



BRIDGE TECHNICAL DIRECTION BTD2008/12

PROVISIONS FOR CONCRETE STRUCTURES IN ACID SULFATE SOILS

Background

RTA has recognised the hazards posed by Acid Sulfate Soils and has issued related policies, procedures and guidelines since the mid 1990's. RTA further expanded and consolidated its policies to cover acid sulfate materials and issued "Guidelines for the Management of Acid Sulfate Materials: Acid Sulfate Soils, Acid Sulfate Rock and Monosulfidic Black Ooze" in April 2005. Chief Bridge Engineer circular CBE 1996/09 was issued in 1996 to specify provisions to be taken when designing concrete bridge elements located in acid sulfate soils and prescribed the use of RTA policy document "Concrete Structures in Acid Sulfate Soils", RTA Technology, May 1996 for such situations.

Information

RTA Bridge Engineering has revised and updated the document prescribed in CBE 1996/09, which was first revised as "Acid Sulfate Soils – Concrete Structures – Advice for Design and Construction", Edition 2, June 1997.

Bridge Technical Direction

When a site survey for an RTA bridge or related structure identifies that the soil at the site is a potential acid sulfate soil or an actual acid sulfate soil, the structure shall be designed and specified in accordance with RTA policy document "Acid Sulfate Soils – Concrete Structures – Advice for Design and Construction", RTA Bridge Engineering – Policy and Specifications, Edition 3, May 2008.

The Senior Bridge Engineer (Policy and Specifications) can be contacted on telephone (02) 8837 0850, or by facsimile (02) 8837 005, if further clarification is required.

This Bridge Technical Direction supersedes CBE 1996/09.

Reference: CBE1996/09

Effective date: 14/05/2008

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ACID SULFATE SOILS

CONCRETE STRUCTURES – ADVICE FOR DESIGN AND CONSTRUCTION

REVIEW REPORT, EDITION 3 – May 2008

RTA Bridge Engineering - Policy and Specifications

SUMMARY

Acid Sulfate Soils (ASS), which include both Actual Acid Sulfate Soils (Actual ASS) and Potential Acid Sulfate Soils (Potential ASS), have been identified in many parts of Australia, with consequent effects on the environment and structures. For many design and construction engineers and project managers, the knowledge, implications and actions required to deal with ASS are not well understood. This report aims to supply the information necessary for correct decisions to be made regarding concrete structures in environments containing ASS.

This report:

- gives a brief environmental and geological overview and describes deterioration of concrete structures from the effects of ASS (Clauses 1 and 2);
- reviews and recommends methods of exposure classification (Clause 3);
- details factors to be considered when designing and specifying concrete structures in environments containing ASS (Clause 4);
- reviews and recommends coatings and other protection methods (Clauses 4.6 and 4.7); and
- provides a procedure and flowchart for dealing with concrete structures in ASS (Clause 5).

A bibliography of selected papers, standards, manuals, etc is provided for detailed explanation of the contents of this report.

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1 INTRODUCTION

RTA issued Guidelines²⁵ in April 2005 to update and replace RTA's *Acid sulphate soil policies and procedures* (1995) and *Acid sulphate soil guidelines* (1996) to address environmental issues and risks posed by acid sulfate soils (ASS), acid sulfate rock (ASR) and monosulfidic black ooze (MBO), all described as acid sulfate materials (ASM). The Guidelines address the management of ASM and should be used for project development, construction, maintenance and decommissioning of roadworks in areas containing such soils.

The Guidelines focus on the impact of RTA works on environments where ASM exist, and the identification, classification, risk assessment, treatment, monitoring and management of such materials.

This report provides information and advice to structural designers and project managers based on RTA bridge policy on this topic to ensure that concrete structures in naturally occurring ASS (both actual and potential) environments have the required durability. Although this report provides information and advice for structures in ASS, a similar approach may be used to deal with other soils and environments causing similar effects.

This report does not apply to pavements or concrete pipes, or ground conditions such as refuse waste, for which a specialist site specific study should be carried out.

2 ACID SULFATE SOILS (ASS)

2.1 General

Actual ASS contain highly acidic soil horizons or layers resulting from the oxidation of soil materials that are rich in iron sulfides. Oxidation produces hydrogen ions in excess of the sediments' capacity to neutralise this acidity, resulting in soils with pH of 4 or less when measured in the dry season.

Potential ASS contain iron sulfides or sulfidic material that has not been exposed to air and oxidised. The measured pH of these soils in their undisturbed state is usually 4 or more (and may be neutral or even slightly alkaline).

ASS includes both actual ASS and potential ASS. Both types may be found in a soil profile.

When water passes through actual ASS, sulphuric acid is leached out to react with the minerals in the soil to change its properties. If the soil has insufficient buffering capacity to neutralise the acid, the soil water, ground water and drainage water will all become acidic, and will contain dissolved aluminium, iron and heavy metals.

Engineering works on ASS, such as excavation, dredging and draining accelerate the exposure to air of pyritic soils i.e. those that contain natural sulfide, otherwise known as iron pyrites, (FeS₂). These operations can speed up the production of acidic ground water to many times the natural rate.

Passing into waterways and ground water, the sulphuric acid produced as a result of soil disturbance affects plant growth, aquatic life, animal and human health, and degrades engineering structures.

In addition to the risk of deterioration of engineering structures in actual ASS, unconsolidated estuarine sediments containing potential ASS may cause uneven subsidence under relatively low loads, causing structural problems.

2.2 Locations in NSW

ASS occur predominantly in low lying coastal areas with elevations generally up to 5 metres above Australian Height Datum (AHD). Maps of ASS distribution in the coastal zone were prepared in 1998 for NSW. There are approximately 4000 square kilometres of ASS in NSW with incidences having been reported in every estuary along the coast.

Although ASS generally occur in and around estuarine floodplains in the coastal zone, they have also been reported from several other locations in Australia. Inland ASS have also been reported around Yass in NSW.

