# CONCRETE IN AUSTRALIA

CONCRETE INSTITUTE of AUSTRALIA

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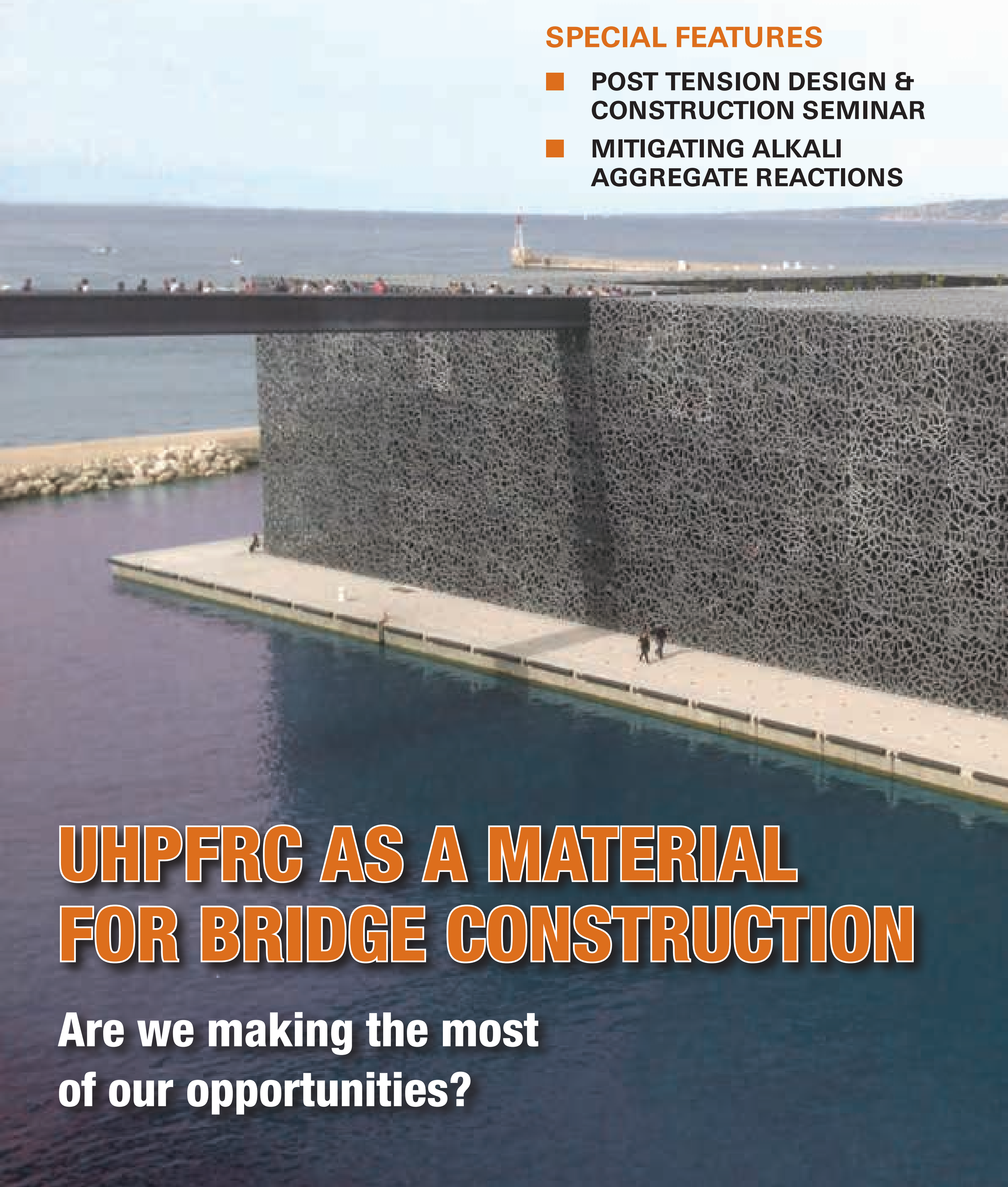
*excellence in concrete*

## SPECIAL FEATURES

- POST TENSION DESIGN & CONSTRUCTION SEMINAR
- MITIGATING ALKALI AGGREGATE REACTIONS

# UHPFRC AS A MATERIAL FOR BRIDGE CONSTRUCTION

## Are we making the most of our opportunities?

*Douglas Jenkins*

# Engineering and the Einstein Test

My favourite quote from that famous engineer, Albert Einstein, states that everything should be simplified as far as possible, but no further. This is a good summary of the task of the engineer at all stages of their work from analysis and design, through to construction, monitoring and remediation. There are many great examples of simple and elegant design from ancient structures such as the Roman Pont du Garde to the modern Millau Viaduct, but the history of structures is also literally littered with structures where simplification of analysis and design has been taken too far.

