Exposure Period (days)	S1			S2			S3		
	0.4	**0.5**	**0.65**	**0.4**	**0.5**	**0.65**	**0.4**	**0.5**	**0.65**
	S1A	S1B	S1C	S2A	S2B	S2C	S3A	S3B	S3C
0	100	100	100	100	100	100	100	100	100
365	132	139	154	103	103	112	93	110	87
570	130	133	149	99	99	111	95	90	10
1075	125	127	152	97	93	65	110	45	0

Table II Retention of cylindrical compressive strength as % of 28-day strength in **pH 3.5**

Exposure Period (days	C1		C2		C3		C4		C5	
	0.4	**0.5**	**0.4**	**0.5**	**0.4**	**0.5**	**0.4**	**0.5**	**0.4**	**0.5**
0	100	100	100	100	100	100	100	100	100	100
514	125	130	136	151	146	158	117	137	125	123
776	120	116	141	153	136	151	109	128	118	109
939	120	122	138	151	135	146	113	129	115	106
1240	123	127	136	163	131	149	111	136	115	108

Exposure Period (days)	S1			S2			S3		
	0.4	**0.5**	**0.65**	**0.4**	**0.5**	**0.65**	**0.4**	**0.5**	**0.65**
	S1A	S1B	S1C	S2A	S2B	S2C	S3A	S3B	S3C
0	100	100	100	100	100	100	100	100	100
365	119	123	156	87	97	112	90	102	90
570	120	128	136	77	95	97	102	86	6
1075	101	116	135	90	91	87	93	24	11

In **Tables I and II,** it can be observed that the compressive strength of the concrete increased well above the 28 day strength in the first 1–2 years of immersion, followed by a gradual reduction in strengths. After three-year exposure in both neutral and acidic sodium sulfate solutions, the strengths remained at or above the 28-day strength level for Type SR cement concretes with water-cement ratios of 0.4 and 0.5. This clearly showed the integrity of the concrete and its mechanical resistance to sulfate attack.

The condition of the concrete cylinders after 3-years exposure was quite varied with most retaining their integrity but some were badly cracked especially around the top edges. See **Plate 3** showing contrast in colour of cylinders after 3-year exposure.

Grey in neutral sulfate solution Rustic red in acidic sulfate solution

Plate 3 Cylinders after 3 years exposure prior to compression test

Performance of partly buried concrete

While most buried concrete elements such as piles and footings are likely to be kept moist throughout their service life, parts of some of them (e.g. the top of footings and pile caps) may be exposed to periodic wetting and drying conditions. The PCA study confirmed that the exposure to alternate immersion and atmospheric drying in the sodium sulfate-rich soil was a more severe exposure condition than continuous immersion in the same solution. Attention must therefore be given to the sulfate resistance of concrete under such exposure conditions. Stark [14] found a consistently improved trend in the rating of the surface deterioration of concrete with increased cement content irrespective of the type of cement. In the PCA's 17 concrete mixtures with a cement content of 390 kg/m^3, most concretes had a rating between 1.4 and 3.8 after 12–years exposure in the sulfate-rich soil ground in Sacramento. This is considered to be a good performance of the concrete under such an aggressive sulfate environment. Stark found that the observed severe deterioration in the outdoor exposure was due largely to cyclic crystallisation of $NaSO_4$ salts after sufficient evaporation of moisture from the outdoor soils exposure as postulated by Folliard and Sandberg [8]. This is probably the reason for the effectiveness of a sealer, such as silicon and linseed oil, in limiting the capillary-induced migration of sulfate, and thus improving the performance of concrete including concrete with higher w/c of 0.49–0.52.

With all Type SR cement concrete mixes performing exceedingly well under full immersion in sodium sulfate solutions at both neutral and acidic conditions, and a minimum cement content of 415 kg/m^3 in the 0.4 w/c series, it is likely that the low water–cement ratio concretes will also perform very well in the severe wetting and drying condition. With appropriate surface protection, the 0.5 w/c series of concrete with a minimum cement content of 335 kg/m^3 would also be expected to perform well in the more aggressive wetting and drying condition.

Specifying sulfate-resisting concrete

Sulfate-resisting concrete has traditionally been specified prescriptively by the type of cement and mix proportion limits in terms of maximum water–cement ratio and minimum cement content. In highly acidic and permeable soils where pH is below 3.5, additional protective measures are required to isolate the concrete from direct contact with the aggressive ground condition. ACI 318 [9] and BRE SD1 [10] are examples of these specifications. BRE SD1 is particularly progressive in recommending specifications for sulfate-resisting concrete for intended working life of 50 years for building works and 100 years for civil engineering structures.

