Physical & Chemical Performance of Concrete
Part 1 Performance Specifications

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Professor of Concrete Engineering

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KEY MESSAGES

1. Performance is derived through good specifications
2. Concrete production control depends on whether prescriptive or performance-based specifications
3. Use systematic engineering approach to evaluate new construction materials
OUTLINE

This presentation will cover:

Are there DURABILITY issues?

1. Lessons from past
   - Inappropriate use or lack of use of SCM
   - Lack of effective quality control
2. AS 3600 50 year design life & AS 1379
   - No guidance in SCM
   - No post-pour control of cover Quantity
3. Optimising concrete performance
4. Specifying durability for infrastructures
5. Current materials research

Impact of MATERIAL specifications

1. Roles of binders on the resistance to chloride, sulfate & carbonation
2. Roles of limestone addition
3. Aggregates
ARE THERE DURABILITY ISSUES?
1. LESSONS FROM THE PAST
1.1 INAPPROPRIATE USE OF SCM
LESSONS FROM THE PAST

1.2 LACK OF EFFECTIVE QC
LESSONS FROM THE PAST

1.3 GOOD CONCRETE COVER

Port Kemble swimming pool

Illuka wharf
## HISTORICAL DEVELOPMENT LEADING TO BS 8110 & AS 3600

<table>
<thead>
<tr>
<th>Code of Practice Standards</th>
<th>Performance Specifications</th>
<th>Control</th>
</tr>
</thead>
</table>
| Australia: AS 1481 & 1482  | Structural requirement: Compressive strength grade 1  
                            | Durability requirement: Min cement content, Max w/c                                         | Strength None                  |
| UK: CP110-1972            |                                                                                             |                                |
| Australia: AS 3600-1988   | Structural requirement: Compressive strength grade 1  
                            | Durability requirement: Max w/b ~ Strength 2                                              | The higher of the two strengths|
| UK: BS8110-1985           | Wide spread acceptance of blended cements                                                    |                                |
| RTA B80-1990s UK Highway  | Combined prescriptive & performance-based specs  
                            | UK Highway structural concrete series_1700                                                 | Strength, Sorptivity           |
                            |                                                                                             | *Post-pour Cover*               |
2. AS3600 CONCRETE STRUCTURES

50 YEARS DESIGN LIFE

The 2009 Revision

Minimum standard for Type GP cement, and based on 2005 data 50 year design life

Durability covers carbonation- & chloride-induced corrosion, sulfate & acid sulfate attack, and abrasion & skid.

Referencing HB79 for AAR.
## 2.1 ENVIRONMENTAL LOADS

### TABLE 4.3 EXPOSURE CLASSIFICATION

<table>
<thead>
<tr>
<th>Surface and exposure environment</th>
<th>Exposure classification R.C. or prestressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Surface of members in contact with ground (d) Members in aggressive soils (i) sulfate bearing (magnesium content &lt; 1 g/L)</td>
<td>See Table 4.8.1</td>
</tr>
<tr>
<td>3. Surfaces of members in above-ground exterior environments in areas that are: (b) Near-coastal (1-50 km from coastline) (c) Coastal</td>
<td>B1, B2</td>
</tr>
<tr>
<td>5. Surfaces of maritime structures in sea water (a) permanently submerged (b) in spray zone (c) in tidal/splash zone</td>
<td>B2, C1, C2</td>
</tr>
</tbody>
</table>
### 2.2 SPECIFYING SR CONCRETE

#### Table 3
Strength and cover requirements for sulfate soils with a magnesium content of less than 1000 ppm

(See Sulfate-resisting Concrete. CCAA Technical Note TN68, May 2011, 8 p.)

<table>
<thead>
<tr>
<th>SO$_4^-$</th>
<th>Exposure classification</th>
<th>Characteristic strength (MPa)</th>
<th>Minimum cover ( mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In groundwater (mg/L)</td>
<td>In soil (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 1000</td>
<td>&lt; 0.5</td>
<td>A2</td>
<td>25</td>
</tr>
<tr>
<td>1000 – 3000</td>
<td>0.5-1</td>
<td>B1</td>
<td>32</td>
</tr>
<tr>
<td>3000 – 10,000</td>
<td>1-2</td>
<td>B2</td>
<td>40</td>
</tr>
<tr>
<td>&gt;10,000</td>
<td>&gt;2</td>
<td>C1 and C2</td>
<td>≥50</td>
</tr>
</tbody>
</table>

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.
## 2.3 PROTECT REINFORCING STEEL

### TABLE 4.10.3.2 REQUIRED COVER

<table>
<thead>
<tr>
<th>Exposure class</th>
<th>Required cover, mm</th>
<th>Characteristic strength, (f’c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 MPa</td>
<td>25 MPa</td>
</tr>
<tr>
<td>A1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>A2</td>
<td>(50)</td>
<td>30</td>
</tr>
<tr>
<td>B1</td>
<td>(60)</td>
<td>40</td>
</tr>
<tr>
<td>B2</td>
<td>(65)</td>
<td>45</td>
</tr>
<tr>
<td>C1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3 CRACK CONTROL MEASURES

Limiting stress in tensile steel

AS 5100 (Bridge design) limits the permissible stress to 150 MPa (Grade 500 MPa)
AS 4997 (Maritime structures)
maximum stress 185-150 MPa depending on bar sizes.

