ABSTRACT:
Research and development of Self-Consolidating Concrete (SCC) technology in Australia started at the University of Wollongong and at the laboratories of Blue Circle Southern Cement Pty Ltd and Boral Resources Pty Ltd in 1996. The results of the earlier research and development have been being successfully applied in real structures in various countries in Asia-Pacific, European and North American regions. This paper highlights on development and application of sustainable SCC in Australia. Testing procedures for flowability, passing ability, segregation resistance and form-surface finish, as well as laboratory test results of sustainable SCC, which contained relatively high amount of supplementary materials, namely limestone powder, fly ash and slag, are summarized. Field trials and applications of sustainable SCC in some real structures in bridge and road construction in Australia are presented. Various advantages and challenges of the use of SCC technology are also highlighted in the paper.

Keywords: Advantage, Challenge, Drying shrinkage, Heat of hydration, Milled limestone, Passing ability, Segregation resistance, Self-consolidating concrete, Sustainable SCC
INTRODUCTION

Research and development of Self-Consolidating Concrete (SCC) technology started in Australia at the University of Wollongong and at the laboratories of Blue Circle Southern Cement Pty Ltd and Boral Resources Pty Ltd in 1996. The three-year research project was funded by the University of Wollongong and Blue Circle Southern Cement Pty Ltd. In this project, technology on sustainable cements, high performance vibrated concrete and SCC were developed. Ones of the main topics of the research focused on the development of various models, testing methods and high performance sustainable SCC, which contained large amount of supplementary materials such as milled limestone, fly ash and slag. A comprehensive approach of SCC mixture design was also proposed and successfully applied in real structures in a number of projects in Asia-Pacific, European and North American regions, including some very high-profile projects such as 92-storey Trump Tower in Chicago, Freedom Towers at One World Trade Center in New York, Underwater SCC for a Casino in Mississippi, All Four Seasons in San Francisco, Aquarium in Wisconsin, Cathedral of Christ the Light in California and Sacramento City Hall in California, etc. In parallel, field trials and application of SCC technology have been also implemented in Australia. Further laboratory works, pilot investigation and specification development have been undertaken. The SCC technology has been successfully used in real structures for both precast and ready mixed concrete applications in Australia. This paper summarizes some of the test results of the earlier research works and presents recent development and application of SCC technology in bridge and road construction in Australia. Various advantages and challenges of the use of sustainable SCC are also highlighted in the paper.

EARLIER RESEARCH WORKS

The test results of the earlier research works on the sustainable cements, high-performance vibrated concrete and SCC at the University of Wollongong and at the laboratories of Blue Circle Southern Cement Pty Ltd and Boral Resources Pty Ltd were partially reported in various publications. Only some of the research works and results are summarized in the following sections.

Development of test methods

The development focused on the test methods for the main properties of fresh SCC, which include flowability, passing ability, segregation resistance and formed-surface finish (Figure 1).

Flowability — The test method assessing flowability of fresh SCC in laboratory was based on the previous works with the use of slump mold and test board. Average value of two spreads, which were measured at two right angle directions, was calculated. Higher average value of spreads (hereafter called slump flow) indicates greater flowability. Flow time (T_500), which defines as the time of SCC reaching slump flow of 500 mm (20 inches) after lifting the slump mold, was also recorded to assess a relative viscosity among different mixes.

Passing ability — The passing ability of SCC was assessed with the use of L-box apparatus similar to those designed in previous studies of first author with a minor modification, which includes a wedge (Wedge W) to enhance the easiness in lifting the gate (Gate G) during the passing ability test (Figure 1). Filling head drop of SCC top surface was recorded, and passing ability behavior of SCC around reinforcement bars was visually observed. Higher filling head drop indicates better passing ability of SCC. Details of passing ability test were published in references.

Segregation resistance — For assessing SCC segregation resistance, a penetration apparatus (see Figure 1) was developed. The penetration apparatus was positioned on the top surface of SCC filled in vertical leg of L-box before testing passing ability. The plastic cylinder head of the apparatus was then released to penetrate freely into fresh concrete. The penetration depth of the cylinder head was recorded. Lower penetration depth indicates better segregation resistance of SCC. Details of the apparatus and testing procedure were published elsewhere. The segregation resistance test method was further developed and adopted to be ASTM C 1712.

