compliance with this Part is that surface-carbonation is assured by exposure of the precast concrete to air for a minimum of 10 days after curing. Since such carbonation provides a degree of resistance to sulfate attack, the recommendations for the derivation of DC Class in respect of sulfates is relaxed by one level. Other than this, the recommendations of Part D are followed for concrete specification.

**Part F** includes Design Guides for specification of specific precast concrete products, including pipeline systems, box culverts, and segmental linings for tunnels and shafts. These products are manufactured under rigorous quality control to ensure appropriate mix composition and achieve relatively low concrete permeability. Together these provide an inherently high quality in respect of chemical resistance. Consequently, a further relaxation (beyond that allowed for surface-carbonation) is permitted in respect of specification of DC Class for aggressive sulfate conditions. In practice this relaxation is used to offset the general-use recommendation that a higher DC Class should be specified where concrete is of thin cross-section, or will encounter a relatively high hydraulic gradient.

Part F also covers specification of precast concrete masonry units (concrete blocks) for aggressive ground conditions. The guidance is based on Design Sulfate Class rather than ACEC Class as there is currently no correlation of block performance with the latter, though work on this is ongoing.

A glossary of terms is included as Appendix A1.

**A2.4 Diagrammatic overview of ground assessment and concrete specification**
An overview of the various procedures for ground assessment and specification of concrete is given in Figure A2. This is arranged in four stages according to the construction sector that has key responsibility. Within each of these stages the principal tasks are shown in boxes, with references to the relevant Sections of SD1. Whilst most steps are equally applicable to all uses of concrete, there is a differentiation in Stage 3 for the determination of DC Class and APM between the three categories of concrete element dealt with in Parts D, E and F.
Figure A2: Procedure for design of buried concrete for use in an aggressive chemical environment.
A3. Background to guidance on sulfate attack

One of the key drivers for revision of BRE Digests dealing with concrete in aggressive ground since the 1990s has been a growing recognition of the occurrence of the thaumasite form of sulfate attack (TSA) in UK buildings and structures.

It has long been known in the UK that concretes made with Portland cements are vulnerable to attack by sulfates in the ground. For many years it was considered that the affected components of the concrete matrix 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 made available in the UK by the 1950s to meet this ‘conventional’ form of sulfate attack. Later the benefits of using fly ash (pfa) and blastfurnace slag based cements were appreciated. Guidance on designing concretes to resist conventional sulfate attack was developed 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.

Since the late 1980s, however, deterioration of concrete as a result of the formation of thaumasite has become recognised as a separate form of sulfate attack. The distinguishing features of TSA are that it

- occurs preferentially at low temperatures (below 15°C, such as is typically found in the ground);
- requires availability of carbonate ions in addition to sulfate ions, from sources including limestone aggregate and bicarbonate in groundwater;
- targets the calcium silicate phases within hardened cement paste, potentially reducing concrete to a mush.

A growing number of cases of TSA have been identified worldwide, although the majority have been found in the UK.

In the 1990s BRE investigated three cases of TSA in the concrete foundations to domestic properties in the Cotswold area of England. [2, 3] In all three 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 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 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 motorway bridges in Gloucestershire. As in the previous cases, the concrete contained carbonate-bearing aggregates.[1, 4 - 6] The most severe occurrence had resulted in severe concrete deterioration to a depth of up to 50 mm, exposing steel reinforcement to corrosion. [7] The high profile of these cases ensured a co-ordinated national review, culminating in 1999 with a report from a Thaumasite Expert Group [1] set up by 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 gave recommendations for further research on occurrence of TSA and mitigating measures.

Following publication of the Thaumasite Expert Group report, BRE guidance was revised to incorporate the interim recommendations. This was published in 2001 as Special Digest 1: Concrete in aggressive ground (SD1:2001). There were minor revisions to the guidance in a new edition published in 2003 (SD1:2003). These were principally to bring nomenclature used for cements and combinations into line with newly published European Standards.

Subsequently, much of the research recommended by the Thaumasite Expert Group has been completed. Key outcomes in respect of the mechanism of TSA and concrete specification have been:

(i) Confirmation that the carbonate required for TSA may come from a source other than aggregates in the concrete. In particular, it can come from bicarbonate dissolved in groundwater. [4, 8]
(ii) Clarification of the performance of various compositions for concrete recommended in SD1:2001 for aggressive sulfate conditions.

Together with other findings, such as deficiencies in guidance for ground assessment, the new knowledge has prompted the current major revision of SD1.

A4. Key changes in SD1:2005
Two key changes have been made to the procedure for ground assessment from the 2003 edition of SD1:
- The limits of the Design Sulfate Classes based on 2:1 water/soil extract tests on soil have been reduced, making this classification route more conservative. The change stems from findings of several research investigations on ground carried out by BRE and others. [9 - 11] Sulfate class limits based on 2:1 water / soil extract tests on soil have been found to be substantially lower than sulfate class based on sulfate in groundwater. The new limits bring sulfate classification based on 2:1 water/soil extract tests into parity with sulfate classification based on groundwater.
- High magnesium levels are not taken into account when determining the ACEC class of natural ground in the UK.

