Challenges in material specification for concrete performance
A consultant's view
John Figueroa
24 & 30 July 2018
Durability Requirements and Design Standards

DESIGN LIFE OF CONCRETE STRUCTURES

Guides to Pavement Technology

AS 3600-2009

AS 5100-2009

30 to 40

40 to 60

100
This Standard sets out the minimum requirements for:

(a) the materials, plant and equipment used in the supply of concrete;

(b) the production and, if applicable, the delivery of concrete in the plastic state;

(c) specifying, sampling, testing and compliance with specified properties of plastic and hardened concrete; and

(d) the uniformity of mixing.
Concrete aggregates

AS 2758.1:2014

AS 2558 is called up by AS 3600, Concrete structures. In this Standard, extensive reference is made to AS 1141, Methods for sampling and testing aggregates (series), which is designed to include all aggregate tests, not only those for concrete.
General purpose and blended cements

Due to the Global warming effect the Australian Government has initiated programs to reduce Australia’s carbon emissions. Portland cement is recognised as an energy intensive material and the aim is to reduce its environmental effect in terms of reducing greenhouse gas emissions.
Supplementary Cementitious Material (SCM)

Fly Ash
AS 3582.1:2016

Fly ash replacements beyond 35% are problematical, high replacement levels of fly ash lead to significantly lower rates of strength gain in the concrete and significantly increase the curing time required to achieve durable concrete.

Although most fly ash spheres are solid, some particles, called cenospheres, are hollow.

Source: Design and Control of Concrete Mixtures EB001, PCA (2016)
SCM – Ground granulated blast furnace slag

Non-metallic molten material (slag) obtained from the waste stream of iron ore blast furnace. Glassy granulated material.

Granules are ground to a suitable fineness (generally finer than Portland cement). It can be used in concrete mixtures to enhance strength, durability and sustainability.
SCM – Amorphous silica

AS 3582.3:2014

The most benefit is obtained in Exposure Class C conditions or where concrete is directly exposed to chlorides or other aggressive environments. Silica fume should not generally be used at a replacement level greater than 10%.

Typically used in high performance concrete
Construction Specifications for Concrete in NSW

R82
SUBBASE

R83
BASE

R53
GENERAL WORK

B80
BRIDGES

B82 & R68
SHOTCRETE
# B80 - Range of SCM Limits

## Table 3211/A.1 – Range of Single SCM in Binary Blend Cement for Concrete

<table>
<thead>
<tr>
<th>SCM</th>
<th>Min (% by mass)</th>
<th>Max (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General</td>
<td>Special</td>
</tr>
<tr>
<td></td>
<td>Applications</td>
<td>Applications</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>GGBFS</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Amorphous Silica</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

* refer Clause A4

## Table 3211/A.2 – Range of SCMs in Ternary Blend Cement for Concrete where TWO SCMs Used

<table>
<thead>
<tr>
<th>SCM I</th>
<th>SCM II</th>
<th>Combination A (% by mass)</th>
<th>Combination B (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max % SCM I</td>
<td>Min % SCM I</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Amorphous Silica</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>GGBFS</td>
<td>Amorphous Silica</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>GGBFS</td>
<td>Fly Ash</td>
<td>50</td>
<td>20</td>
</tr>
</tbody>
</table>
Range of SCM Limits (B82 & R68)

Table 3211/B.1 – Range of Single SCM in Binary Blend Cement for Shotcrete

<table>
<thead>
<tr>
<th>SCM</th>
<th>Min (% by mass)</th>
<th>Max (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General</td>
<td>Special</td>
</tr>
<tr>
<td>SCM</td>
<td>Applications</td>
<td>Applications</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>GGBFS</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Amorphous Silica</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3211/B.2 – Range of SCMs in Ternary Blend Cement for Shotcrete where TWO SCMs Used