Formed-surface finish — In order to assess formed-surface finish of SCC and compared among different SCC, small boxes, which can be made of plexi-glass or wood and have a height of 600 mm and cross section of 200 mm x 100 mm, were used. With the plexi-glass box, the formed-surface finish can be observed immediately after SCC mixtures filled. For the use of wooden box, the formed-surface finish can be assessed after demolding. The formed-surface finish can also be observed immediately after SCC filled in the vertical leg of the L-box made of plexi-glass.
Laboratory test results of SCC containing milled limestone, fly ash and slag

Materials used — Five types of cement, comprising two types of shrinkage limited portland cement, one type of ordinary portland cement and two types of blast furnace slag cement, were used. The two types of shrinkage limited portland cement and ordinary portland cement are designated as SPC1, SPC2 and OPC, respectively, while the two types of blast furnace slag cement, which contain 30% and 65% of blast furnace slag, are designated as BFC1 and BFC2, respectively. Five types of mineral admixtures, namely three sources of milled limestone, fly ash and blast furnace slag were also used in laboratory tests. The milled limestones, which were designated as LS1, LS2 and LS3, had the fineness being coarse, medium and very fine, respectively. Milled limestone with replacement of 10%, 20%, 30%, 25%, 30% and 40% by mass were used. Class F fly ash with 30% and 65% replacement was designed in some SCC mixtures.

Six combinations of crushed basalt coarse aggregate and two sources of river sand were used in the concrete testing program. The six combinations of the coarse aggregates include two with maximum size of 20 mm, two with maximum size of 14 mm and two with maximum size of 10 mm. Two sources of river sand and superplasticizer in dry and liquid forms were used. The test results were partially reported elsewhere\textsuperscript{1,2,3,4,5,6,10}, only some results are highlighted in the following sections.

Properties of fresh SCC — SCC mixtures with milled limestone of 10% to 40% replacement, with fly ash content of 30% and 65% replacement or blast-furnace slag of 30% and 65% replacement were successfully designed. They had slump flow in range of 600 mm to 725 mm, satisfactory passing ability and good segregation resistance as well as good formed-surface finish. Details of fresh SCC properties were published in reference\textsuperscript{2}.

Compressive strength — For the same water-to-powder ratio (w/p) of 0.30, constant total binder content and 20% replacement, compressive strength of milled limestone LS1 (coarse fineness), LS2 (medium fineness) and LS3 (very fine fineness) were generally similar at ages of 3 days and 28 days (Figure 2). SCC mix with 20% LS2 exhibited the highest 7-day strength compared to that of milled limestone LS1 and LS3. Milled limestone, LS2 with medium fineness was selected for further investigation with SCC containing milled limestone LS2 having different percentages of replacement and different w/p.

As seen in Figure 3, for w/p of 0.30 and milled limestone LS2 with 0%, 10%, 20%, 25%, 30% and 40% replacement, 3-day compressive strength was 56.3 MPa, 66.4 MPa, 54.6 MPa, 60.5 MPa, 50.8 MPa and 45.6 MPa, respectively; 28-day compressive strength was 82.1 MPa, 91.9 MPa, 82.4 MPa, 80.1 MPa, 73.8 MPa and 64.2 MPa, respectively; and 362-day compressive strength was 89.7 MPa, 90 MPa, 89.1 MPa, 89.1 MPa, 85.9 MPa and 75 MPa, respectively. The results showed that, compared to mix without milled limestone, compressive strength of SCC with up to 25% limestone, LS2 were high and were generally not compromised at all ages; while those with 30% and 40% limestone LS2 were lower those without milled limestone, but they are still relatively high. This test and other results from author’s study\textsuperscript{4,9} showed that, depended on specific application requirements, higher milled limestone content can be successfully designed for SCC.
Drying shrinkage — Figure 4 shows drying shrinkage of SCC with different sources of milled limestone LS1, LS2, and LS3 with coarse, medium, and very fine fineness, respectively. At all ages, SCC with milled limestone LS2 and LS3 having medium and very fine fineness had similar drying shrinkages, being lower than those of SCC with milled limestone LS1 having coarse fineness. For w/p of 0.30, drying shrinkage of SCC with 20% milled limestone LS2 was lowest, while for w/p of 0.35, mix with 40% milled limestone LS2 had the lowest drying shrinkage at all ages. More test data were reported elsewhere. The test results show that, besides other well-known factors, suitable fineness (i.e., particle size distribution) and optimal content of milled limestone, which can enhance in lowering drying shrinkage, depend also on w/p and other parameters of the mixture compositions (e.g., sand-to-total aggregates ratio, aggregate interactions, etc.). These are perhaps due to filling effect of milled limestone in the concrete mixture.