Australian Standards

In the revision of the Australian Standard for concrete structures AS 3600 [16], specifications for concrete in sulfate soils with a magnesium content of less that 1000 mg/L have been introduced. For each exposure classification, concrete is specified in terms of concrete grade and minimum concrete cover, see **Table III**. The current Australian Standards for piling, AS 2159 [17] and for concrete structures for retaining liquids, AS 3735 [18], recommend the specification of certain concrete grades and corresponding covers for a design life 40–60 years in a range of exposure classifications. The exposure classification is defined by the magnitude of sulfate in the soil or in groundwater, pH level and the soil conditions in term of its permeability. In severe and very severe conditions, where sulfate levels exceed 2000 ppm in groundwater or 1% in soil, AS 3735 Supplement [19] recommends a minimum cement content of 320 kg/m^3 and a maximum water–cement ratio of 0.5 and the use of Type SR cement.

Table III Strength and cover requirements for sulfate soils
(Summarised from Tables 4.8.1 and 4.10.3.2 in the AS 3600 – 2009)

SO4		**Exposure classification**	**Characteristic strength (MPa)**	**Minimum cover (mm)**
In groundwater (mg/L)	**In soil (%)**			
< 1000	< 0.5	A2	25	50
1000 – 3000	0.5-1	B1	32	50[1]
3000 – 10,000	1-2	B2	40	50[1,2]
>10,000	>2	C1 and C2	≥50	65[1,2,3]

Notes:
1 It is recommended that cement be Type SR.
2 Additional protective coating is recommended.
3 The cover may be reduced to 50 mm if protective coating or barriers are used.

The findings in terms of compressive strengths, dimensional and strength stability in 5% (50,000 ppm) sodium sulfate solution described in the previous section, supported the specification of sulfate resisting concrete by strength grade and cover (AS 2159 and AS 3600), and in particular, confirmed the expected performance of the sulfate resisting concrete in the moderate (B2) and severe to very severe (C1 and C2) exposure classifications shown in Table 3.
It should be noted that the Australian Standard for bridge design AS 5100 [20] provides no specific guidance on specifying concrete for 100 years design life in sulfate conditions.

Table IV Additional requirements (from Table 8 of QDMR MSR11.70)

Exposure Classification	**Minimum Cementitious Content (kg/m3)**	**Maximum Water–cementitious Ratio**	**Strength Grade (MPa)**
B1	320	0.56	32
B2	390	0.46	40
C	450	0.40	50

As can be noted, the findings from CCAA research project also support the above specifications.

Other Specifications

Road authorities, such as the RTA in New South Wales and the Queensland Department of Main Roads, are specifying sulfate-resisting concrete based on exposure classifications in Austroads Bridge Design Code (superseded by

AS 5100), but with additional limits on maximum w/c and minimum cement content. Queensland Department of Main Roads refers to MRS11.70 with the additional requirements shown in **Table IV**.

Performance-based Specifications

Sulfate resisting concrete has traditionally been specified prescriptively by the maximum water–cement ratio and a specific type of SR cement. This is to ensure good physical resistance of the concrete to limit the penetrating sulfate ions, and good chemical resistance of the cement matrix to the deleterious sulfate reactions. A performance specification based on water permeability of the concrete has been proposed by Sirivivatnanon and Khatri [11]. As part of CCAA research, a further attempt has been made to develop a performance-based specification for sulfate resisting concrete based on the physical resistance of the concrete (e.g. water permeability, rapid sulfate permeability) and the chemical resistance of the cement (sulfate expansion). A six-hour accelerated test method for a rapid sulfate permeability determination was developed and is shown in **Figure 4**.

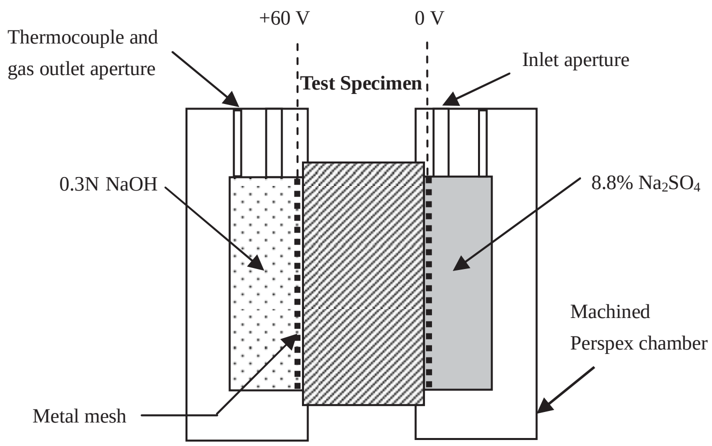

Figure 4 An accelerated test set-up for the rapid sulfate permeability determination