Controlling crack width

AS 3600 (40-60 years)
Limits on bars spacing
AS 5100 (100 years)
Minimum steel of 500 mm²/m

Similar approach to European Standard
<table>
<thead>
<tr>
<th>Exposure classification</th>
<th>Minimum $f'_c$</th>
<th>Minimum cement material content</th>
<th>Maximum water/cement (W/C) ratio</th>
<th>Minimum initial curing requirement (see Clause 17.3.5.1)</th>
<th>Cure continuously for at least</th>
<th>Column 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>kg/m³</td>
<td></td>
<td></td>
<td>days</td>
<td>MPa</td>
</tr>
<tr>
<td>A</td>
<td>25</td>
<td>280</td>
<td>—</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>B1</td>
<td>32</td>
<td>330</td>
<td>0.50</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>B2</td>
<td>40</td>
<td>400</td>
<td>0.45</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>C1</td>
<td>50</td>
<td>450</td>
<td>0.40</td>
<td></td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>C2</td>
<td>50</td>
<td>470</td>
<td>0.36</td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Exposure classification</td>
<td>Fly ash (FA)</td>
<td>Slag</td>
<td>Amorphous silica (SF)</td>
<td>Triple blends</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>--------------</td>
<td>------</td>
<td>-----------------------</td>
<td>--------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>100*/0 to 70*/30↑</td>
<td>100*/0 to 60*/40↓</td>
<td>100*/0 to 90*/10§</td>
<td>Up to 60*/up to 40↑, up to 25↓, up to 10§</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>100*/0 to 70*/30↑</td>
<td>100*/0 to 60*/40↓</td>
<td>100*/0 to 90*/10§</td>
<td>Up to 60*/up to 40↑, up to 25↓, up to 10§</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>80*/20↑ to 70*/30↑</td>
<td>70*/30↑ to 60*/40↓</td>
<td>92*/8§ to 90*/10§</td>
<td>Up to 60*/up to 40↑, up to 25↓, up to 10§</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>75*/25↑ to 60*/40↑</td>
<td>50*/50↑ to 30*/70↓</td>
<td>92*/8§ to 90*/10§</td>
<td>25* – 30*/60↑ – 67*/8§ – 10§</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>75*/25↑ to 60*/40↑</td>
<td>50*/50↑ to 30*/70↓</td>
<td>92*/8§ to 90*/10§</td>
<td>25* – 30*/60↑ – 67*/8§ – 10§</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfates (expressed as SO₄)</td>
<td>Exposure conditions</td>
<td>Chlorides in groundwater ppm</td>
<td>Exposure classification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------</td>
<td>------------------------------</td>
<td>------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In soil ppm</td>
<td>In groundwater ppm</td>
<td>pH</td>
<td>ppm</td>
<td>Soil conditions A</td>
<td>Soil conditions B</td>
<td></td>
</tr>
<tr>
<td>&lt;1000 ppm</td>
<td>&lt;400 ppm</td>
<td>&gt;5.5</td>
<td>&lt;2000 ppm</td>
<td>B1</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1000–10 000 ppm</td>
<td>400–1500 ppm</td>
<td>4.5–5.5</td>
<td>2000–8000 ppm</td>
<td>B2</td>
<td>B1</td>
<td></td>
</tr>
<tr>
<td>3000–20 000 ppm</td>
<td>1500–10 000 ppm</td>
<td>4–4.5</td>
<td>8000–18000 ppm</td>
<td>C1</td>
<td>B2</td>
<td></td>
</tr>
<tr>
<td>&gt;20 000 ppm</td>
<td>&gt;10 000 ppm</td>
<td>&lt;4</td>
<td>&gt;18000 ppm</td>
<td>C2</td>
<td>C1</td>
<td></td>
</tr>
</tbody>
</table>

**LEGEND:**
* Acid sulfate soils or to sulfate soils with a magnesium ions content of less than 1000 ppm.
† Approximately 100 ppm SO₄ = 80 ppm SO₃
‡ Soil conditions A—high permeability soils (e.g., sands and gravels) that are in groundwater
§ Soil conditions B—low permeability soils (e.g., silts and clays) or all soils above groundwater
### 2.4 Abrasion Resistance

**Table 4.6: Strength Requirements for Abrasion**

<table>
<thead>
<tr>
<th>Member and/or Traffic</th>
<th>Minimum Characteristic Strength ($f'_c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footpaths and residential driveways</td>
<td>20 MPa</td>
</tr>
<tr>
<td>Commercial and industrial floors not subject to vehicular traffic</td>
<td>25 MPa</td>
</tr>
<tr>
<td>Pavements or floors subject to:</td>
<td></td>
</tr>
<tr>
<td>(a) Pneumatic-tyred traffic</td>
<td>32 MPa</td>
</tr>
<tr>
<td>(b) Non-pneumatic-tyred traffic</td>
<td>40 MPa</td>
</tr>
<tr>
<td>(c) Steel-wheeled traffic</td>
<td>To be assessed but not less than 40 MPa</td>
</tr>
</tbody>
</table>

**Note:** $f'_c$ refers to the strength of the wearing surface.
2.5 LACK OF NATIONAL APPROACH TO PREVENT ASR

Australian Standards

AS 1141.60.1 Accelerated Mortar Bar Test, AMBT
AS 1141.60.2 Concrete Prism Test, CPT

Handbook HB79: Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia

First edition – 1996
Second edition – 2015
2.6 QUALITY CONTROL (QC) OF COVER QUALITY AS1379 SPECIFICATION AND SUPPLY OF CONCRETE

6.5 PROJECT ASSESSMENT OF STRENGTH GRADE

6.5.2 Project assessment for plants subject to production assessment

(b) At least one sample from each 50 m³

(d) Concrete deemed not to comply if the moving average strength of 3 consecutive samples is less than $f_{c}'$

(e) If less than 3 samples, concrete deemed not to comply if strength is less than $0.85f_{c}'$