2.3 Indicator – “pH”

pH is one of the indicators used to identify potential ASS. Other acidic soils which do not contain iron pyrites exist. The acidic or alkaline character of a liquid depends on its H^+ (hydrogen) ion and OH^- (hydroxyl) ion contents. Both types of ions are present in water. The pH of any aqueous solution relates to its hydrogen ion concentration. pH is $-\log_{10}$ (hydrogen ion concentration).

In neutral water the number of H^+ ions is equal to the number of OH^- ions. Any increase in one type of ion is accompanied by a corresponding decrease in the other type. Neutral water has a pH of 7. A pH less than 7 indicates acidity. A pH greater than 7 indicates alkalinity. The smaller the pH the greater the acidity down to a value of zero. The larger the pH the higher the alkalinity up to a value of 14.

A small change in the pH value is significant since the scale is logarithmic.

Table A can be used to classify water according to its pH.

Table A - Classification of water according to pH values

	pH				
	0-1-2-3	4-5-6	7	8-9-10	11-12-13-14
Classification	Acidic	Mildly acidic	Neutral	Mildly alkaline	Alkaline
pH content	H^+ ions predominant			OH^- ions predominant	

2.4 Hazards to Structures

NSW legislation is in place to protect the environment against deterioration due to the effects of ASS. Under this legislation, acid sulfate soils are those which contain greater than 0.1% sulfide and net acid generation potential greater than 0.0.

RTA's *Guidelines for the Management of Acid Sulfate Materials* require the identification of acid sulfate soils at an early stage of project planning. Procedures for identification of ASM, environmental impact assessment, ASM management planning and selection of ASM controls have been set out in those Guidelines.

Much of the information required for concrete durability design will be obtained when obtaining data for preparation of the Environmental Management Plan for the project.

Identification of ASM is carried out in two stages - preliminary identification and detailed identification. The former is undertaken during the investigation for assessing route options, proposal development and approvals. The latter is undertaken for detail design development and approval.

There are several methods and tests available to identify ASS. For the purposes of this report, two simple methods of identification are:

- (i) visual indicators of ASS;
- (ii) on-site pH measurements.

Visual indicators of ASS at a site may include yellow efflorescence on the soil surface, sulphurous smell, iron staining and iron flocculants in streams.

On-site pH of streams and fresh ground water samples and of 1:5 soil:water samples provide a good indication of acid sulfate conditions at the site.

Where soils contain enough sulfides, the sulfate content of ground water in construction pits, wells or boreholes may increase over a period of weeks to several times the original value. After backfilling, the sulfate content soon drops to previous levels, since the supply of air has been interrupted. This explains why water samples taken from construction pits are usually higher in sulfates than those obtained from exploratory drilling. Protective measures based on the higher sulfate content of samples taken from construction pits could be excessively conservative.

Moving water is particularly harmful to concrete. In stagnant water, dissolved salts will tend to combine with components of the hardened cement paste. Sodium sulfate in ground water will react with calcium hydroxide in the cement to form gypsum. The concrete pores are then partially sealed by the precipitated gypsum to form a natural protective layer on and near the concrete surface. In moving water aggressive acid sulfates may be replenished. In stagnant water the acid sulfates are consumed with time. In cohesive soils such as clay the seepage rate of ground water is of the order 10^{-5} m/s whilst in granular soils seepage rates a hundred or even a thousand times greater are possible. Therefore, in granular soils higher rates of deterioration should be expected.

2.5 Deterioration of Concrete Structures

2.5.1 General

Depending on the predominant chemical reaction, concrete deterioration processes can be classified into three groups according to their effects on the hardened cement paste:

- leaching;
- exchange reactions and removal of readily soluble compounds; and
- swelling, due to the formation of new, stable compounds.

2.5.2 Acids

Acids in concentrations common to natural waters can dissolve carbonates at the surface of the concrete and leach out lime. The concrete deteriorates because the calcium hydroxide in the cement paste is attacked by the acids to form water soluble salts subsequently leached out. Sulphuric acids may also cause swelling of the paste with subsequent cracking.

The rate of attack on the concrete is controlled by the nature of the acid, the pH value and the solubility of the calcium salts formed.

2.5.3 Sulfates

Sulfate attack on concrete is caused by an expansive chemical reaction between tricalcium aluminate (C_3A) components in the cement and the sulfates in solution to produce gypsum and calcium sulphoaluminate (ettringite). The crystals of ettringite occupy a larger volume than the original cement components that leads to expansion, cracking, and disintegration of the concrete.

The aggressiveness of soil containing sulfates is classified according to SO_3 content, more recently according to SO_4 content. SO_3 can be converted to SO_4 as follows:

$$SO_3 = 0.83 SO_4$$

Ammonium, calcium, magnesium and sodium sulfates are most detrimental to Portland cement. Potassium, copper and aluminium sulfates are less harmful. Barium sulfate and lead sulfate, which are insoluble in water, do not affect concrete.

3 EXPOSURE CLASSIFICATIONS

3.1 General

There are a number of codes, standards and other references which deal with environmental exposure classifications. This clause reviews the classifications to give guidance and recommendations when selecting exposure classifications for ASS conditions.

According to the exposure classification, concrete quality, chemical content restrictions, cover and other requirements are determined.

In determining the exposure classification of structural members in ASS, designers/specifiers in conjunction with Project Managers should assess possible environmental changes over the design life of the structure.

Since change in pH with time depends on many factors, there is no direct valid laboratory method capable of measuring potential pH. However, by carefully studying the various factors and examining test results, potential changes to pH can be estimated within a reasonable range. Such estimates should be requested from the geotechnical consultant.

For example, if pH of ground water is measured as 7 at the investigation stage, but other tests have shown that the soil is potential ASS, the pH can drop significantly if the soil is disturbed or drained. Therefore, construction methods, future development, and other factors which result in draining or disturbing potential ASS should be considered when determining the exposure classification.