<table>
<thead>
<tr>
<th>SCM I</th>
<th>SCM II</th>
<th>Combination A (% by mass)</th>
<th>Combination B (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max % SCM I</td>
<td>Min % SCM II</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Amorphous Silica</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>GGBFS</td>
<td>Amorphous Silica</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>GGBFS</td>
<td>Fly Ash</td>
<td>50</td>
<td>20</td>
</tr>
</tbody>
</table>
Range of SCM Limits (R82)

The minimum mass of cementitious material must be 250 kg/m³

The minimum SL cement content must be 90 kg/m³

Table 3211/C.1 - Range of Single SCM in Binary Blend

<table>
<thead>
<tr>
<th>SCM</th>
<th>Min (% by mass)</th>
<th>Max (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly Ash</td>
<td>40</td>
<td>75</td>
</tr>
<tr>
<td>GGBFS</td>
<td>10</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 3211/C.2 - Range of SCMs in Ternary Blend where TWO SCMs Used

<table>
<thead>
<tr>
<th>SCM I</th>
<th>SCM II</th>
<th>Combination A (% by mass)</th>
<th>Combination B (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max % SCM I</td>
<td>Min % SCM II</td>
</tr>
<tr>
<td>GGBFS</td>
<td>Fly Ash</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>
## Range of SCM Limits (R83)

### Table 3211/D.2 – Range of SCM Limits (Binary and Ternary)

<table>
<thead>
<tr>
<th>SCM</th>
<th>AAR Class</th>
<th>Limits $^{(1), (2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min (%)</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Non-reactive</td>
<td>$15 - (0.5 \times GGBFS%)$</td>
</tr>
<tr>
<td></td>
<td>Reactive</td>
<td>$20 - (0.5 \times GGBFS%)$</td>
</tr>
<tr>
<td>GGBFS</td>
<td>Non-reactive</td>
<td>$10 - (2.0 \times FA%)$</td>
</tr>
<tr>
<td></td>
<td>Reactive</td>
<td>$40 - (2.0 \times FA%)$</td>
</tr>
</tbody>
</table>
# Durability Requirements

### B80

<table>
<thead>
<tr>
<th>Exposure classification</th>
<th>Minimum cement content (kg/m³)</th>
<th>Maximum cement content (kg/m³)</th>
<th>Maximum water/cement ratio (by mass)</th>
<th>Minimum water/cement ratio (by mass)</th>
<th>Maximum chloride test coefficients at 20°C ($x \times 10^{12}$ m²/sec)</th>
<th>Minimum strength for durability ($f_{c,\text{min}}$ (MPa))</th>
<th>Actions required</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>320</td>
<td>400</td>
<td>0.56</td>
<td>0.4</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B1</td>
<td>320</td>
<td>450</td>
<td>0.50</td>
<td>0.4</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B2</td>
<td>370</td>
<td>500</td>
<td>0.46</td>
<td>0.32</td>
<td>3.5</td>
<td>8.0</td>
<td>Use blended cement with minimum 25% FA or 50% BFS</td>
</tr>
<tr>
<td>C</td>
<td>420</td>
<td>550</td>
<td>0.40</td>
<td>0.32</td>
<td>2.0</td>
<td>4.0</td>
<td>Use blended cement with minimum 65% BFS</td>
</tr>
<tr>
<td>U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>In accordance with Annexure B80/A1</td>
</tr>
</tbody>
</table>

**Cast-in-place Concrete**

- **A**: 320, 400, 0.56, 0.4, N/A, N/A, 25, N/A
- **B1**: 320, 450, 0.50, 0.4, N/A, N/A, 32, N/A
- **B2**: 370, 500, 0.46, 0.32, 3.5, 8.0, 40, Use blended cement with minimum 25% FA or 50% BFS
- **C**: 420, 550, 0.40, 0.32, 2.0, 4.0, 50, Use blended cement with minimum 65% BFS

**Precast Concrete**

- **A, B1**: 320, 600, 0.5, 0.28, N/A, N/A, 40, N/A
- **B2**: 370, 600, 0.46, 0.28, 3.5, 8.0, 60, Use blended cement
- **C**: 420, 600, 0.40, 0.28, 2.0, 4.0, 60, Use blended cement