2.6 QUALITY CONTROL (QC) OF COVER QUALITY AS1379 SPECIFICATION AND SUPPLY OF CONCRETE

6.5 ASSESSMENT BY ALTERNATIVE METHODS WITH AN ACCEPTED OPERATING CHARACTERISTIC*

Acceptable if can be demonstrated that the methods provide a reliable statistical operating characteristic so that -

(a) Concrete with a proportion defective of 0.05 has a probability of acceptance of at least 50%; and
(b) Concrete with a proportion defective of 0.30 has a probability of rejection of at least 98%;

2.7 QUALITY CONTROL (QC) OF COVER QUANTITY

AS3600 & AS5100.5

tolerances for cover

Pre-pour control by inspection of gaps between steel and formwork

17.5.3 Tolerance on position of reinforcement and tendons

The deviation from the specified position of reinforcement and tendons shall not exceed the following:

(a) For positions controlled by cover—

(i) in beams, slabs, columns and walls .................................................. −5, +10 mm;

(ii) in slabs-on-ground .............................................................................. −10, +20 mm; and

(iii) in footings cast in the ground ............................................................. −10, +40 mm,

where a positive value indicates the amount the cover may increase and a negative value indicates the amount the cover may decrease.

(b) For positions not controlled by cover, namely—

(i) the location of tendons on a profile ......................................................... 5 mm;

(ii) the position of the ends of reinforcement ............................................. 50 mm; and

(iii) the spacing of bars in walls and slabs and of fitments in beams and columns .................. 10% of the specified spacing or 15 mm, whichever is greater.
2.8 RELATIVE IMPORTANCE OF COVER QUANTITY & QUALITY

\[ t = \frac{x^2}{2D_a} \left[ \text{erf}^{-1}\left(1 - \frac{C_x}{C_s}\right) \right]^2 \]

- Time to corrosion initiation, \( t \), is highly dependent on the depth of cover – a function of the \textbf{square of cover} \( x \)
- Field observation and studies* confirmed that lack of adequate cover to be the overwhelming cause of premature corrosion

2.9 QUALITY CONTROL (QC) OF CONCRETE QUANTITY

The need for and a method to control concrete cover (1991)*

Post-pour inspection and quantification of cover
Balancing the risks of cover assessment

UK Highway & RMS

Practical control of concrete cover
eg. RMS B80 clause 8.4 specifies measurement of cover by a covermeter.
UK Highway structural concrete series_1700

CONCLUSIONS ON AS3600 & AS5100.5

1. Good foundation for design life specifications
2. AS 3600 was based on research but silent on SCM
AS 5100.5 make explicit use of SCM research
3. AS 3600: Good control of cover quality
AS 5100.5: Difficult to QC prescriptive requirements
4. Lack of control of cover Quantity
3. A GOOD EXAMPLE OF OPTIMISING CONCRETE PERFORMANCE
SORRELL CAUSEWAY BRIDGE

100 year design life

Gibbens, Smith and Joynson, ‘Sorell Causeway Channel Bridge, Tasmania’ CIA Seminar.
4. SPECIFYING DURABILITY FOR INFRASTRUCTURES (BRIDGES)

Various state road authorities have used both prescriptive & performance-based specifications.

For marine exposure, various test methods used have been studied in terms of:

correlation to long-term (1-year) diffusion coefficient,
Proficiency of test method
Lack of background on 100 year design life

<table>
<thead>
<tr>
<th></th>
<th>$D_{e.28}$</th>
<th>$Sorptivity_{28}$</th>
<th>$VPV_{28}$</th>
<th>$RCPT_{28}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10$^{-12}$ m$^2$/s)</td>
<td>(mm/s$^{0.5}$)</td>
<td>(%)</td>
<td>(Coulomb)</td>
</tr>
<tr>
<td>Precision from relevant standards or other sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sources of Precision</strong></td>
<td>ASTM C1566</td>
<td>ASTM C1585</td>
<td>ASTM C642</td>
<td>ASTM C1202</td>
</tr>
<tr>
<td>Reportable to</td>
<td>0.001</td>
<td>0.1x10$^{-4}$</td>
<td>0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Repeatability CV</td>
<td>14%</td>
<td>6%</td>
<td>1.8%(2)</td>
<td>12.3%</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>20%</td>
<td>NA(1)</td>
<td>6.5%(2)</td>
<td>18%</td>
</tr>
<tr>
<td><strong>Correlation to $D_{e.365}$ of a GP &amp; 3 GB cement concretes (CSIRO, 1998)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range of value</td>
<td>10–60</td>
<td>15–100mm</td>
<td>6–13, 13–18</td>
<td>1000–5000</td>
</tr>
<tr>
<td>Correlation coef, $R$</td>
<td>74%</td>
<td>76%</td>
<td>12%, 86%(3)</td>
<td>76%</td>
</tr>
<tr>
<td>Critical range: one order change in $D_{e.365}$ from 1 to 10 m$^2$/s</td>
<td>28</td>
<td>41 mm</td>
<td>1.5</td>
<td>1270</td>
</tr>
<tr>
<td>Increment used in classifications</td>
<td>RTA B80 12 mm</td>
<td>VicRoads 1–2%</td>
<td>C1202 1000</td>
<td></td>
</tr>
</tbody>
</table>
The principal chloride transport mechanisms are diffusion and capillary absorption.

The use of prescriptive specifications of cement type & w/c has been effective in specifying chloride resistance. QC may post a challenge.

Diffusion coefficient, capillary absorption (sorptivity & VPV) and migration properties (RCPT) are all good indicators of long-term chloride resistance.