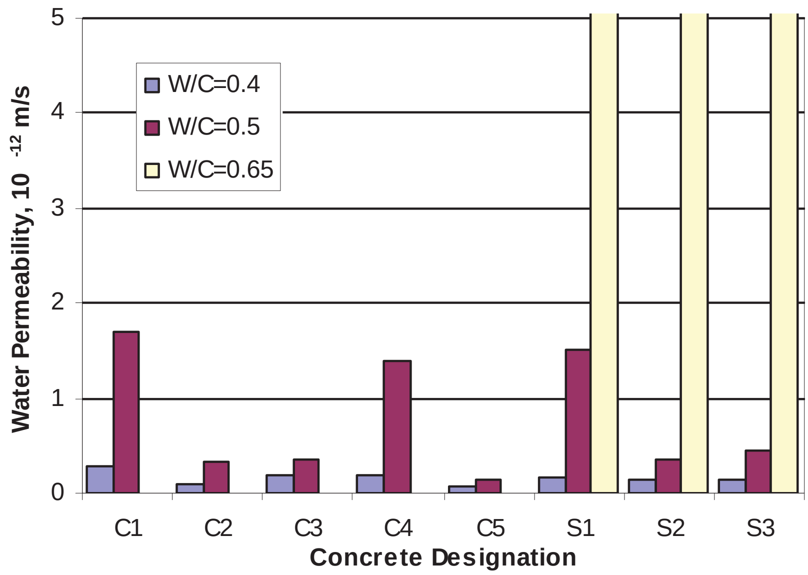

Figure 5 Water permeability of the concretes at w/c of 0.4, 0.5 and 0.65

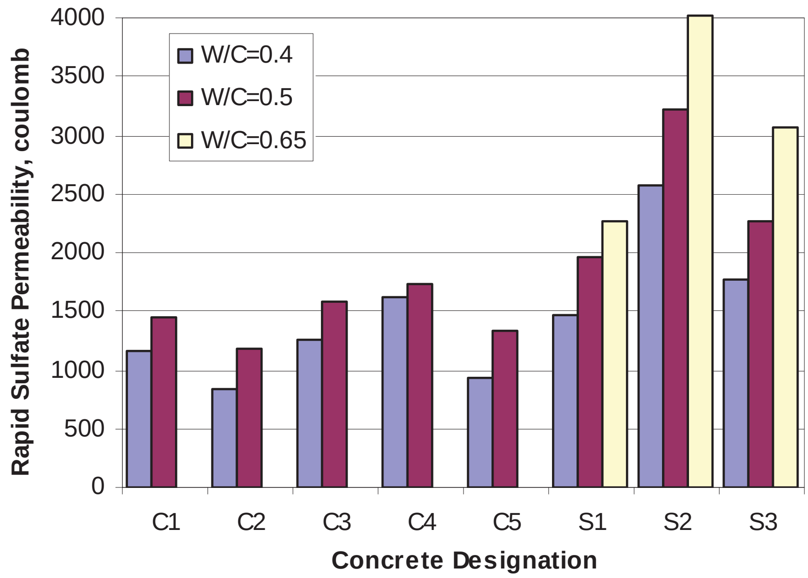

Figure 6 Rapid sulfate permeability of the concretes at w/c of 0.4, 0.5 and 0.65

The dimensional stability and strength retention properties of the nineteen concrete mixes were evaluated in accordance with the criteria established in section 4.1. Concrete passing both expansion and strength retention criterion is considered sulfate-resisting concrete. The mix prescription in water-cement ratio, and performance properties: water permeability coefficient and rapid sulfate permeability; are summarised in Table V and shown in Figures 5 and 6 above.

Table V Summary of long-term performance and possible specifications

Concrete Properties	C1-C5		S1			S2			S3		
	0.4	0.5	0.4	0.5	0.65	0.4	0.5	0.65	0.4	0.5	0.65
Water permeability, $x10^{-12}$ m/s	0.07-0.28	0.34-1.70	0.16	1.5	70.3	0.14	0.35	13.4	0.13	0.44	16
Rapid sulfate permeability, coulombs	940-1260	1180-1450	1475	1965	2260	2580	3225	4010	1780	2265	3060
Water-to-cement	0.40-0.41	0.50	0.39	0.50	0.63	0.39	0.5	0.66	0.40	0.50	0.66
28-day Compressive Strength, MPa	47.5-75.5	32.5-59.0	52.5	49.5	29.5	68.0	64.0	37.0	68.0	58.0	34.5

Based on these properties, a semi-prescriptive and performance-based specification for sulfate-resisting concrete is proposed as follows.

1. Type SR cement and water-cement ratio ≤ 0.5, and
2. Type SR cement and a water permeability coefficient ≤ 2x10-12 m/s or rapid sulfate permeability ≤ 2000 coulombs.