The permeability of soil, as discussed earlier, is another factor to be taken into account when determining the exposure classification. In this report, soils with permeability less than 10^{-5} m/s are referred to as low permeability soils (e.g. clay). Soils with permeability greater than 10^{-5} m/s are referred to as high permeability soils (e.g. sand). Exposure to free water such as streams and rivers is classified as high permeability for the purposes of this report.

Designers and specifiers must ensure that appropriate and complete information is collected during site investigation, evaluated and then used when selecting an exposure classification.

3.2 AS 5100.5 Bridge design

AS 5100.5 applies to concrete bridges and related structural concrete members with a design life of 100 years and permits the adoption of AS 3600 for structures with design lives of 40 to 60 years.

Concrete exposure classifications are given in order of increasing severity from A, B1, B2 to C. Exposure classification U is used for other exposures subject to special consideration and includes a range of exposures from more severe than C, down to as benign as A.

For ASS, concrete exposure classification U must be used since the specific environment for such soils is not included in classifications A through to C. The Standard requires designers and specifiers to identify such exposures and specify appropriately for durability.

The Standard considers permeable soils with a pH < 4.0 or ground containing more than one gram per litre (1000 mg/l or 1000 ppm) of sulfate ions to be aggressive.

The exposure classifications in AS 5100.5 have been, except for minor changes such as the chemical content of cement, almost completely adopted from '92 AUSTROADS¹.

3.3 AS 3600 Concrete structures

AS 3600 applies to concrete structures and members with a design life of 40 to 60 years.

The approach and classifications used in the Standard are similar to those of AS 5100.5 with an additional subdivision of exposure classification A into A1 and A2.

The Commentary to AS 3600⁹ lists references for guidance for specification for exposure classification "U" similar to that of the Commentary to '92 AUSTROADS².

3.4 AS 3735 Concrete structures for retaining liquids

The Supplement to AS 3735¹⁰ states that the durability requirements of the Standard are appropriate for a design life of 40 to 60 years, and specifies four basic exposure classifications in order of increasing aggressiveness from A to D.

The exposure classification of the Standard is in line with AS 5100.5 and AS 3600 but with an additional classification D for which AS 3735 requires isolation from the environment for all concrete surfaces.

The exposure classifications are determined for a range of environments which are:

1. Fresh water	4. Corrosive liquids, vapours or gases
2. Sewage and waste water	5. Other liquids
3. Sea water	6. Ground water

The applicable item for ASS is No. 6 Ground water, for which a broad range of classifications is given. Reference can be made to the Supplement for assistance. Comprehensive guidance is given in the Supplement with specific details given for exposure classification U. Information for Item No. 6, together with material from the Supplement, has been rearranged and detailed in Appendix A of this report.

The exposure classification for the surface of a member is determined from the Standard and from AS 3600 for the most severe environment or use to which the concrete will be subjected during its operational life. However in the case of ASS, AS 3735 requirements are more detailed than AS 3600 and overrule and provide further direction to deal with aggressive environments. The requirements of AS 3735 and those of AS 3600 have been used in this report to determine the exposure classification of the surface of a concrete member.

For ASS, the exposure classification needs to be determined for both sulfate aggressiveness and acidity and the higher classification of the two is used. The use of sulfate resisting concrete and/or the use of calcareous (containing calcium carbonate or calcite) coarse aggregates are also specified depending on the severity.

The Standard recognises the use of the following as methods for obtaining durable concrete:

- sulfate resisting (SR) cements (superseded cement classification Type D);
- pozzolanic material (e.g. fly ash) blended with Portland cement i.e. blended cements;
- waterproofing agents with Portland cement.

Sulfate resisting cement and RTA preferred methods for obtaining sulfate resistance are discussed in later clauses of this report.

3.5 AS 2159 Piling – Design and installation

AS 2159 specifies that its durability requirements are for a design life of 40 to 60 years.

The Standard uses different exposure classifications to AS 5100.5 and the other Australian Standards reviewed above. The classification is self explanatory and comprises Non-aggressive, Mild, Moderate, Severe and Very Severe.

The relevant classifications for ASS have been rearranged and summarised in Appendix B of this report. The Standard uses sulfate expressed as SO_3 . To maintain consistency of this report and to enable comparisons, SO_3 has been converted for Appendix B to SO_4 using the equation $\text{SO}_3 = 0.83 \text{SO}_4$.

The sulfate limits of AS 2159 approximate those of AS 3735. However direct correlation for the two different classifications of the two standards is not appropriate since the specified minimum concrete strengths and cover differ. AS 2159 refers to AS 3735 for the design of concrete which is exposed to severe and very severe sulfate environments. AS 2159 also uses separate tables for acid and sulfate exposure. This limits the Standard's usefulness for ASS.

3.6 Other Classifications

In a Special Digest published by the U.K. Building Research Establishment ¹⁵, concrete in aggressive ground is extensively addressed including ASS and “brownfield” (sites which may contain chemical residues remaining from previous industrial use or from imported wastes). The exposure classifications are given in a different form to the Australian standards above.

The Digest considers another form of sulfate attack known as thaumasite sulfate attack (TSA) that reduces concrete to a white mushy reaction product rich in thaumasite. Several factors such as source of sulfate, mobile ground water, source of calcium silicate hydrate (CSH) in the cement paste, presence of carbonate (generally in limestone and similar aggregates) and low temperatures (most active below 15°C) must generally coincide for TSA to occur in susceptible concrete.

The significance of the BRE classification is the progressive selection of exposure classification and the relationship between various exposures. But its approach is somewhat

complicated as it has three different stages to assess the severity of conditions to derive the concrete specification.

The design sulfate class (DS Class) is determined firstly from soluble sulfate and magnesium contents, and from potential sulfate. It is used with pH and mobility of ground water to define the aggressive chemical environment for concrete class (ACEC Class) applicable to the location. Using the DS Class and ACEC Class, and the hydraulic gradient due to ground water, type and thickness of concrete element and the design life, the design chemical class (DC Class) is derived. The DC Class is used to specify the concrete in terms of maximum free-water/cement ratio, minimum cement content and type of cement. Additional protective measures are sometimes recommended for highly aggressive conditions.