The effective range of these properties are:

- Sorptivity: 15-100mm
- VPV: 13-17%
- RCPT: 1000-5000 coulombs
5. CURRENT RESEARCH

Limit-state service life design (CSIRO/CCAA)
Sustainability & utilisation of scarce resources

**GP cement with higher mineral addition (CCAA)**
**Use of manufactured sand (CCAA)**
**Use of reactive aggregates in HPC (UTS/CCAA)**
Prevention of DEF in precast concrete (UTS/Humes)
Making full use of all available fly ashes (RMS/UTS)
Durability & applications of geopolymer concrete (UTS, UNSW)
LIMIT-STATE SERVICE-LIFE DESIGN

SUSTAINABILITY & UTILISATION OF SCARCE RESOURCES

GP cement with higher mineral addition (CCAA)
Use of manufactured sand (CCAA)
Use of reactive aggregates in HPC (UTS/CCAA)

Hierarchy of test methods
Use of reaction kinetics to measure level of reactivity
Influence of chemical composition of SCM in mitigating ASR
PREVENTION OF DEF IN PRECAST CONCRETE (UTS/HUMES RESEARCH)
MAKING FULL USE OF ALL AVAILABLE FLY ASHES (UTS/RMS)
CONCLUSIONS

1. Australian specifications enable good concrete performance if used appropriately.

2. Concrete production control requires emphasis on both quality and quantity of concrete.

3. Need to use systematic engineering approach to evaluate new construction materials.

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   - Lack of effective quality control
2. AS 3600 50 year design life & AS 1379
   - No guidance in SCM
   - No post-pour control of cover Quantity
   - Lack of National approach to prevent ASR
3. Specifying durability for infrastructures
4. Current materials research

Impact of MATERIAL specifications
1. Roles of binders on the resistance to chloride, sulfate & carbonation
2. Roles of limestone addition
3. Aggregates
1. SUPPLEMENTARY CEMENTITIOUS MATERIALS

Important aspects of SCM

1. Pozzolanic or semi-hydraulic material contributing to improved binder performance

2. Consistency in the quality and availability of supply, and hence the popularity of industrial by-products

3. Contribution to sustainability

Much of earlier research in the 1990’s focused on their effect on strength and specific durability mostly in qualitative term. More recent research attempts to examine durability in more quantitative term focusing on performance measurement.
1.1 QUALITATIVE PERFORMANCE: FLY ASH

Chloride Concentration (%)

Charge Transfer Values (Coulombs)

Expansion (microstrain)

Exposure to Sulphate environment (days)
1.2 **QUALITATIVE PERFORMANCE: FA**

1.3 QUALITATIVE PERFORMANCE: HVFA

Development of high volume fly ash (HVFA) concrete and first applications in

- Concrete pavement at Mount Piper power station
- Foundation of Crown Casino in Melbourne.

1.4 QUALITATIVE PERFORMANCE: SLAG

High slag cement concrete was first used in the construction of Sydney Harbour Tunnel (SHT) followed by Bream B & West Tuna offshore oil platform and subsequently in Wandoo.
1.5 SCM: SEMI-QUANTITATIVE PERFORMANCE
DEVELOPMENT OF SULFATE-RESISTING CONCRETE

Experimental Programme
Properties & Performance Tests

28-day Properties
– compressive strength,
– water to cement ratio,
– water permeability,
– rapid sulfate permeability

Results used in specifying sulfate-resisting concrete

3-year immersion in 5% Na$_2$SO$_4$ kept at pH 7 & pH 3.5
– Expansion of prisms
– Strengths retention
  > Compression
  > Flexural & cube compression

Characteristics of concrete subject to sulfate attack leading to expansion and strength loss.
PERFORMANCE PROPERTIES

3-day water-cured & tested at 28-day

Water permeability (Darcy’s)
Rapid sulfate permeability (6-hour test)
Water-to-cement ratio
CONCRETE 28-DAY PROPERTIES
COMPRESSIVE STRENGTH, MPA

Compressive Strength, MPa

water/cement
WATER AND RAPID-SULFATE PERMEABILITY

Water permeability, $10^{-12}$ m/s

- $S_1$
- $S_2$
- $S_3$
- Limit

Cement 1
Cement 2
Cement 3
Cement 4
Cement 5

Rapid sulfate permeability, coulomb

- $S_1$
- $S_2$
- $S_3$
- Limit

Cement 1
Cement 2
Cement 3
Cement 4
Cement 5

UTS: ENGINEERING AND INFORMATION TECHNOLOGY
3-YEAR DIMENSIONAL & STRENGTH STABILITY
EXPANSION OF PRISMS IN 5% $\text{Na}_2\text{SO}_4$ @ PH7

USBR failure criterion 5000

pH 7, W/C=0.5

Limit on expansion rate
EXPANSION OF PRISMS IN 5% NA$_2$SO$_4$ @ PH3.5

P H 3.5, W/C=0.5

Limit on expansion rate
## RATINGS OF EXPANSION & STRENGTH RETENTION

<table>
<thead>
<tr>
<th>Long-term criteria</th>
<th>Type SR cements</th>
<th>Non SR cements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1-C5</td>
<td>S1</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Expansion</strong></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>Strength</strong></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>Expansion</strong></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>Strength</strong></td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

**Conclusion 1:** Type SR cement is essential in sulfate-resisting concrete
Conclusion 2: Sulfate-resisting concrete can be specified by permeability
## Exposure conditions