### R83

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Minimum Mass (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCP, JRCP, CRCP</td>
<td>300</td>
</tr>
<tr>
<td>SFCP</td>
<td>350</td>
</tr>
</tbody>
</table>
Chemical Attack on Concrete

- Corrosion of reinforcement by
  (a) Chloride ingress
  (b) Carbonation
- Sulphate Attack
- Sea water attack
- Acid attack
- Delayed ettringite formation
- Alkali aggregate reaction
- Alkali carbonate reaction
- Freezing and thawing related damage

Need to reduce permeation mechanisms
- Permeability
- Absorption
- Diffusion
# Concrete Standards for Shotcrete

<table>
<thead>
<tr>
<th>Material</th>
<th>Standard</th>
<th>Title</th>
</tr>
</thead>
</table>
| **Concrete** | DBV, 2001  
German Society for Concrete and Construction Technology (superseded) | Steel Fibre Concrete [DBV-Guide to Good Practice] |
| | BS EN 14889-1, 2006  
British Standards Institution, EuroCode | Fibres for Concrete. Steel Fibres. Definition, specifications and conformity |
| | DAFStb, 2015  
German Committee for Reinforced Concrete | Commentary on the DAFStb Guideline Steel fibre reinforced concrete |
| | ASTM A820, 2016  
American Society for Testing and Materials | Specification for Steel Fibres for Fibre Reinforced Concrete |
| **Shotcrete** | CS, 2007  
UK Concrete Society | TR 63 Guidance for the design of steel-fibre-reinforced concrete (includes amendment No. 1 Oct 2007) |

Source: Bertuzzi (2017)
Shotcrete Evolution

- Gunite was used in Swedish u/g mines
- Helca Mining Co. in USA started using s’crete routinely as u/g support
- Norwegians 1st to realize benefits of silica fume
- Norwegians introduce steel fibres as replacement for mesh
- Robotic spraying of wet s’crete starting to emerge
- Introduction of non caustic alkali free accelerators
- w/c ratio < 0.4 using “Hyperplasticisers”

Source: Australian Shotcrete Society
Tunnel Project in NSW

Concrete cast in situ

Shotcrete with steel fibre

CRCP (not built yet)

Lean Concrete Subbase
Shrinkage Limits

AS 1379
1,000 microstrain

The default values in AS 5100 are:

800 microstrain for Sydney and Brisbane,

900 microstrain for Melbourne and

1000 microstrain elsewhere.
16.3.3.3 Residual tensile strength

The standard characteristic residual tensile strength grades \( (f'_{1.5}) \) are 0.4 MPa, 0.6 MPa, 0.8 MPa, 1.2 MPa, 1.6 MPa and 2.0 MPa.

The characteristic residual tensile strengths of concrete at 28 days \( (f'_{1.5}) \) shall be determined statistically from tests carried out in accordance Clause 16.3.3.4 or Clause 16.3.3.5.

Higher residual tensile strength grades may be used, provided they are supported by direct tensile testing undertaken in accordance with Clause 16.3.3.4.
Concrete Roundabout Pavements in NSW

Approaching 40 years of construction (fixed-formed) experience

Introduced with a fibre content of 1% or 75 kg/m$^3$

Reduced to 55 kg/m$^3$ depending on ultimate tensile strength, aspect ratio and hardness pf fibres
Maintenance of Concrete Pavement Roundabouts

Diamond Grinding after 25 - 30 years of service
SFRC in Industrial Floors

16.3.3.8 Minimum fibre dosage
The dosage of fibres shall be not less than the greater of—
(a) $12\gamma_s (d_f / l_f)^2$; and
(b) 20 kg/m$^3$,
where $\gamma_s$ is the mass density of steel, taken as 7850 kg/m$^3$.