All three classes have five basic levels from 1 to 5. Additional variations are sometimes introduced to allow for other factors such as magnesium content.

For ASS, DS Classes are defined based on different limits for sulfate content determined on soil samples from:

- a) Water soluble sulfate in 2:1 water:soil extract;
- b) Total sulfate content determined by the acid soluble sulfate method;
- c) Total potential sulfate calculated from total sulfur present as 3 times total sulfur; and
- d) pH of 2.5:1 water:soil extract.

The BRE Special Digest also stipulates tests, if possible, on ground water samples to determine:

- a) water soluble sulfate; and
- b) pH.

The BRE Special Digest provides a method to identify the presence of pyrites based on these tests. The amount of oxidisable sulfides is calculated as the difference of total potential sulfate content and acid soluble sulfate. When this amount is greater than 0.3% SO₄ in a significant number of samples, it indicates the probable presence of pyrites which can be confirmed by X-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis.

The DS Class of the location is independently assessed based on the water soluble sulfate in the 2:1 water:soil extracts and ground water samples and the total potential sulfate determined from soil samples for suspected pyritic soils. The highest class from these methods is the DS Class of that site.

Ground water conditions - static, mobile and flowing - are considered in the BRE Special Digest. Threshold values of pH 3.5 in static water and pH 5.5 in mobile water exist for most DS Classes and are used to separate two adjacent ACEC Classes for natural soil with the same DS Class. Flowing water is only considered when the water is pure or potentially aggressive due to significant levels of carbon dioxide.

Since the scope of the BRE report includes structures in addition to bridge and road infrastructure, only the classifications and modifications applicable to bridge and road structures have been included in Appendix C of this report. One of the rearranged classification tables, Table C/1 shows the five main ACEC Classes directly linked to exposure

classifications. Table C/2 shows the adjustments made to those values to arrive at the exposure classification in terms of DC Class for both low and high permeable soils.

The BRE Special Digest notes that the use of acid soluble sulfate content alone in more recent standards will not detect sulfides which might be oxidised to sulfates as a result of ground disturbance. However, concrete in pyritic ground does not have to be designed to withstand high sulfates if the oxidization is expected to be limited or prevented due to use of appropriate construction methods such as piles instead of footings which require excavation and backfilling that disturb the ground.

The BRE report limits the application of its recommended precautions to concrete placed in ground where $\text{pH} > 2.5$ since pH readings below 2.5 are reported only in very exceptional circumstances in the U.K.

3.7 RTA Design Requirements

As the Australian Standards referred to in previous clauses of this report specify measurements of SO_4 contents of soil or ground water, this report is based on ground water measurements. When disturbance of ASS may occur, the total potential sulfate content of the soil must be estimated and its implications for concrete structures taken into account.

Tables 1a and 1b below relate exposures applicable to bridge foundations in ASS to the exposure classifications in AS 5100.5. Exposure classifications are B1, B2, C, and U. Exposure classification A is not used, as B1 is the minimum exposure classification for members in soil or water specified in AS 5100.5.

Except for exposure classification U, in Table 1a and Table 1b concrete quality, cover and other durability requirements correspond to those of the exposure classifications in AS 5100.5.

Design requirements B1, B2, and C indicate equivalent concrete requirements to those specified for that exposure classification in AS 5100.5.

For exposure classification U, RTA design requirements are given in Table 2a and Table 2b below. These two tables relate the exposures applicable to bridge foundations in ASS to the exposure classifications in AS 5100.5 with additional protection measures and conditions.

RTA requirements that are not equivalent to the exposure classification in AS 5100 are a variant of exposure classification U to indicate it is outside the scope of AS 5100.5. In this report only design requirement U1 is used, defined as equivalent concrete design requirements to those of exposure classification C in AS 5100.5 with additional full isolation of the concrete from the environment.

For retaining walls and culverts, the relevant design requirements for high permeability soils should be used because RTA construction specifications for these structures specify that free draining granular soils for the backfill.

Table 1a - AS 5100.5 Exposure Classifications for LOW Permeability Soil*

SO ₄ (mg/l or ppm)	AS 5100.5 Exposure Classifications			
	pH			
	≤ 3.5	> 3.5 ≤ 4.5	> 4.5 ≤ 5.5	> 5.5
< 400	U	U	B1	B1
400 – 1500	U	U	B1	B1
1500 – 3000	U	U	B1	B1
3000 – 6000	U	U	U	U
> 6000	U	U	U	U

mg/l: milligrams per litre; ppm: parts per million

* See also Table 2a for actions in regard to equivalent exposure classification U

Table 1b - AS 5100.5 Exposure Classifications for HIGH Permeability Soil*

SO ₄ (mg/l or ppm)	AS 5100.5 Exposure Classifications			
	pH			
	≤ 3.5	> 3.5 ≤ 4.5	> 4.5 ≤ 5.5	> 5.5
< 400	U	U	B2	B1
400 – 1500	U	U	C	B2
1500 – 3000	U	U	U	U
3000 – 6000	U	U	U	U
> 6000	U	U	U	U

mg/l: milligrams per litre; ppm: parts per million

* See also Table 2b for actions in regard to equivalent exposure classification U

**Table 2a - RTA Design Requirements for Exposure Classification Type U of
Table 1a for LOW Permeability Soil**

SO ₄ (mg/l or ppm)	RTA Design Requirements (See Table 2a Notes below)			
	pH			
	> 2.5 ≤ 3.5	> 3.5 ≤ 4.5	> 4.5 ≤ 5.5	> 5.5
< 400	B2	B1	See Table 1a	
400 – 1500	B2	B1		
1500 – 3000	B2	B1		
3000 – 6000	C	B2	B2	B2
> 6000	U1	C	B2	B2

mg/l: milligrams per litre; ppm: parts per million

Table 2a Notes:

1. Table 2b is to be used for soil retaining structures and culverts.
2. Design requirements B1, B2, C indicate equivalent concrete requirements to that specified for the relevant exposure classification in AS 5100.5 and RTA B80.
3. Design requirement U1 indicates equivalent concrete requirements to that specified for exposure classification C in AS 5100.5 and RTA B80 with the addition of full isolation of the concrete surface from the environment.
4. Environments under the dark horizontal line require sulfate-resisting blended cement (Refer to Clauses 4.5.1 and 4.5.2 of this report).
5. Environments to the left of the dark vertical line require blended cement concretes containing calcareous aggregate with an increased concrete cover unless design requirement U1 is achieved (Refer to Clauses 4.2 and 4.3 of this report).
6. If pH is lower than 2.5, specialist advice should be sought.