<table>
<thead>
<tr>
<th>Sulfates (expressed as SO₄)</th>
<th>pH</th>
<th>Soil conditions A (high permeability)</th>
<th>Soil conditions B (Low permeability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In soil ppm</td>
<td>In groundwater ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 000</td>
<td>&lt;1 000</td>
<td>&gt;5.5</td>
<td>A2 (25/30)</td>
</tr>
<tr>
<td>5 000-10 000</td>
<td>1 000-3 000</td>
<td>4.5-5.5</td>
<td>B1 (32/40)</td>
</tr>
<tr>
<td>10 000-20 000</td>
<td>3 000-10 000</td>
<td>4-4.5</td>
<td>B2 (40/45)</td>
</tr>
<tr>
<td>&gt;20 000</td>
<td>&gt;10 000</td>
<td>&lt;4</td>
<td>C2 (50/65)</td>
</tr>
<tr>
<td>CCAA Australia</td>
<td>50 000</td>
<td>3.5, 7</td>
<td>3 years in solution with failure criteria from PCA &amp; CSIRO study</td>
</tr>
<tr>
<td>PCA - USA</td>
<td>65 000</td>
<td>Not reported</td>
<td>12 years immersion in solution or semi burial field condition</td>
</tr>
<tr>
<td>USBR - USA</td>
<td>21 000</td>
<td>Not reported</td>
<td>40 years partial immersion</td>
</tr>
</tbody>
</table>
# RMS BTD 2008/12: CONCRETE STRUCTURES
## RMS QA SPECIFICATION B80

<table>
<thead>
<tr>
<th>Exposure conditions</th>
<th>Exposure classification</th>
</tr>
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<tbody>
<tr>
<td>Sulfates (expressed as SO4)</td>
<td>Soil conditions high permeability &gt; 10^{-5} m/s</td>
</tr>
<tr>
<td>In soil ppm</td>
<td>In groundwater ppm</td>
</tr>
<tr>
<td>-</td>
<td>&lt; 400</td>
</tr>
<tr>
<td>-</td>
<td>400-1 500</td>
</tr>
<tr>
<td>-</td>
<td>1 500-3 000</td>
</tr>
<tr>
<td>-</td>
<td>3 000-6 000</td>
</tr>
<tr>
<td>-</td>
<td>&gt;6 000</td>
</tr>
<tr>
<td>CCAA Australia</td>
<td>50 000</td>
</tr>
<tr>
<td>USBR - USA</td>
<td>21 000</td>
</tr>
</tbody>
</table>
CONCLUSIONS ON SULFATE-RESISTING CONCRETE

1. Type SR cement or blended cements are essential in producing highly sulfate-resisting concrete.

2. Sulfate-resisting concrete are characterised by
   - Long-term volume stability (ettringite), and
   - Long-term strength retention (gypsum & decalcification)

3. Acidic sulfate condition is slightly more aggressive than the neutral sulfate condition.

4. The research outcomes supported AS3600-2009 specification for concrete in the most aggressive category of sulfate and acid sulfate soil conditions, as well as RMS specifications.

1.6 SCM: QUANTITATIVE PERFORMANCE
LONG-TERM EXPOSURE OF CONCRETE IN TIDAL CONDITIONS
2.6 SCM: QUATITATIVE PERFORMANCE
RESISTANCE OF CONCRETE TO CHLORIDE PENETRATION
NON-STEADY STATE

\[ C_s = 1.0\% \text{ for LS4} \]
(a capillary absorption-diffusion)

\[ C_s = 0.7\% \]
(A diffusion)

---

**Measured LS4**
**Calculated LS4**
**Measured G4**
**Calculated G4**
## CCAA RESEARCH DATA
### CONCRETE 9-YEAR TIDAL EXPOSURE

<table>
<thead>
<tr>
<th>Binder</th>
<th>w/b</th>
<th>F28 (MPa)</th>
<th>Cs</th>
<th>D_{1\text{year}} (10^{12} m^2/s)</th>
<th>Alpha</th>
<th>Critical Chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP</td>
<td>0.6</td>
<td>38.0</td>
<td>0.8</td>
<td>7.93</td>
<td>0.60</td>
<td>0.15</td>
</tr>
<tr>
<td>GP</td>
<td>0.4</td>
<td>63.0</td>
<td>2.8</td>
<td>1.15</td>
<td>0.55</td>
<td>0.12</td>
</tr>
<tr>
<td>50% Slag</td>
<td>0.6</td>
<td>33.5</td>
<td>1.6</td>
<td>2.87</td>
<td>0.75</td>
<td>0.05</td>
</tr>
<tr>
<td>50% Slag</td>
<td>0.4</td>
<td>45.5</td>
<td>0.5</td>
<td>1.24</td>
<td>0.60</td>
<td>0.03</td>
</tr>
<tr>
<td>30% Fly Ash</td>
<td>0.6</td>
<td>25.5</td>
<td>1.5</td>
<td>2.80</td>
<td>0.85</td>
<td>0.10</td>
</tr>
<tr>
<td>30% Fly Ash</td>
<td>0.4</td>
<td>62.5</td>
<td>1.4</td>
<td>0.90</td>
<td>0.55</td>
<td>0.05</td>
</tr>
</tbody>
</table>

LONG-TERM EXPOSURE OF CONCRETE IN TIDAL CONDITIONS

CARBONATION & DURABILITY REQUIREMENTS OF AS3600

Carbonation in 4% CO₂ (mm/y^{0.5})

28-day compressive strength (MPa)
WATER SORPTIVITY & DURABILITY REQUIREMENTS OF AS3600

![Diagram showing water sorptivity and 28-day compressive strength relationship.](chart.png)
2. ROLES OF LIMESTONE ADDITION

Examine the possible increase in limestone mineral addition (LS) in the type of cement commonly used in all general applications from the sustainability viewpoint.