The following key changes have been made to the procedure for concrete specification:
- The recommended maximum w/c ratio and minimum cement content have been revised, and a new classification for cements and combinations has been introduced.
- The recommended concrete quality now caters for the ever-present possibility of exposure to an external source of the carbonate required for TSA (principally bicarbonate in groundwater). The concept of Aggregate Carbonate Range is therefore no longer included, since the revised concrete specification simultaneously caters for an internal source from carbonate in aggregates. A further consequence is that starred and double-starred concrete qualities that related to restricted aggregate carbonate content are no longer included.
- The number of APM to be applied at higher sulfate levels has been reduced, in general by two. This follows from a higher level of confidence in the provisions for the concrete.
- The use of the concept ‘Intended Working Life’ replaces that of ‘Structural Performance Level’. This is for harmony with European standards such as BS EN 206-1.

Further detail in respect of these changes is included in Parts C and D.

A5. Relationship between SD1:2005 and BS and EN Standards for concrete
For several decades there has been liaison between groups responsible for guidance in BRE Digests on concrete in aggressive ground and British Standards dealing with the specification of concrete, the latest of which is BS 8500. Consequently there has been a basic harmony between these documents in respect of concrete specification for general use in the ground. In other respects the BRE Digests and Standards have been complementary. BRE guidance has presented more background information on chemical attack, given detailed guidance on ground assessment, and included dedicated guidance for the specification of concrete in certain precast concrete products, such as pipeline systems and masonry blocks. In contrast, BS guidance for concrete has integrated the provisions for resistance to chemical attack into the numerous other requirements for practical concrete specification, such as strength class and consistence, resistance to alkali-silica reaction and chloride content in respect of corrosion of reinforcing steel.

At the time of preparation of this edition of SD1 the current edition of the British Standard for concrete is BS 8500: 2002. However, a revision of this is underway that will include bringing it into line with SD1:2005 in respect of resistance to aggressive ground. It is expected that an amended document will be issued for public comment in the first half of 2005, followed by publication some months later.
Appendix A1: Glossary of terms

Aggressive Carbon dioxide
Carbon dioxide (CO₂) dissolved in water essentially comprises three fractions:
• a part combined with calcium ions to form highly soluble calcium bicarbonate (Ca(HCO₃)₂);
• a part remaining as dissolved carbon dioxide that is needed to stabilise the calcium bicarbonate;
• the remainder, forming carbonic acid (H₂CO₃) which has the potential to attack concrete. This portion of the dissolved carbon dioxide is termed aggressive carbon dioxide.

Aggressive carbon dioxide is usually only present to an appreciable extent in rather pure natural waters, since in most cases, where the water contains dissolved salts, sufficient calcium carbonate is available to combine with the carbon dioxide as calcium bicarbonate.

Aggressive Chemical Environment for Concrete C Class (ACEC Class)
This system for the classification of aggressive ground conditions for concrete was introduced in SD1:2001. ACEC Class is derived from Design Sulfate Class, taking additional account of the type of site (natural or brownfield) and the mobility and pH of groundwater. See Section C5.2 and Tables C1 and C2.

Additional Protective Measures (APM)
APM were first defined in SD1:2001. They comprise five options for extra measures that can be taken to protect concrete where it is considered that the basic provisions of the concrete specification might not provide adequate resistance to chemical attack for some uses of concrete. See Section D6 and Table D4.

Brownfield sites
A brownfield location is defined as a site or part of a site that has been subject to industrial development, storage of chemicals (including agricultural use) or deposition of waste, and which may contain aggressive chemicals in residual surface materials or in ground penetrated by leachates. See Section C5.1.3.

Cements and combinations
Cements are pre-blended from appropriate cementitious materials and are supplied by cement manufacturers. Combinations comprise similar cementitious materials that are combined in the concrete mixer. Cements and combinations prepared from the same ingredients, taken in the same proportion, are equivalent in respect of resistance to sulfure attack. Consequently, this Special Digest sometimes loosely uses the term ‘cement’ to cover both cements and combinations in generality or of a particular type.

Conventional form of sulfate attack
This is a form of sulfate attack in which sulfate ions that have penetrated concrete react with calcium aluminate hydrate to form calcium sulfo-aluminate hydrate (ettringite), or with calcium hydroxide, to form gypsum. Initially these reactions may result in non-destructive void filling. Attack is distinguished by onset of expansion and related cracking of the concrete. See Section B2.1.1.

Design Sulfate Class (DS Class)
This is a five-level classification for sites based principally on sulfate content (including Total Potential Sulfate) of the ground and/or groundwater. It is dependent on the presence or absence of substances including magnesium ions, pyrite and, for pH less than 5.5, chloride and nitrate ions. See Section C5 and Tables C1 and C2.