Famous 20th century examples are the collapse of steel box girder bridge structures (including the Westgate Bridge in Melbourne), due to over-simplification of shear-lag and buckling behaviour, and the extreme resonant vibration behaviour of the Millennium Bridge in London. These structures (along with many other examples) have in common that the theory and procedures that would have allowed a successful design to be completed were available at the time of their design, but not widely used in the types of structures where the problems occurred.

Other less high profile but widespread problems related to over-simplification of design procedures include unexpected deflections, concrete shear failures and problems related to fixings and connections.

In retrospect these problems are likely to be seen as easily avoidable, but optimising the balance between simplification and avoiding over-simplification is far from easy; it requires both a thorough understanding of the underlying theory, and a knowledge of how the theory is applied in practice, including problems encountered in the past, and an appreciation of the limits of application of any proposed design simplification.

The Concrete Institute's national and state based seminars are one of the key ways in which we can help engineers to develop their practical design skills, but I would here like to focus on three other, perhaps lesser known, sources of information available to Institute members:

As one of the benefits of membership of the international *fib* the Concrete Institute has access to online copies of the *fib* "technical bulletins". The bulletins are now available to members for free download on the Institute website, with a total of 68 documents currently available. The name "bulletin" perhaps suggests a brief summary document, but this is not the case; each bulletin is of textbook length, and the series includes works on all aspects of concrete engineering, including a four volume manual of concrete design, and the *fib* model concrete code.

In Australia the leading source of technical papers on concrete research, design developments and construction practice is the Concrete Institute's biennial conferences. The full set of papers from each conference is freely available to members on the Institute website, for all conferences since 2001.

Membership of the American Concrete Institute, available to Australian Institute members at substantially reduced rates, entitles members to not only access the monthly *Concrete International* magazine and discounted rates for the vast range of ACI publications, but also free online access to their excellent bi-monthly structural and materials journals. Each journal carries a wide range of papers reporting the latest concrete research, both in the US and around the world.

These three sources provide the latest reports on research, development, design and construction practice either free to members or at a very moderate additional cost (for ACI Membership). These are invaluable resources which I recommend to all members who wish to apply the "Einstein Test" to their engineering work.

***Douglas Jenkins***
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*president@concreteinstitute.com.au*

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# CONCRETE IN AUSTRALIA

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## Contents

*Average Net Distribution*
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*The cover story on page 32 asks if we're making the most of our opportunities with UHPFRC.*

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# Will you be the one to make a difference?

The Concrete Institute of Australia is an independent, not for profit organisation, that is made up of Members who share a common interest in staying at the forefront of concrete technology, design and construction in Australia. This brief can be found on the home page of the Institute's web site, in the Strategic Plan, and in the Charter – but the important word to focus on is Members.

To effectively communicate with the Members, and to react to their needs, the Institute supports an Executive, a National Council, and six State Branch committees. All of these Committees are made up of elected Members of the Institute to facilitate these needs. To support the continual progress of the Institute and to refresh ideas and enthusiasm, nominations for these committees are sought every two years.

So why be on a committee? Effective committee participation brings together Member viewpoints which might not otherwise be heard. As a committee member, you can not only help create value for our Members and achieve the Institute's strategic goals, but you can also develop professionally as an individual and meet a number of personal objectives.

Some of the benefits of being an effective Committee Member include:

- exchanging information and ideas with your peers
- developing professional relationships and strengthening of ties in the concrete industry
- establishing contacts with leading industry decision makers and influencers
- building your knowledge of the industry through contribution
- gaining expertise in new areas or gathering new ideas for your current area
- contributing to the success and visibility of your company
- planning and attending social, educational and networking events
- adding to your own CPD points.

*David Millar*

This year is an election year and Members have an opportunity to serve on State Branch committees or on Council. This is one of the great benefits of membership and this opportunity is available to Individual Members, Young Professional Members, Retired Members, Life and Honorary Members, and Institute nominated representatives of Company Members and Academic Members.

It is an exciting time to be involved with the Institute. We are developing and strengthening global ties with like-minded organisations, hosting international conferences and meetings, developing initiatives to bring academia closer to the commercial world, increasing our focus on technical forums and publications, looking at educational opportunities to suit the market, and of course, running our biennial conference, Concrete 2015, in Melbourne later this year.

The Institute will call for nominations for State Branch Committees in May and for National Council in June.

We encourage Members to consider this opportunity and to join us in the 'concrete mix'.

***David Millar***
*CEO, Concrete Institute of Australia*

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# Concrete design for extreme events

The recent seminar series on Structural Concrete Design for Extreme Events was very well received by delegates from around the country who attended. As one delegate from Adelaide noted, “The presentation was of a very high level and the knowledge gained from it can be used directly in my work as a structural engineer.”