**USA** allows up to 5% LS in ASTM Type I cement, and 15% in PLC.

**European**: 5%LS in Type ??

**France** has used up to 45%LS in PLC for specific applications.

**Canada**: 15% LS in portland limestone cement used in most construction work.

**New Zealand**: 12%LS in GP cement.

**Australia**: 7.5% in General Purpose (Type GP) cement.

Further increase must be based on the full implication on sustainability.

---

### 3 Pillars of Sustainability

<table>
<thead>
<tr>
<th>Essence of Construction Materials</th>
<th>Environmental Impact</th>
<th>Social Impact</th>
<th>Optimum Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Strength</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Durability</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

---

**UTS: Engineering and Information Technology**

[eng.uts.edu.au](http://eng.uts.edu.au)  
[ita.uts.edu.au](http://ita.uts.edu.au)
## 2.1 INCREASED LIMESTONE & SUSTAINABILITY

### Essence of construction materials

<table>
<thead>
<tr>
<th>Sustainability reference points</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental Impact</strong></td>
</tr>
<tr>
<td><strong>Social Impact</strong></td>
</tr>
<tr>
<td><strong>Optimum Cost</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Essence of Construction Materials</strong></th>
<th><strong>Construction</strong></th>
<th><strong>Strength</strong></th>
<th><strong>Durability</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental Impact</strong></td>
<td>Reduction in clinker content &amp; hence CO2 with no negative impact on strength &amp; durability</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Social Impact</strong></td>
<td>Neutral (Limestone from same source)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Optimum Cost</strong></td>
<td>Cost neutral or possible saving due to reduced energy cost per tonne of cement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2 IMPACT ON STRENGTH & VOLUME STABILITY

Earlier research on lab-blended cement with ground limestone by Dhir et al. (2007) suggested possible replacement of up to 15%

Effect of % limestone on the compressive strength of concrete at various cement contents (Dhir et al., 2007)

Effect of % limestone on the compressive strength, creep and drying shrinkage of a concrete with w/c of 0.6 and 310 kg/m³ (Dhir et al., 2007)
2.2 IMPACT ON DURABILITY

Tsvillls et al. (1999) found PLC concrete with 20% limestone to have higher porosity (P) and gas permeability coefficient (K_g) but lower water permeability (K_w) than PC concrete. Matthew (1994) found the depth of carbonation to increase with water to cement ratio and limestone content (0-25%), and that the depth of carbonation was reliably correlated with the 28-day strength of concrete.

Barker and Matthews (1994) confirmed the finding that concretes of equal strength carbonate at similar rates irrespective of the limestone content.

<table>
<thead>
<tr>
<th>Lime-</th>
<th>Blaine</th>
<th>Strength at</th>
<th>w/c</th>
<th>Strength at</th>
<th>K_g</th>
<th>K_w</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>stone</td>
<td>m²/kg</td>
<td>28 day MPa</td>
<td></td>
<td>28 day MPa</td>
<td>10^-17 m/s</td>
<td>10^-12 m/s</td>
<td>mm/min</td>
<td>%</td>
</tr>
<tr>
<td>0</td>
<td>260</td>
<td>51.1</td>
<td>0.70</td>
<td>31.9</td>
<td>2.26</td>
<td>2.39</td>
<td>0.237</td>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
<td>340</td>
<td>47.9</td>
<td>0.70</td>
<td>27.4</td>
<td>2.65</td>
<td>2.30</td>
<td>0.238</td>
<td>12.3</td>
</tr>
<tr>
<td>15</td>
<td>366</td>
<td>48.5</td>
<td>0.70</td>
<td>27.3</td>
<td>2.80</td>
<td>2.22</td>
<td>0.226</td>
<td>12.3</td>
</tr>
<tr>
<td>20</td>
<td>470</td>
<td>48.1</td>
<td>0.70</td>
<td>28.0</td>
<td>2.95</td>
<td>2.00</td>
<td>0.220</td>
<td>13.1</td>
</tr>
<tr>
<td>20</td>
<td>325</td>
<td>39.8</td>
<td>0.62</td>
<td>28.2</td>
<td>3.03</td>
<td>1.81</td>
<td>0.228</td>
<td>12.9</td>
</tr>
<tr>
<td>25</td>
<td>380</td>
<td>40.0</td>
<td>0.62</td>
<td>26.5</td>
<td>2.82</td>
<td>2.07</td>
<td>0.229</td>
<td>13.6</td>
</tr>
<tr>
<td>35</td>
<td>530</td>
<td>32.9</td>
<td>0.62</td>
<td>26.6</td>
<td>2.10</td>
<td>2.23</td>
<td>0.224</td>
<td>14.6</td>
</tr>
</tbody>
</table>
In Australia, substantial research are on-going as to optimum % of limestone permissible in the production of GP cement. Some of these research findings can be found on CCAA website.

Apart from satisfying all the essential requirements shown, it is vital that the followings apply:

1. Compatibility with SCM
2. Existing framework in relevant Australian Standards and leading Government specifications assure full compliance of the quality of concrete
3. AGGREGATES

The relative importance of aggregates is evident from the fact that most concrete consist of a large volume of aggregates (70-80% by volume). Current challenges include:

1. Shortage of natural sand and source of sound rock, and the environmental impact of new quarries
2. Improved supply of manufactured sand
   - better management of fines & deleterious clay
   - re-examine prescriptive-based specifications
   - better crushing to improve shape & water demand
3. Greater use of marginal aggregates & appropriate risks management
3.1 MANUFACTURED SAND IN AUSTRALIAN STANDARD

Cement Concrete & Aggregates Australia (CCAA) examines a range of physical, mechanical and chemical properties of manufactured sand and test methods. Recommendations such as grading and deleterious fines, which measure both the quantity and activity of the fines, were derived from the research.