Design Chemical Class (DC Class)
DC Class was introduced in SD1:2001 to define qualities of concrete that are required to resist chemical attack. It is derived from the ACEC Class, but takes into account a number of other factors, including the type of concrete element and its Intended Working Life, and any exposure to hydraulic gradient due to groundwater. See Section D4 and Table D1.

Disturbed ground
Initially unweathered ground that is substantially disturbed, eg by cutting and filling to terrace a site, or by excavation and backfilling, such that air can enter and oxidise any pyrite contained therein. Simply cutting through ground without opening up the ground beyond the cut face, eg piling operations or excavation without backfill, does not generally result in disturbed ground.
Enhanced concrete quality
This is an increase in concrete quality used as an Additional Protective Measure (APM). The necessary enhancement may be determined from Table D2. In this Table, bold horizontal lines separate the various concrete qualities in respect of aggressive ground. Use of the option ‘Enhance concrete quality’ as an APM is satisfied by using the recommendations of the next higher DC Class. See Section D6.1.

Flowing groundwater
Flowing groundwater is defined in this Special Digest to cover the following two conditions (see Section C3.3):
- water that percolates through the ground under a permanent head in substantial quantity and at a relatively rapid rate, say, greater than 1 m/day;
- water that is flowing in surface conduits or streams.

Hydraulic gradient
The hydraulic gradient across a concrete element is the difference in hydrostatic head on the two sides of the concrete, in metres, divided by section thickness, in metres. For example a 3 m head of water external to the foot of a 0.3 m thick wall of a basement results in a hydraulic gradient of 10. This is greater than the hydraulic gradient of 5 that generally calls for increased provision against chemical attack on concrete.

Hydrostatic head
The hydrostatic head of water at a point in the ground is the height to which the water would rise in an open standpipe above that point.

Intended Working Life
This is the period of time during which the performance of the concrete in the structure will be kept at a level compatible with the fulfilment of the performance requirements of the structure, provided it is properly maintained. See BS EN 206-1. This definition has been adapted here to take some account of structural performance factors, such as the consequence of serious concrete degradation and ease of repair. Two categories are defined: ‘at least 50 years’ and ‘at least 100 years’. See Section D7 and Table D1.

Mobile groundwater
The term Mobile groundwater covers the following range of conditions (see Section C3.2):
- water held in pores and structural discontinuities in the soil which will flow into an excavation to give a standing water level;
- water which is percolating slowly through the ground, say at less than 1 m/day;
- still water in ponds, sumps, or similar accumulations of free water.

Oxidisable Sulfides (OS)
This is the amount of sulfate that may result from the oxidation of pyrite or similar sulfides in the ground (most likely due to ground disturbance). OS (expressed as % SO4) can be calculated from:

\[ \text{OS} = \text{TPS} - \text{AS} \]

where:
\[ \text{TPS} = \text{Total Potential Sulfate content as } \% \ SO_4 \]
\[ \text{AS} = \text{acid-soluble sulfate content as } \% \ SO_4 \]
See Section C5.1.2.

Pyritic ground
This is ground that contains the natural sulfide, pyrite, (FeS2). It is essential to take account of the additional sulfate content that might result from the oxidation of pyrite following ground disturbance. See Section C5.1.2.

Sacrificial layer
This is an Additional Protective Measure for concrete that increases the thickness of a construction element so that aggressive chemicals to which it is exposed are absorbed in a sacrificial outer layer. Use of this measure will not be appropriate in circumstances where the surface of the concrete must remain sound to prevent loss of frictional resistance or settlement, for example for skin friction piles. See Section D6.5. It is additional to the nominal cover, including any allowances for casting against uneven ground.

Static groundwater
Static groundwater sites will be confined to sites where the ground is either permanently dry or contains water but is relatively impermeable (virtually no water movement is possible). The mass permeability in the latter case will generally be less
than $10^{-7}$ m/s. A typical example would be clayey soils with tight fissures and no included sand or silt horizons. See Section C3.1.

**Thaumasite form of sulfate attack (TSA)**
TSA is a form of sulfate attack that consumes the binding calcium silicate hydrates in Portland cement, so weakening the concrete as well as causing some expansion. For occurrence, it requires availability of sulfates, calcium silicate, carbonate and water. Attack is most vigorous at temperatures below 15°C. See Section B2.1.2.

**Total Potential Sulfate (TPS)**
TPS is an upper limit value for sulfates in the ground. It is calculated as the sum of sulfates already present in the ground, plus those that may result from oxidation of pyrite or similar minerals. See Section C5.1.2.

**Water / cement ratio (w/c ratio)**
This is the ratio of the mass of free water in the fresh concrete to the mass of the cement or combination. Free water content is the water available for hydration of the cementitious material, this being less than the 'total' water content, which includes water that is held within aggregates.
References – Part A


British Standards Institution
BS 8500: 2002 Concrete – Complementary British Standard to BS EN 206-1

BS EN 197-1: 2000 Cement

Part 1: Composition, specification and conformity criteria for common cements

BS EN 206-1: 2000 Concrete

Part 1: Specification, performance, production and conformity