AS 5100-2017

Industry Guides before AS 5100-2017

Typical dosage rates
20 – 40 kg/m$^3$

ASTM C1550 - 10
Flexural Toughness
AS 5100 does not preclude the use of techniques or materials other than those specified in AS 5100.

Source: Hilton (2014)
Use of Synthetic Fibres in Concrete

Refer to Concrete Society TR65

**Micro Synthetic**

- Used for plastic shrinkage control, improved abrasion resistance and passive fire protection

**Macro Synthetic**

- May provide additional structural strength in concrete elements or shotcrete

Refer to Concrete Society TR65
Short-Slab PCP over unbound subbase
US Study on Thin Concrete Overlays

- Over 90% of all fibre reinforced overlays in the USA were constructed with structural synthetic fibres.
- Macro synthetic fibres do not significantly improve the compressive strength, modulus of elasticity and modulus of rupture of concrete.
- The residual strength of structural FRC is improved with macro synthetic fibres.
- Dosage of 3.5 - 5.0 kg/m³ to improve early-age strength of concrete.
- The geometry, length, aspect ratio and stiffness of synthetic fibres have a significant influence in improving post-crack properties of concrete. Crimped, embossed, or twisted fibres showed better performance than straight synthetic fibres.
Design Philosophy in AS 5100

Design must consider:

- Intended function
- Aesthetics
- Constructability
- Maintainability
- Sustainability
- Climate change
- Safety in design
AS 5100 Clause 8.3 Limit states

Cl 8.3.1 All ultimate design actions are now defined as actions which have a 5% probability of being exceeded during the design life. For a design life of 100 years this represents a return interval of 2000 years.
**AS 5100 Section 10 Sustainability**

- **“Social” sustainability**
  Does the structure as constructed effectively fulfil its functional intention?

- **“Economic” sustainability**
  Is the structure as constructed, cost effective over its full life cycle?

- **“Environmental” sustainability**
  Does the structure, as constructed, provide unnecessary harm to the environment?
Social Sustainability

- Is the structure in the right location?
- Does it most effectively draw communities together?
- Does it enhance the safety and security of people?
- Does it promote and encourage equity and diversity?
- Does it promote wellbeing by being developed from an understanding of what people need from places where they live and work?
- Is the structure safe to construct and maintain?
Economic Sustainability

- Is the cost of the structure the most cost effective?
- Is the anticipated maintenance costs of the structure minimal?
- Is the design life of the bridge commensurate with its intended function?
- Will the structure require widening, strengthening, lengthening in the future and thus require an unnecessary expense compared to undertaking this work now?
- Is the form and function of the structure sufficiently robust that the designated design life is expected to be achieved?
- Does the construction and maintenance of the structure unnecessarily deplete non-renewable resources?
- Does the design or function affect the future economic value of natural resources?
- Does the design provide optimal economic value?
Environmental Sustainability

Does the structure, as constructed, provide unnecessary harm to the environment?

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied energy (GJ/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>155</td>
</tr>
<tr>
<td>Bitumen</td>
<td>47</td>
</tr>
<tr>
<td>Brick</td>
<td>3</td>
</tr>
<tr>
<td>Concrete (100% cement)</td>
<td>1.2</td>
</tr>
<tr>
<td>Concrete (25% fly ash)</td>
<td>1.0</td>
</tr>
<tr>
<td>Paint</td>
<td>68</td>
</tr>
<tr>
<td>Reinf concrete (25% fly ash)</td>
<td>2.3</td>
</tr>
<tr>
<td>Rubber</td>
<td>102</td>
</tr>
<tr>
<td>Steel</td>
<td>24</td>
</tr>
<tr>
<td>Stone</td>
<td>0.1</td>
</tr>
<tr>
<td>Timber</td>
<td>8</td>
</tr>
</tbody>
</table>
Industry Initiatives to reduce Carbon Emissions