Table 2b - RTA Design Requirements for Exposure Classification Type U of Table 1b for HIGH Permeability Soil

SO ₄ (mg/l or ppm)	RTA Design Requirements (See Table 2b Notes below)			
	pH			
	> 2.5 ≤ 3.5	> 3.5 ≤ 4.5	> 4.5 ≤ 5.5	> 5.5
< 400	U1	C	See Table 1b	
400 – 1500	U1	C		
1500 – 3000	U1	C	C	B2
3000 – 6000	U1	U1	C	C
> 6000	U1	U1	U1	U1

mg/l: milligrams per litre; ppm: parts per million

Table 2b Notes:

- Design requirements B1, B2, C indicate equivalent concrete requirements to that specified for the relevant exposure classification in AS 5100.5 and RTA B80.
- Design requirement U1 indicates equivalent concrete requirements to that specified for exposure classification C in AS 5100.5 and RTA B80 with the addition of full isolation of the concrete surface from the environment.
- Environments under the dark horizontal line require sulfate-resisting blended cement (Refer to Clauses 4.5.1 and 4.5.2 of this report).
- Environments to the left of the dark vertical line require blended cement concretes containing calcareous aggregate with an increased concrete cover unless design requirement U1 is achieved (Refer to Clauses 4.2 and 4.3 of this report).
- For soil retaining structures and culverts, the following modifications to the table apply:
 - Calcareous aggregate shall not be used;
 - B2 becomes B2 plus full isolation;
 - C becomes U1;
 - U1: no change.
- If pH is lower than 2.5, specialist advice should be sought.

4 STRUCTURAL DESIGN CONSIDERATIONS

4.1 General

In addition to the normal design process, design and construction of any structures in ASS requires careful consideration of the options available to mitigate the effects of sulfate and acid attack and incorporating these options from the beginning of the concept design stage. Some protective methods such as minimizing soil disturbance, quality of concrete, sacrificial layers, protective coating, addressing site drainage and the like are briefly explained. Any of these measures alone or in combination should be used to achieve durable concrete structures.

4.2 Soil Disturbance

Soil disturbance in ASS should be avoided wherever possible or minimised to limit the extent of oxidization of ASS during construction e.g. driven piles should be selected over cast in-situ bored piles; the possibility of extending piles above ground level to the headstocks or having above ground pile caps to avoid excavation should be considered.

4.3 Design Effects

The structural behaviour of any protective measures should be considered during design.

If the shaft of a concrete pile is covered by a special casing, liner or coating, account for the reduction in the shaft resistance for that length of pile which is protected. The axial load carrying capacity of friction piles is likely to be greatly reduced compared to mainly end-bearing piles. Where cast-in-situ piles have to be installed full depth in highly aggressive ground, use fully sleeved pile shafts on expanded bases of inert aggregate, but the end bearing capacity may be less than when the pile bases are formed with concrete.

The use of a sacrificial outer layer for friction piles is not appropriate since the surface of the concrete must remain sound to prevent loss of skin friction or settlement.

4.4 Sacrificial Concrete Layer

Under stagnant soil water conditions, the use of reactive aggregate can mitigate the degree of chemical attack on the concrete e.g. good quality limestone aggregate can neutralise some of the acid that would otherwise attack the cement paste.

There are some advantages in having a coarse aggregate which is not completely immune to attack, because the acid concentration can be reduced more rapidly if the acid reacts with the aggregate in addition to the cement.

Since limestone-aggregate concrete is capable of maintaining a reasonably smooth surface during erosion, it can be practicable to design for relatively thick sacrificial layers. Based on Hughes et al, the rate of erosion for 0.0016% acid concentration (pH of approximately 3.5)

was about 0.75 mm per year, so for a life of 20 years and a safety factor of 2, the required sacrificial layer would be 30 mm.

When total cover, comprising the design cover plus the sacrificial layer thickness, exceeds 80 mm, supplementary mesh reinforcement in the cover zone is required.

The use of limestone aggregate without an increase in concrete cover is disastrous. Therefore it is crucial that when limestone aggregate is specified for ASS an increase in concrete cover as a sacrificial layer is made. The contribution of the increased concrete thickness should be discounted when calculating the design strength of the member.

4.5 Quality of Concrete

4.5.1 Sulfate Attack

It is essential that the concrete is dense and well compacted to enable it to resist sulfate attack. Low concrete permeability and choice of cement type is more important than high characteristic strength.

Concrete should be fully cured and mature before exposure to sulphates as it has been found that more mature concretes are far more resistant to sulphate attack than immature concretes.

In neutral to alkaline environments, some resistance to sulfate attack is obtained when the tricalcium aluminate - C_3A - content of the cement is low. Traditional sulfate resisting Portland cements with low C_3A have been and are still used in such environments.

In acidic environments, the effectiveness of Portland cement of low C_3A alone in resisting sulfate attack is questionable. Work done by the CSIRO and others has demonstrated that the addition of supplementary cementitious materials to Portland cement improves sulfate resistance in neutral to acidic environments. Several papers report that blended cements give protection against sulfate attack superior to sulfate resisting Portland cement, due to the lower C_3A content from the Portland cement replacement, refined pore structure, and reduction of calcium hydroxide available to form gypsum that contributes to the attack.