The three speakers for the event, Professor Steven Foster (robust concrete design), Professor John Wilson (earthquake design for regions in lower seismicity) and Professor Jose Torero (fire and the impact on concrete), are all experts in their fields and were extremely generous in providing the Institute and the delegates with their time and knowledge.

The quality of the content, notes and presentations was extremely high and the Institute is looking to making these available in webinar format later in the year for those who were unable to attend but would like to download the content in their own time.

# Breakthrough technology reduces pre-cast concrete footprint

Lafarge, a worldwide player in cement, aggregates and concrete businesses, has signed an agreement with US start-up Solidia Technologies to commercialise a technology that allows a significant reduction in the environmental footprint of pre-cast concrete.

The patented technology allows lower $CO_2$ emissions in the cement production process and utilises $CO_2$ in pre-cast concrete manufacturing. It reduces the carbon footprint of the end-to-end process by up to 70%.

Solidia has developed a new binder made from similar raw materials to Ordinary Portland Cement (OPC) and produced it in a traditional rotary kiln at lower temperatures and through a different chemical reaction that generates less $CO_2$.

Used afterwards in the manufacture of precast concrete, Solidia Cement hardens through the addition and absorption of $CO_2$ ('carbonation'), in a curing process that reduces the overall carbon footprint by up to 70%.

Produced at traditional pre-cast concrete manufacturing facilities, Solidia Concrete is higher performing and reaches full strength in less than 24 hours, compared to 28 days for precast concrete made using OPC. This, according to Solidia, offers considerable energy savings and cost reductions to pre-cast concrete manufacturers.

Under the terms of this agreement, Lafarge will have the right to commercialise this technology worldwide and will offer a complete solution (sustainable cement and $CO_2$-cured concrete) in partnership with Solidia.

Commercial launch will first take place in the key markets of North America and Europe for the manufacturing of concrete elements such as paving stones, roof tiles and concrete blocks.

Lafarge said it had been working for over 20 years to reduce its environmental footprint and, in particular, its $CO_2$ emissions. These have been reduced by 26% per ton of cement since 1990, the company stated. Lafarge has been working with Solidia on the technology since 2013.

# Concrete stabilises Sydney sinkholes

Concrete has been pumped into two sinkholes that opened up in Western Sydney following heavy rain in early May.

Around 50 residents in two apartment blocks near Parramatta were evacuated by police due to concerns of the foundations collapsing.

The sinkholes appeared within centimetres of the Harris Park apartment blocks after heavy rain caused water to pool in an adjacent empty construction lot. It is thought that soil erosion and flooding was the cause of the holes forming.

After three days, geotechnical engineers said the two apartment blocks had not moved, however it was still too dangerous to allow people to move back in, *ABC News* reported.

Parramatta's Lord Mayor Scott Lloyd said that property owners had inspected the site with their insurance agent and engineers, with the decision made to fill the holes with concrete.

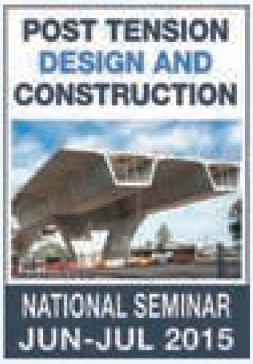
Lloyd said concrete trucks were sent in to pump concrete into the holes overnight, in an attempt to stabilise the site and prevent further erosion.

At the time of going to print, engineers were assessing whether the ground was stable enough to allow the residents to return to their apartments.


Source: AAP

# CIA EVENTS CALE

## NATIONAL




### POST-TENSION DESIGN AND CONSTRUCTION

| | |
|---|---|
| Sydney | 23 June |
| Adelaide | 24 June |
| Perth | 25 June |
| Brisbane | 30 June |
| Melbourne | 1 July |
| Hobart | 2 July |

**FOR MORE INFORMATION ON ALL 2015 EVENTS PLEASE VISIT**

**http://www.concreteinstitute.com.au/posttension**

ALL EVENTS HELD IN CAPITAL CITIES UNLESS STATED OTHERWISE.