Heat of hydration — Figures 7 and 8 show heat of hydration of mortars containing cements SPC1 and SPC2 and different contents of milled limestone LS2. Compared to mix without milled limestone, mixes with milled limestone LS2 exhibited considerably reduced heat of hydration. Higher content of milled limestone led to lower heat of hydration.
Specifications development
Acknowledging the emergence of SCC as a viable concrete technology, the Concrete Institute of Australia initiated the development of a standard practice guide in 2003, with participation from construction, concrete industry and road authorities. In 2005, Concrete Institute of Australia published ‘Z40: Super-Workable Concrete – Recommended Practice’ adopting super-workable concrete (SWC) as the Australian equivalent terminology for self-compacting concrete.

One of the road authorities in Australia, VicRoads, introduced SCC into the September 2005 version of the ‘VicRoads Standard Specifications Section 610: Structural Concrete’ with limits on the use of SCC for underwater and dry bore applications only. In 2006, Roads and Maritime Services, (RMS, then Roads and Traffic Authority in NSW), allowed the use of super-workable concrete in the ‘RMS QA Specifications B80: Concrete Work for Bridges Ed5 Rev6’ for precast concrete only. RMS, through its Technology Program, then embarked on a study to verify the viability of SCC for cast-in-situ application using local resources, hereinafter referred to as the RMS SCC Study.

Laboratory development and results
The RMS SCC Study started in 2008 which turned out to be timely as various recent publications from studies all over the world became available. From the information gathered from the literature review, a draft specification was developed to suit the current performance requirements in identified RMS applications, including bored piles and elements where access for mechanical vibration is difficult.

Although certain test methods were nominated in the CIA Z40 publication, no test method for SCC is yet standardized in Australia. Hence, the selection of the test methods for verification, identified from the current standards adopted in Europe and North America, took into consideration the results of earlier studies by ICAR and the Testing SCC project, as follows:

- For filling ability, ASTM C 1611 was preferred to EN 12350-08 as it incorporates a way of reporting the degree of potential for segregation of the SCC mix through the visual stability index (VSI) rating.
- For passing ability, ASTM C 1621 and EN 12350-12 were used in tandem as they provide a way to verify the correlation of the two tests. Parameters measured from similar test methods were also done for comparison.
- For stability, EN 12350-11 was preferred to ASTM C 1610 as it is easy to perform. The VSI rating in ASTM C 1611 was also recorded for correlation and reference for field acceptance testing.

A total of three laboratory and full scale mock-up trials were carried out to date. RMS engaged different industry players for each full scale trial which included the development of SCC mixes suitable for the identified application. The first set of trials was carried out in collaboration with a ready mix concrete supplier involved in an RMS bridge project. The mix was a binary blend with fly ash. BORAL Resources (NSW) Pty Ltd was engaged for the second set of trials. Two SCC design mixes were batched in the laboratory three times with the fresh properties tested using the identified test methods. Mix A was a binary blend with fly ash while Mix B was a ternary blend with fly ash and micro silica. The early laboratory results indicated that passing ability appeared to be difficult to achieve.
Full scale field trials and results
The selected mix developed during the laboratory trials were batched for the full scale mock-up trials. During the actual trial pour, the produced mix batches were cast after testing for fresh properties.

![Image](9a: Slump flow spread, VSI = 3)
![Image](9b: Trial column set-up)
![Image](9c: Segregation at top of element)

Figure 9: First full scale mock-up trial (column T and F was cast with tremie and free-fall, respectively)

The first full scale mock-up trial produced an SCC mix that indicated severe segregation. SCC was produced from the batching plant set-up for a bridge project. The hardened element manifested the segregation to 600 mm to 700 mm at the top portion (see wedge cut in Figure 9). Aside from the segregated portion, the hardened properties of the rest of the element satisfied the performance requirement.

The second full scale mock-up trial used the laboratory trial mix optimized to satisfy the passing ability performance requirement. The installed reinforcement was maximized to 0.04Ag plus simulated lapping at the top and bottom with Ø10 mm ties spaced at 75 mm. Two SCC mixes supplied were produced from a working plant closest to the trial site. Sample cores, beam and wedge prism were secured from each trial column to assess the hardened SCC properties and resistance to segregation performance (see Figure 10).

![Image](10a: Slump flow spread, VSI = 0)
![Image](10b: Trial column set-up)
![Image](10c: Aggregate distribution at top)

Figure 10: Second full scale mock-up trial (use of Mix 01 and 02 for test column T1 and T2, respectively)

The results, particularly for the second trial, indicated that SCC could be produced from local materials and existing concrete batching plant satisfying the desired SCC fresh and hardened performance requirement.