For concrete subjected to the physio-chemical process in wetting and drying condition, an additional sealer will be required. Alternatively more stringent water-cement ratio limit of 0.4 or a water permeability coefficient limit of 0.5x10-12 m/s or a rapid sulfate permeability limit of 1750 coulombs would be required for the corresponding semi-prescriptive and performance-based specifications.

Conclusions

Sulfate resistance of concrete is a function of its physical and chemical resistance to penetrating sulfate ions. Good physical resistance of the concrete is directly related to the water-cement ratio and the cement content. Good chemical resistance is related to the resistance of the cement matrix to the deleterious sulfate reactions.

Sulfate-resisting concrete can be achieved using a sufficient quantity of a sulfate-resisting cement (Type SR complying with AS 3972) and a low water–cement ratio to obtain a concrete with low water permeability. For fully buried concrete structures in saturated soils, a sulfate-resisting concrete can be achieved from Type SR cement at a cement content of 335 kg/m3 and a water–cement ratio of 0.5. For partially buried structures exposed to a wetting and drying condition, the same sulfate-resisting concrete can be used but with additional protective measure such as the application of an appropriate sealer to the surface of the exposed concrete. Alternatively, a sulfate-resisting concrete can be achieved from Type SR cement at a cement content of 415 kg/m3 and a water–cement ratio of 0.4. The AS 3600 specifications for concrete structures in acid sulfate soils, based on minimum compressive strength and Type SR cement, is shown to produce adequate sulfate-resisting concrete for the exposure condition indicated. Alternatively, performance-based specifications based on Type SR cement and a concrete with a limit on either water permeability or rapid sulfate permeability can be used.

References

[1] AS 3972 *General purpose and blended cements*. Standards Australia, Sydney 2010.

[2] ASTM C 1202 *Indication of Concrete's Ability to Resist Chloride Ion Penetration*

[3] NSW Acid Sulfate Soils Management Advisory Committee. *Acid Sulfate Soils Assessment Guidelines*, 1998.

[4] Selim H, Forster, G and Chirgwin G, 'Concrete Structures in Acid Sulfate Soils', Proceedings of Austroads Bridging the Millennia Conference, edited by G.J. Chirgwin,
Vol. 2, Sydney, 1997, pp 393–409.

[5] Carse A 'The design of concrete road structures for aggressive environments', Proc of Concrete Institute of Australia 22nd Biennial Conference, Melbourne, 2005.

[6] Lea F M *Chemistry of Cement and Concrete*. 4th edition, Elsevier, London, 2004.

[7] Biczok I *Concrete Corrosion: Concrete Protection*. 8th edition, Akademiai Kiado, Budapest, 1980.

[8] Folliard K J and Sandberg P, 'Mechanisms of Concrete Deterioration by Sodium Sulfate Crystallization', American Concrete Institute, SP145, Durability of Concrete, Third International Conference, Nice, France, pp 933–945.

[9] American Concrete Institute. *Building Code Requirements for Reinforced Concrete*, ACI 318–10.

[10] Building Research Establishment. Concrete in aggressive ground, BRE Special Digest 1:2005.

[11] Sirivivatnanon V and Khatri R P 'Performance Based Specification for Sulphate Resisting Concrete,' Proceedings of International Conference on a Vision for the Next Millennium, edited by R N Swamy, Sheffield, U.K., June, 1999, pp 1097–1106.

[12] Tumidajski P J and Turc I, *A Rapid Test for Sulfate Ingress into Concrete*, Cement and Concrete Research, Vol. 25, No. 5, pp 924–928, 1995.

[13] Verbeck G J 'Field and Laboratory Studies of the Sulphate Resistance of Concrete', Proceeding of a symposium in honour of Thorbergur Thorvaldson, Candana, 1967, 113–124.

[14] Stark D C 'Performance of Concrete in Sulfate Environments, RD129, Portland Cement Association, (USA), 2002.

[15] Monteiro P J M and Kurtis K E, 'Time to failure for concrete exposed to severe sulfate attack', Cement and Concrete Research, Vol. 33, No. 7, pp 987–993, 2003.

[16] AS 3600 *Concrete Structures*, Standards Australia, Sydney, 2009.

[17] AS 2159 *Piling – Design and installation*, Standards Australia, Sydney, 1995.

[18] AS 3735 Concrete structures for retaining liquids, Standards Australia, Sydney 2001.

[19] AS 3735 *Concrete structures for retaining liquids Supplement – Commentary*, Standards Australia, Sydney, 2001.

[20] AS 5100 *Australian Standard for Bridge Design*, Standards Australia, Sydney, 2004.