Outcomes: No further distinctions were made between natural and manufactured sand in AS2758.1 and specification of a limit on “deleterious fines”, being a multiple of MBV and %passing 75microns, in all sands to control durability of concrete.

References:
3.2 MANUFACTURED SAND IN CONCRETE PAVEMENT

A joint CCAA/RTA (Roads & Traffic Authority – New South Wales) research, conducted both on laboratory concrete and on actual concrete pavement, found the influence of sand on skid resistance of concrete pavement to be dependent on its resistance to physical abrasion in a micro-Deval test, rather than its stability in acid (testing the amount of hard silica).

Outcomes: RTA adopts performance-based specification for fine aggregates used in road pavement. This enables good quality man sand to be used in concrete pavement.

References:
3.3 ALKALI SILICA REACTIVITY (ASR)

National guideline such as HB79 and AASHTO PP65 provide guidance to minimise the risk to structural deterioration or damage due to alkali-carbonate and alkali-silica reactivity.

Both such guidelines provide a framework for engineer to select ASR avoidance strategies in accordance with the severity of the exposed environment, the importance & design life of the structure, and the mitigation of ASR by controlling the alkali from cement and the appropriate use of SCM.

References:
AASHTO PP65 – Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction.
LAB-FIELD RESEARCH OUTLINE

MAN SAND TESTING
- Micro-Deval - abrasion
- Na₂SO₄ Soundness - stability
- Absorption – stability
- MBV x Passing 75-micron - durability

LAB CONCRETE TESTING
- Skid before & after wear
- Abrasion loss
  (or Wehner-Schulze)

FIELD ASSESSMENTS
- SCRIMS by Road Authority
- Pendulum Friction

Historical perspective

Source Rocks
- Coarse Aggregates
- Natural Sand

Mineralogical compositions

Lab-prepared Concrete Specimens

Field-retrieved Concrete specimens

Performance Criteria
CONDITION PRIOR TO POLISHING

MITTAGONG BYPASS

TARCUTTA RANGE
PAFV ABRASION RESISTANCE (AS 1141.41)
33-35 REVS/MIN (8,000&16,000 CYCLES AFTER 4&8 HOURS)

2-hr with coarse abrasion
[Balck silicon carbide No. 320 @ 2g/min]

2-hr with fine abrasion
[Optical emery No. 600 @ 2g/min]
DURABILITY TESTS

Micro-Deval: abrasion in water
Sodium Soundness: stability due to expansive salt crystallization
Absorption: porosity
To Wagga Wagga

Tarcutta Range test site

Test site is on the S/B, opposite the entrance to the Truck Bay
COMPRESSIVE STRENGTHS OF CONCRETE

40-58 MPA AT 28-DAY

Compressive Strength

<table>
<thead>
<tr>
<th>Mix 1-Emu</th>
<th>Mix 2-50% MS1</th>
<th>Mix 3-80% MS1</th>
<th>Mix 4-50% MS2</th>
<th>Mix 5-80% MS2</th>
<th>Mix 6-50% MS3</th>
<th>Mix 7-80% MS3</th>
<th>Mix 8-50% MS4</th>
<th>Mix 9-80% MS4</th>
<th>Mix 10-50% MS5</th>
<th>Mix 11-80% MS5</th>
<th>Mix 12-50% MS6</th>
<th>Mix 13-80% MS6</th>
<th>Mix 14-50% MS7</th>
<th>Mix 15-80% MS7</th>
<th>Mix 16-50% MS8</th>
<th>Mix 17-80% MS8</th>
<th>Mix 18-50% MS9</th>
<th>Mix 19-80% MS9</th>
<th>Mix 20-NS10</th>
<th>Mix 21-NS11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg of 7d compressive strength</td>
<td>Avg of 28d compressive strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>40.2</td>
<td>43.8</td>
<td>41.8</td>
<td>43.4</td>
<td>42.4</td>
<td>46.7</td>
<td>46.4</td>
<td>48.1</td>
<td>49.1</td>
<td>50.1</td>
<td>51.9</td>
<td>48.0</td>
<td>45.6</td>
<td>44.5</td>
<td>45.4</td>
<td>49.0</td>
<td>51.9</td>
<td>50.8</td>
<td>53.7</td>
<td>34.5</td>
<td>36.2</td>
</tr>
<tr>
<td>Mix 1-Emu</td>
<td>Mix 2-50% MS1</td>
<td>Mix 3-80% MS1</td>
<td>Mix 4-50% MS2</td>
<td>Mix 5-80% MS2</td>
<td>Mix 6-50% MS3</td>
<td>Mix 7-80% MS3</td>
<td>Mix 8-50% MS4</td>
<td>Mix 9-80% MS4</td>
<td>Mix 10-50% MS5</td>
<td>Mix 11-80% MS5</td>
<td>Mix 12-50% MS6</td>
<td>Mix 13-80% MS6</td>
<td>Mix 14-50% MS7</td>
<td>Mix 15-80% MS7</td>
<td>Mix 16-50% MS8</td>
<td>Mix 17-80% MS8</td>
<td>Mix 18-50% MS9</td>
<td>Mix 19-80% MS9</td>
<td>Mix 20-NS10</td>
<td>Mix 21-NS11</td>
</tr>
<tr>
<td>Avg of 7d compressive strength</td>
<td>Avg of 28d compressive strength</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
CHARACTERISTICS OF SKID BEFORE & AFTER WEAR