A third full scale mock-up trial was carried out to compare the effects of placement scenarios to the in-place hardened properties of SCC, as part of the project validation stage of the RMS SCC Study, undertaken in cooperation with Hume Highway Woomargama Alliance (HHWA, composed of Roads and Maritime Services, Abigroup Limited, and Sinclair Knight Merz Pty Ltd). The full scale trial pile section was a replica of the production pile used in the HHWA bridge projects. The piles were poured in three placement scenarios, namely: (1) tremie on dry hole, (2) tremie on wet hole, and (3) free fall on dry hole.
Based on the results of the previous trials, availability of new test methods and the specific requirements of the
document.
Van Bui and Huber Madrio

Figure 11: Pile test location configuration for third full scale mock-up trial

Table 2: Average values of in-place hardened properties for third full scale mock-up trial

<table>
<thead>
<tr>
<th>Section</th>
<th>Rebound Number at Core Locations</th>
<th>Direct UPV at Pile Core Locations, km/s</th>
<th>UPV at Secured Cores, km/s</th>
<th>Compressive Strength, MPa</th>
<th>Mass per Unit Volume, kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TW TD FD</td>
<td>TW TD FD</td>
<td>TW TD FD</td>
<td>TW TD FD</td>
<td>TW TD FD</td>
</tr>
<tr>
<td>Top</td>
<td>54 59 58</td>
<td>4.7 4.7 4.7</td>
<td>4.8 4.8 4.7</td>
<td>56 51 70</td>
<td>2320 2280 2270</td>
</tr>
<tr>
<td>Middle</td>
<td>58 61 59</td>
<td>4.8 4.7 4.7</td>
<td>4.8 4.8 4.7</td>
<td>51 50 74</td>
<td>2330 2290 2290</td>
</tr>
<tr>
<td>Bottom</td>
<td>60 64 61</td>
<td>4.8 4.7 4.7</td>
<td>4.8 4.8 4.8</td>
<td>57 59 66</td>
<td>2370 2320 2330</td>
</tr>
</tbody>
</table>

Three core samples secured for each of the top (T), middle (M) and bottom (B) sections.

Table 3: Average in-place durability properties for third full scale mock-up trial

<table>
<thead>
<tr>
<th>Core Sample Location</th>
<th>Sorptivity$^1$, RMS T362 (mm)</th>
<th>Sorptivity, ASTM C1585 (mm$^3$/sec)</th>
<th>AVPV, AS 1012.21 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TW TD FD</td>
<td>Criteria: RMS B80 Exposure</td>
<td>TW TD FD</td>
</tr>
<tr>
<td>Top</td>
<td></td>
<td>≤ 25mm, B1</td>
<td>7.2E-04 3.8E-04 8.7E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≤ 20mm, B2</td>
<td>3.3E-04 2.2E-04 4.1E-04</td>
</tr>
<tr>
<td>Average values</td>
<td>8.2 8.4 18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sample used Ø 100 mm instead of 100 mm x 100 mm x 300 mm prism.

Field application and results
The following are some SCC applications in New South Wales, Australia.
Hume Highway Tarcutta Alliance — Two of the ten bridges in the project, the Twin Bridges over Tarcutta Creek, used SCC for its substructure as part of the project validation activity of the RMS SCC Study.

- Foundation is a combination of 24 - Ø 700 mm and 48 - Ø 1200 mm bored piles (see Figure 12).
- Bored pile with depth averaging 12,000 mm and with moderately congested reinforcement was constructed using the continuous flight auger method.
- SCC with 20 percent supplementary cementitious material was supplied by the mobile wet batching plant owned by the principal contractor alliance partner.
- Briefing of all personnel involved in the SCC use conducted prior to actual SCC pour
- Site acceptance test adopted the draft RMS QA Specifications B80.

![Figure 12: Twin bridges over Tarcutta Creek (Courtesy of Hume Highway Tarcutta Alliance)](image)

Hume Highway Woomargama Alliance — The four bridges of the project, Twin Bridges over Mountain Creek and Twin Bridges over Sandy Creek, used SCC for the bored piles (see Figure 13).

- Foundation is a combination of square driven RC piles and RC bored piles Ø 900 mm diameter averaging 14,000 mm deep
- SCC, with 20 percent supplementary cementitious material and produced by a local concrete supplier, was placed by tremie method for the bored piles provided with temporary steel casing
- Briefing of all personnel involved in the SCC use was conducted prior to actual SCC pour
- Site acceptance test adopted the draft RMS QA Specifications B80.

![13a: Twin bridges over Mountain Creek](image)

![13b: Twin bridges over Sandy Creek](image)

Figure 13: Hume Highway Woomargama Alliance bridges (Courtesy of Hume Highway Woomargama Alliance)

Railway Underbridge over Boundary Street at Roseville — The new bridge replaces the narrow 92 year old railway bridge (see Figure 14).