Blended cements are effective only when proportioned correctly.

Fly ash blends have good sulfate-resisting properties only when the fly ash content is more than 25% of the cement. Fly ash proportions exceeding 40% are not generally recommended because of placement difficulties and a lack of data on performance.

Slag blended cements with more than 65% slag are considered sulfate resisting. The higher the slag content up to a maximum of 75% of the total cement, the higher the resistance to sulfate attack, but such high slag contents should be used only for concrete surfaces either permanently wet or permanently isolated from the air, to guard against the risk of carbonation when exposed to atmospheric carbon dioxide.

Silica fume blends of 5-15 % of the cement also have good sulfate-resisting characteristics.

Care should be taken when specifying sulfate resisting cement in acidic environments. AS 3972 Type SR cement should not be specified for use in ASS without specification of

blend proportions, contents and quality to achieve required resistance. RTA 3211 does not include Type SR cement as a cement acceptable for use in RTA structures.

Thaumasite sulfate attack should be considered and precautionary measures taken if any of the conditions described in Clause 3.6 occur.

4.5.2 Acid Attack

Concrete erosion by acidic water depends more on concrete quality than the type of cement. The lower porosity and permeability of blended cements is generally beneficial. Blended cements incorporating fly ash and/or slag in the proportions discussed above should be used.

The use of limestone aggregate in a sacrificial concrete layer is discussed in Clause 4.4.

For piles installed in an impermeable clay soil, acid or sulfate attack may only penetrate the concrete to such a small extent that only a small thickness of dense sacrificial concrete may remove the need for special cements. In other circumstances where the soil is of higher permeability, additional measures may also be necessary.

4.6 Protective Coatings

4.6.1 General

Protective coatings are a specialised field outside the scope of this report; this clause is provided for reference only.

Use of coatings for steel members is well established with a wide range of references and standards available. Concrete coatings are covered in many references but not to the extent of those for steel.

Concrete coatings should be considered as only one line of defence against an aggressive environment for use with other measures. As a general rule, use of coatings does not permit relaxation of concrete quality and composition discussed in earlier clauses of this report.

The selection of a coating for concrete is a complex process and is affected by several factors. These factors include:

- The type of surface to be coated and its condition;
- Surface orientation (e.g. horizontal, vertical);
- Construction methods;
- The environment and level of aggressiveness;
- Duration and changes of exposure;
- Temperature at time of curing of coating;
- System life required;
- Maintenance frequency and methods, if feasible.

Attempting to recommend a general coating system for a specified environment is not appropriate since the environment is not the only factor. Expert advice should be sought on a case by case basis.

4.6.2 Surface Preparation – An Essential Element

Surface preparation and conditions under which the coating is applied are extremely critical. Such operations should be supervised to ensure that the coating will perform its function.

Minimum requirements for surface quality and cleanliness are usually specified by the coating supplier in its instructions for surface preparation, to ensure that the coating bonds to the concrete surface. Mechanical cleaning such as grit blasting is usually required.

In ACI 515.1R-79 (85)³, a few quick and simple methods are specified to measure the cleanliness of a surface, three of which are:

Dust: Wipe the surface with a dark cloth. If a white powder is evident on the cloth, the surface is too dusty and unsatisfactory for some coating systems.

Oils: Sprinkle water on the dried concrete surface. If the water spreads out immediately instead of standing as droplets, the surface is not contaminated by oils or dust.

Laitance: Laitance may be detected by scraping the surface with a putty knife. If loose powdery material is observed, laitance is excessive and could adversely affect adhesion.

The repair of defects in concrete to be covered with a coating requires special attention. Patches should be cured and full bond achieved prior to applying the coating. If poor adhesion and/or unsound patching is suspected, then remove the patch and replace it with a new sound patch prior to applying the coating.

The dryness of the concrete surface is also critical, with a maximum moisture content of 5 to 8 % usually recommended by suppliers. Moisture content is excessive if moisture collects at the interface between the concrete and the coating before the coating has cured. This is assessed by taping a 1 m x 1 m clear polyethylene sheet to the concrete surface and determining the time required for moisture to collect on its underside. This can be compared with the required coating curing time specified by the supplier. A primer facilitates the process as its curing time is normally shorter than that of the coating.

4.6.3 Types of Coating Systems

There are a number and variety of coating systems which are differentiated by the basis of the coating and the curing process, with the following generic systems recommended for concrete:

1. Chlorinated Rubber;
2. Epoxy;
3. Vinyl Ester;
4. Bituminous.

Epoxy coatings generally have satisfactory acid resistance where $\text{pH} > 3.0$. They are not suitable where $\text{pH} < 3.0$.

Coal tar epoxies should not be used for coatings; their use is not approved by the Australian Paint Approval Committee for health hazard reasons.

Bitumen provides an economical alternative to proprietary paints for coating buried concrete elements, with good resistance to acid attack and water penetration. It adheres well to properly prepared concrete surfaces. Application procedure should be Steps 1 and 2 below followed by priming with cutback bitumen or thinned bitumen emulsion followed by application of two sprayed coats of cutback bitumen or bitumen emulsion with at least one day between coats. Take care when placing granular fill against bitumen coated concrete, as bitumen when cured is usually not as hard or abrasion resistant as paint. Bitumen coating of culverts should ideally be carried out in place to avoid damaging the coating during transport/installation.

Vinyl ester coatings are the most appropriate coating for the protection of concrete in acid soil conditions where $\text{pH} < 3.0$.

A complete concrete protection system using any of the above coating systems includes surface preparation, priming and one or more coats of the coating e.g. the recommended procedure for applying a vinyl ester system for a highly acidic environment is as follows:

1. Lightly brush blast concrete surface to remove laitance;
2. Fill voids in the concrete surface. Where many small voids exist, apply a cement render. Use a cementitious paste to fill voids greater than 2 mm in depth and/or diameter;
3. Apply a moisture cured urethane primer to seal the concrete surface;
4. Apply 1 coat of high build vinyl ester with 2 mm minimum dry film thickness.