- **Mix 1 off-form**
- **Mix 1 saw-cut**
- **Mix 20 off-form**
- **Mix 20 saw-cut**

- **Mix 2 off-form**
- **Mix 2 saw-cut**
- **Mix 3 off-form**
- **Mix 3 saw-cut**

- **Mix 4 off-form**
- **Mix 4 saw-cut**
- **Mix 5 off-form**
- **Mix 5 saw-cut**

- **Mix 6 off-form**
- **Mix 6 saw-cut**
- **Mix 7 off-form**
- **Mix 7 saw-cut**
CHARACTERISTIC SKID AFTER 16,000 CYCLES OF POLISHING AND MICRO-DEVAL OR FREE SILICA CONTENT OF SANDS

**R² = 0.4875**

<table>
<thead>
<tr>
<th>% Free Silica (chemical)</th>
<th>Skid of off-form surface after 8 hr polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>70% Corr</td>
</tr>
<tr>
<td>45</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MDV of indiv sand</th>
<th>Skid of off-form surface after 8 hr polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>83% Corr</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

0.6931
FOWLER AND RACHED, ‘EVALUATION OF THE POLISH RESISTANCE OF FINE AGGREGATES IN PCC PAVEMENTS’,
SUMMARY

MIX DESIGN
Most man sands demand greater AEA & SP to give similar air & slump. Greater effect @80% than 50%.

SKID AFTER WEAR (Cycles of polishing)
Skid characteristics of concrete with 50% & 80% manufactured sands are similar. Most man sands give characteristic skid of 50 & above (Tarcutta Range has skid of 50 for saw-cut surface & a satisfactory SCRM value range of 68-74 for the wearing surface).

SKID AFTER WEAR (Cycles of polishing)
There appears to be no relationship between the skid resistance of concrete and the free silica content of sands used.

The intrinsic skid resistance of concrete (skid of off-form surface after 8 hours of polishing) decreases with increasing micro-Deval value of sands.
NECESSARY ELEMENTS FOR DELETERIOUS ASR

- Alkali
- Silica
- Ca
- Moisture

Damaging ASR reaction
EVALUATION OF REACTION POTENTIAL BY TESTING

AS1141.60.1 Accelerated Mortar Bar Test

ASTM C1260, CSA A23.2-25A, RMS T363, VicRoads RC376.03

- 21-day test of mortar expansion – quick & practical
- sand or coarse aggregate (sand grading) – surface area
- exposed to 1N NaOH solution – external alkali
- at 80°C – high temperature

<table>
<thead>
<tr>
<th>Performance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM C1260</strong></td>
</tr>
<tr>
<td><strong>Interpretation</strong></td>
</tr>
<tr>
<td>Innocuous</td>
</tr>
<tr>
<td>&lt; 0.10%</td>
</tr>
<tr>
<td>Uncertain</td>
</tr>
<tr>
<td>0.10 to 0.20%</td>
</tr>
<tr>
<td>Potential deleterious</td>
</tr>
<tr>
<td>≥ 0.2*%</td>
</tr>
</tbody>
</table>

Innocuous: < 0.10%
Non-reactive: < 0.10%
Uncertain: 0.10 to 0.20%
Slowly reactive: < 0.10%
Reactive: ≥ 0.10% or ≥ 0.30%
AS1141.60.2 Concrete Prism Test (CPT)

ASTM C1293, CSA A23.2-27A, RMS T364, VicRoads RC376.04

1-year concrete expansion – time consuming but better representative

- sand or coarse aggregate (with non-reactive coarse or fine aggregate) – normal mix proportion
- Artificially raised alkali to 1.25% Na₂O equivalent – internal alkali
- at 38°C – moderate temperature

Performance criterion

1-year expansion ≥ 0.03% for reactive aggregate (limit is 0.04% in ASTM & CSA)
CONSISTENCY OF AS1141.60.1 & 60.2 TO FIELD PERFORMANCE

AMBT, CPT & Field plus large blocks data from:
- Stark, Margan, Okamoto & Diamond (1993)
- Berube & Fournier (1993)
- Touma (2000)
- Ideker, Bentivegna, Folliard & Juenger (2012)

AMBT expansion at 14-day (ASTM) and 21-day (AS) in various performance limits with solid circle signifying field reactive aggregates (Stark, 1993 & Touma, 2000)
CONSISTENCY OF AS1141.60.1 & 60.2 TO FIELD PERFORMANCE

1. AS AMBT is 85% success in screening reactive aggregates
2. AS CPT is 95% accurate in screening reactive aggregates

Sirivivatnanon et al. (2016)
Based on such limited field data

EFFECTIVENESS OF DIFFERENT SCM IN MITIGATING ASR

Pospischil, D, Sirivivatnanon, V., Sivathasan, U. and Cheney, K. ‘Effectiveness of Traditional and Alternative Supplementary Cementitious Materials in Mitigating Alkali-Silica Reactivity’, Procs 27th Biennial National Conference of the Concrete Institute of Australia in conjunction with the 69th RILEM Week, Melbourne, Sept 2015, pp 694-703.
CONCLUSIONS

1. The use of cement, with an optimum limestone mineral addition, and appropriate type and dosage of SCM can deliver concrete with the required constructability, strength and durability.

2. Both fine and coarse aggregates can be manufactured from selected rock source to provide suitable aggregates for a wide range of concrete applications including concrete pavement. SCM can be used to mitigate potential ASR.

3. Performance-based and semi-prescriptive specifications are useful tool to support the full use of a range of concreting materials.

These are materials and technologies that contribute to the sustainability of concrete in modern construction.
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THANK YOU