- Transfer girder to be constructed underneath an operational railway line inside a temporary steel culvert which is also only eight meters directly on top of an operational railway tunnel requiring vibration to be avoided or kept at a very low level
- The transfer girder, 36,000 mm long x 1,500 mm wide x 2,400 mm high has a congested arrangement of large diameter reinforcement added with multiple stirrups, Ø12 mm spaced at 50 – 75 mm
- SCC mix design included ballast aggregates and high dose of supplementary cementitious materials to minimize heat of hydration.
- Test pour was carried out to simulate congestion of reinforcement and delivery of SCC from the nominated batching plant with site acceptance test adopting the proposed methods in the draft RMS QA B80.
M2 Upgrade — As part of the M2 motorway widening, a number of bridges spanning the motorway were affected. These bridges (see Figure 15) were lengthened which required the relocation of abutments requiring additional diaphragms and strengthening of headstocks. Existing use of asset requires minimal disturbance to traffic resulting in difficult access for mechanical vibration.

- Concrete should maintain good quality performance and good surface finish.
- The SCC mix used targeted the lower slump flow spread of 500 mm, a more stable super-workable concrete range, thereby requiring minimal vibration.
- SCC was vibrated through access holes spaced at 1000 mm at the deck.

Other SCC field applications within Australia were carried out adopting the VicRoads specifications, the provisions of CIA Z40: Super-Workable Concrete – Recommended Practice, and the guidance of professional services contractors involved with major SCC application elsewhere in the world.

ADVANTAGES AND CHALLENGES

Advantages
The experiences in the use of SCC demonstrated the following advantages:

- **High performance in fresh and hardened states** — Excellent flow, stability, formed-surface finish, and able to pour concrete amidst constructability constraints such as difficulty in access and impracticality of mechanical compaction, relatively homogeneous concrete matrix within an element with high durability with better interface with reinforcement.
- **Cost effective technology** — Increased construction speed, high productivity, reduced energy, less equipment use and reduced labor.
- **Environment-friendly technology** — Reduced noise (e.g. suitable for urban application where noise is a community concern), reduced health hazards, and use of large amount of sustainable supplementary materials (e.g. milled limestone, fly ash, slag).
Van Bui and Huber Madrio

**Challenges**

Some challenges encountered in the RMS trials and field applications include:

- Availability of reliable local concrete supplier in the rural/country areas.
- Lack of communication how to select admixtures appropriate for the particular fresh and hardened properties requirement of the project.
- Availability of local testers with appropriate knowledge of the test method specified which may be similar to a method practiced previously.
- Persuading old school of thought that all concrete requires some form of vibration to consider that a properly design SCC could be placed without the need of mechanical compaction.
- For general use of SCC in more application as a normal concrete of particular properties fit for the purpose of the project and not just a solution to a constructability issue.
- Requirement of high level of quality control, compared to that for vibration concrete.

In order to overcome the challenges and apply in wider scale, further development of rapid reliable quality control systems and more cost-effective SCC mixtures, as well as training for personnel from concrete suppliers, contractors and testing laboratories as well as better dissemination of SCC technology understanding among engineers and owners should be enhanced.

**SUMMARY**

1. Earlier research works undertaken at the University of Wollongong and at laboratories of Blue Circle Southern Cement Pty Ltd and Boral Resources Pty Ltd have contributed to development of methods for testing main properties of SCC. The developed sustainable SCC, which contained relatively high content of milled limestone and other sustainable supplementary materials, exhibited high performance in fresh and hardened states. Thus, milled limestone and other supplementary materials can be effectively used in SCC technology and to enhance sustainability in construction.

2. Further development and successful application of SCC in real structures in bridge and road construction in Australia demonstrated a number of advantages and various challenges. Thus, in order to apply SCC technology in wider scale, special attentions should be paid into development of effective rapid quality control systems and reduction of SCC mixture cost. Also, training for technical personnel from concrete suppliers, contractors and testing laboratories as well as better dissemination, specifications and standards on SCC technology should be enhanced among engineers, owners and other stakeholders.

**ACKNOWLEDGEMENTS**

The authors gratefully acknowledge the support of Roads and Maritime Services and BASF Corporation for the review and approval to publish this paper. The authors also gratefully acknowledge the support of the University of Wollongong, Blue Circle Southern Cement Pty Ltd and Boral Resources Pty Ltd for providing a fund and R&D facilities for the earlier research works.

**DISCLAIMER**

The opinions expressed in this paper are entirely those of the authors and not necessarily the policies and practices of the organizations they represent.

**REFERENCES**