Coatings should only be applied by trained and experienced applicators.

4.6.4 Coating System Life

The life of a coating system varies with the system used. Designers, specifiers and Project Managers should be aware of such variations and the relatively short life of coating systems compared with the design life of the structure. It is necessary to consider the coating system life along with the other measures used in these aggressive environments e.g. sacrificial limestone concrete cover, etc.

The life of a coating could vary from 10 to 20 years or more depending on the severity of the exposure conditions and the quality of surface preparation and coating application.

4.7 Other Protection Methods

Protection other than coatings may be required in some circumstances including prolonged exposure to very aggressive environments capable of penetrating any concrete and coating combination.

In such circumstances, a higher level of isolation from the environment is required; some methods used are:

- 10 mm thick permanent mild steel casings with 1.5 mm thick inner liner of heavy duty PVC for piles for extremely high sulfate concentrations e.g. 13,800 to 28,800 ppm;
- In an environment of 3000 ppm sulfates and high chloride concentrations in the Middle East, PVC sleeves coated with nylon fabric were recommended for pile protection;
- Packing a layer of limestone around the exposed face of the concrete element for protection of piles in acidic ground water;
- A sacrificial layer of concrete on piles together with other measures, but this is rarely solely relied on for highly aggressive conditions;
- Local replacement of permeable soil around piles with a layer of impermeable soil.

5 RECOMMENDED PROCEDURES

The following flowchart summarises procedures to be followed by designers, specifiers and/or Project Managers in the design, specification and construction of structures in ASS.

The procedures are grouped in three main stages:

1. Investigation;
2. Design and review; and
3. Construction.

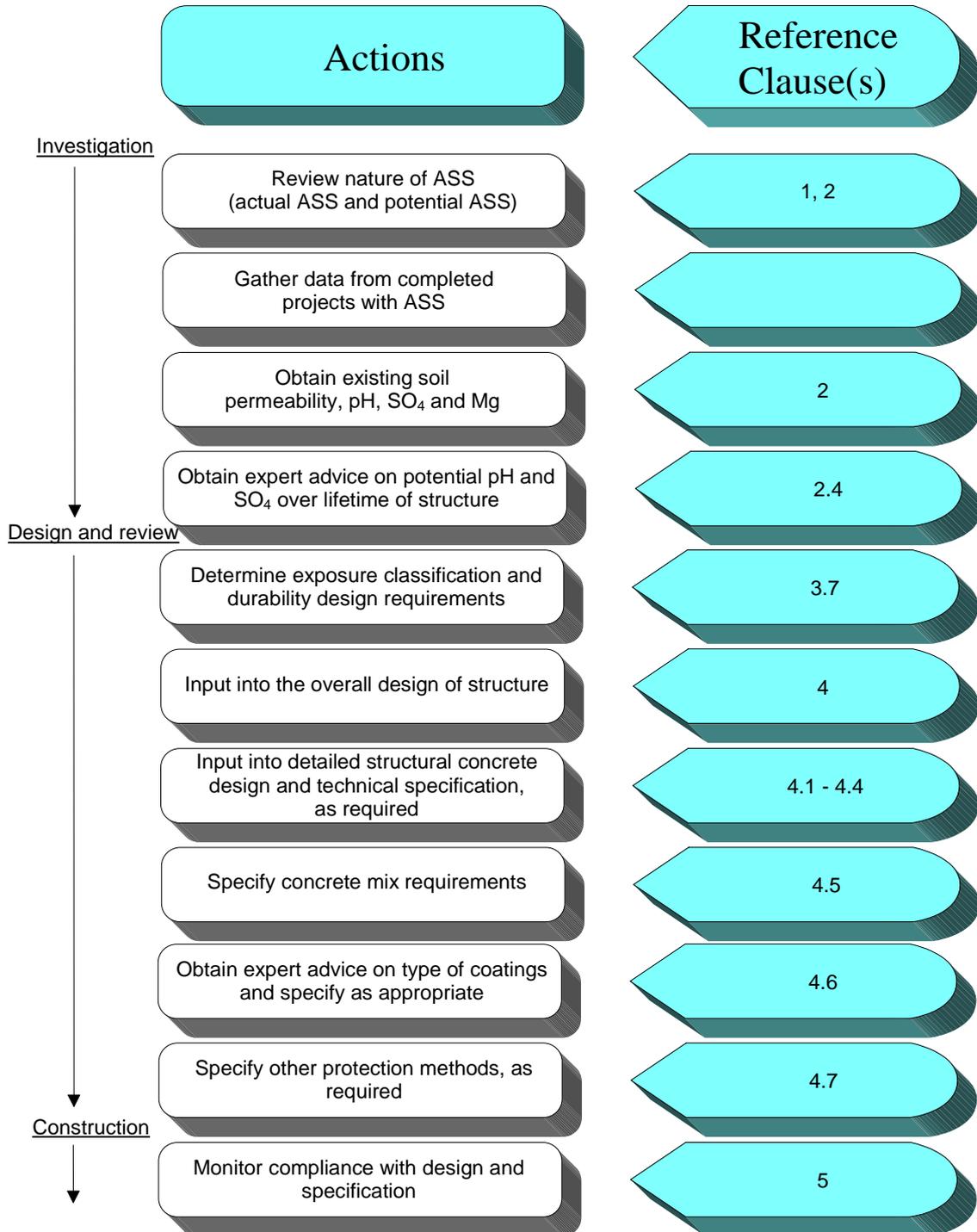
At each stage a number of steps is recommended.

It is essential that designers, specifiers and project managers communicate at all stages of the project development to deliver adequate, buildable and economical structures.

Monitoring and evaluation of design, specification and construction of structures in ASS in a project will not only satisfy that project's requirements but will also benefit other projects in the vicinity.

The relevant clauses of this report are referred to in most of the steps in the flowchart.