**Strategy 1** – Supplying 50% of cement demand with geopolymer cement
**Strategy 2** – Supplying 50% of cement demand with high-blend cements
**Strategy 3** – Employing mineral carbonation
**Strategy 4** – Using less cement
**Strategy 5** – Developing carbon negative cements

6.3 million tonnes CO₂ per year *

---

Zero Emissions

Strategies 1-4 — moving beyond zero emissions in 10 years

Further reductions 30 years and beyond

Source: BZE (2017)
# Calcium Sulfoaluminate (CSA) Cement

## Unconfined Compressive Strength

<table>
<thead>
<tr>
<th>Water: Cement</th>
<th>0.20</th>
<th>0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Day</td>
<td>117</td>
<td>93</td>
</tr>
<tr>
<td>56 Day</td>
<td>120</td>
<td>106</td>
</tr>
<tr>
<td>112 Day</td>
<td>125</td>
<td>105</td>
</tr>
<tr>
<td>224 Day</td>
<td>136</td>
<td>120</td>
</tr>
<tr>
<td>448 Day</td>
<td>159</td>
<td>124</td>
</tr>
<tr>
<td>730 Day</td>
<td>160</td>
<td>124</td>
</tr>
<tr>
<td>900 Day (ongoing)</td>
<td>160</td>
<td>126</td>
</tr>
</tbody>
</table>

Source: Bluey Technologies
BLUCEM FSC BINDER
Concrete Runways

Brisbane West Wellcamp Airport

EFC Geopolymer Concrete, supplied and paved by Wagners (2014)

Technology Transfer

O'Hare International Airport in Chicago, 9L - 27R

1993

L: 2.4 km
W: 45 m
T: 400 mm

Professor Dan Zollinger
Texas A&M University
### Improvements in Mix Design

**Workability test for slip-formed concrete pavements**

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Over 50% overall surface voids.</td>
</tr>
<tr>
<td>3</td>
<td>30-50% overall surface voids.</td>
</tr>
<tr>
<td>2</td>
<td>10-30% overall surface voids.</td>
</tr>
<tr>
<td>1</td>
<td>Less than 10% overall surface voids.</td>
</tr>
</tbody>
</table>

Source: Ley (2012)
Workability test for slip-formed concrete pavements

Tarantula Curve

Bottom Edge Slumping

Top Edge Slumping
Improving Concrete Durability and Sustainability Using Internal Curing

Curing is one of seven essential procedures “that make concrete capable of providing decades of service with little or no maintenance.” [ACI 201 2R-08, Guide to Durable Concrete]

ACI: Internal Curing: “supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation.”
What is Light Weight Aggregate

- Expanded shale, clay and slate (ESCS)
- Structural, ceramic aggregate produced in a rotary kiln
- Less than half the unit weight of ordinary aggregate
- Complies with ASTM C-330 and C-331
Mixture Design for IC Concrete

Same method to that of conventional concrete. A portion of the conventional fine aggregate is replaced with a prewetted lightweight fine aggregate. Example:

Source: FHWA Tech Brief (2016)
Large Scale Testing at Purdue University

Test Slabs 4.5m long with end restraint. 0.30 w/c  Curing:  2 days sealed, then 23°C @ 50% RH

Plain Concrete
0.6 mm wide crack
observed @ 12 days

IC Concrete
0.4 mm wide crack
observed @ 43 days

Source: Schlitter (2010)
Benefits of using internal curing

- Less shrinkage, less cracking
- More hydration & SCM reaction
- Improved durability by
  - Lower water absorption
  - Lower chloride permeability & penetration
- Longer service life
- Less life cycle costs
- Increased sustainability
Technology Updates – Concrete Paving

Motorway Project in Sydney

Slab Replacement Work in Sydney

Pavement Replacement System Mix Design Approved by RMS

Triple Roller Tube Paver
Conclusions

Specification choices to achieve the design life

- Australian Standards
- Established specifications (e.g. RMS) with project-specific amendments

Project amendments are generally required to allow the introduction of new technology and achieve improved durability and sustainability requirements.
Thank you