DEALING WITH ASS IN DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES



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APPENDIX A – AS 3735

Table A/1 - Exposure Classification – Sulfate Containing Soils (AS 3735)

SO ₄ Content		Ground water replenishment rate (i.e. soil permeability)	
In soil (%)	In water (mg/l or ppm)	Low (e.g. clay)	High (e.g. sand)
< 0.2	400	A2	B1
0.2 – 0.6	400 – 1500	B1	B2 (or <i>B1 with SR cement</i>)
0.6 – 1.2	1500 – 3000	B1	B2, with SR cement
1.2 – 2.4	3000 – 6000	B2 (or <i>B1 with SR cement</i>)	C, with SR cement
> 2.4	> 6000	B2, with SR cement	D

- Notes: 1. SR cement: Sulfate-Resisting cement
2. mg/l: milligrams per litre; ppm: parts per million

Table A/2 - Exposure Classification – Acidic Soils (AS 3735)

Acidity measure	Ground water replenishment rate (i.e. soil permeability)	
	Low (e.g. clay)	High (e.g. sand)
PH		
> 6.5	A1	B1
5.5 – 6.5	A2	B2
4.5 – 5.5	A2	B2, with calcareous aggregate and at least 125% of nominal cover
3.5 – 4.5	B1	C, with calcareous aggregate and at least 125% of nominal cover
< 3.5	B1, with calcareous aggregate and at least 125% of nominal cover	D

- Notes : 1. Calcareous aggregate is a limestone aggregate that should fulfil the requirements set forth in the Supplement.
2. Nominal cover increment should be increased by amount equal to loss that would occur over the design life.
3. mg/l: milligrams per litre; ppm: parts per million

APPENDIX B – AS 2159

Table B/1 - Exposure Classification - Concrete Piles in Sulfate-Containing Soils (AS 2159)

SO ₄		Exposure Classification	
In soil (%)	In water (mg/l or ppm)	Low permeability soil (e.g. clay)	High permeability soil (e.g. sand)
< 0.25	375	Non-aggressive	Non-aggressive
0.25 – 0.62	375 – 1250	Non-aggressive	Mild
0.62 – 1.25	1250 – 3125	Mild	Moderate
1.25 – 2.5	3125 – 6250	Moderate	Severe
> 2.5	> 6250	Severe	Very Severe

Notes: 1. mg/l: milligrams per litre; ppm: parts per million

Table B/2 - Exposure Classification - Concrete Piles in Acidic Soils (AS 2159)

Acidity (pH)	Exposure Classification	
	Low permeability soil (e.g. clay)	High permeability soil (e.g. sand)
> 6.5	Non aggressive	Non-aggressive
5 – 6	Non-aggressive	Mild
4.5 – 5	Mild	Moderate
4 – 4.5	Moderate	Severe
< 4	Severe	Very severe

APPENDIX C – BRE REPORT

**Table C/1 - Aggressive Chemical Environment for Concrete (ACEC) Class
(Other Classifications from BRE Report ¹⁵)**

SO ₄ content in ground water (mg/l or ppm)	Low permeability soil (e.g. clay)				High permeability soil (e.g. sand)			
	pH				pH			
	>2.5 ≤3.5	>3.5 ≤4.5	>4.5 ≤5.5	>5.5	>2.5 ≤3.5	>3.5 ≤4.5	>4.5 ≤5.5	>5.5
< 400	1s	1s	1s	1s	2z	2z	2z	1
400 – 1400	2s	1s	1s	1s	3z	3z	3z	2
1500 – 3000	3s	2s	2s	2s	4	4	4	3
3100 – 6000	4s	3s	3s	3s	5	5	5	4
> 6000m	5	4s	4s	4s	5	5	5	5

Notes:

1. mg/l: milligrams per litre; ppm: parts per million.
2. s is included when the ground water is static.
3. z is included when concretes have to resist acid conditions.
4. m is included when water soluble Mg is more than 1000 mg per litre and the concrete must resist high levels of magnesium sulfate but this is not expected to be applicable for natural ground conditions in the U.K. due to less magnesium content.

**Table C/2 - Exposure Classification – Design Chemical (DC) Class
(Other Classifications from BRE Report ¹⁵ General Cast-in-situ Use)**

SO ₄ content in ground water (mg/l or ppm)	Low permeability soil (e.g. clay)				High permeability soil (e.g. sand)			
	pH				pH			
	>2.5 ≤3.5	>3.5 ≤4.5	>4.5 ≤5.5	>5.5	>2.5 ≤3.5	>3.5 ≤4.5	>4.5 ≤5.5	>5.5
< 400	1	1	1	1	2z	2z	2z	1
400 – 1400	2	1	1	1	3z	3z	3z	2
1500 – 3000	3	2	2	2	4/1	4/1	4/1	3/1
3100 – 6000	4	3	3	3	4/sp	4/sp	4/sp	4/1
> 6000	4/sp	4	4	4	4/sp	4/sp	4/sp	4/sp

Notes :

1. mg/l: milligrams per litre; ppm: parts per million.
2. z is included when the concretes have to resist acid conditions.
3. The number following / indicates number of additional protective measures (APM) required.
4. sp following / indicates surface protection have to be used as additional protective measure (APM). An extra APM is generally not needed if surface protection is selected for use.
5. Where the hydraulic gradient across a concrete element is greater than 5, one step in DC Class or one APM over and above the number indicated in this table should be applied.
6. A section thickness of 140 mm or less should be avoided in in-situ construction but, where this is not practical, apply one step higher DC Class or an extra APM.
7. Where a section thickness greater than 450 mm is used and some surface chemical attack is acceptable, a relaxation of one step in DC Class may be applied.
8. For reinforced concrete, the cover should be sufficiently thick to allow for estimated surface degradation during the intended working life.
9. When the water soluble Mg is more than 1000 mg per litre and the concrete must resist high levels of magnesium sulfate, only a particular type of blastfurnace cement is allowed for use. This ACEC Class applies to browfield conditions only due to lesser magnesium contents in natural grounds in the U.K.

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