## NSW

**NATIONAL SEMINAR – POST TENSIONING**
23 June

**NSW AWARDS BREAKFAST**
15 July

**SITE VISIT – ONESTEEL SYDNEY STEEL MILL**
19 August

**SLABS & FOOTINGS**
23 September

**WATERPROOFING CONCRETE**
21 October

**NATIONAL SEMINAR – CRACKING, SHRINKAGE, RESTRAINT**
November TBA

**BRIDGES – AS 5100 & AS 3600**
25 November

## QLD

**CONCRETE PAVEMENTS**
16 June

**NATIONAL SEMINAR – POST TENSIONING**
30 June

**BRIDGES & EXCELLENCE AWARDS**
21 July

**BREAKFAST – CONCRETE SPECIFICATIONS**
TBA

**CREEP & SHRINKAGE**
8 September

**DEFLECTION & FINITE ELEMENT ANALYSIS**
20 October

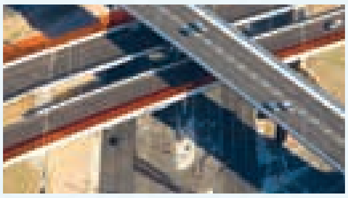
**NATIONAL SEMINAR – CRACKING, SHRINKAGE, RESTRAINT**
November TBA

**PILING**
17 November

# NDAR 2015

CONCRETE INSTITUTE of AUSTRALIA

## VIC



**ADMIXTURE DESIGN / GEOPOLYMER**
16 June

**NATIONAL SEMINAR – POST TENSIONING**
1 July

**PERFORMANCE OF MARINE STRUCTURES**
21 July

**AWARDS – COCKTAIL EVENING**
23 July

**CONFERENCE**
30 August – 2 September

**CONCRETE REPAIR**
15 September

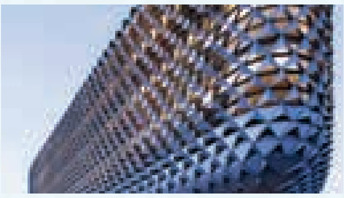
**MAJOR PROJECTS CASE STUDIES**
20 October

**NATIONAL SEMINAR – CRACKING, SHRINKAGE, RESTRAINT**
November TBA

**SEMINAR – BRIDGE DESIGN CODE AS 5100**
17 November

**ANNUAL SPONSORS COCKTAIL EVENING**
1 December

## SA



**NATIONAL SEMINAR – POST TENSIONING**
24 June

**AWARDS – COCKTAIL EVENING**
15 July

**FUNDAMENTALS OF CONCRETE COURSE**
22/29 July
5 or 12 August (TBC)
19/26 August

**COLOURED/DECORATIVE CONCRETE**
9 September

**NT SEMINAR – WATERPROOFING/HOT WEATHER CONCRETING/ CONCRETE REPAIR**
TBA

**NATIONAL SEMINAR – CRACKING, SHRINKAGE, RESTRAINT**
November TBA

**SPONSORS BREAKFAST**
8 December

## WA

**CONCRETE IN BRIDGES**
9 June

**NATIONAL SEMINAR – POST TENSIONING**
25 June

**DINNER – XMAS IN JULY/ ANNUAL AWARDS**
July TBA

**BREAKFAST**
21 August

**MARINE CONCRETE**
8 September

**SLIP FORM POST TENSIONING**
13 October

**GOLF DAY**
November TBA

**NATIONAL SEMINAR – CRACKING, SHRINKAGE, RESTRAINT**
November TBA

**MODULAR CONCRETE**
10 November

**SITE VISIT/SUNDOWNER**
December TBA

## TAS

**NEW TESTING TECHNOLOGY FOR CONCRETE – HOBART**
3 June

**NEW TESTING TECHNOLOGY FOR CONCRETE – INVERMAY**
4 June

**NATIONAL SEMINAR – POST TENSIONING**
2 July

**DESIGNING FOR EARTHQUAKE CODES & FIRE IN CONCRETE STRUCTURES – HOBART**
26 August

**DESIGNING FOR EARTHQUAKE CODES & FIRE IN CONCRETE STRUCTURES – INVERMAY**
27 August

**TILT UP PRECAST – NEW BRACING CODES & SOLUTIONS – HOBART**
30 September

**TILT UP PRECAST – NEW BRACING CODES & SOLUTIONS – INVERMAY**
1 October

**NATIONAL SEMINAR – CRACKING, SHRINKAGE, RESTRAINT**
November TBA

**BEST PRACTICE EVENT – CONCRETE CORING & CUTTING – HOBART**
11 November

**BEST PRACTICE EVENT – CONCRETE CORING & CUTTING – INVERMAY**
12 November

# 3D printed cement in full bloom

A research team at the University of California, Berkeley, has unveiled the first and largest powder-based 3D printed cement structure built to date.

The freestanding pavilion known as Bloom, stands 9 ft high and has a footprint measuring approximately 12 ft x 12 ft. It is composed of 840 customised blocks that were 3D printed using a new type of iron oxide-free Portland cement polymer formulation developed by Associate Prof of Architecture, Ronald Rael.

Bloom is a precise 3D printed cement polymer structure that overcomes many of the previous limitations of 3D printed architecture. Such limitations include the speed and cost of production as well as aesthetic and practical applications.

Rael's team comprises four graduate students, Kent Wilson, Alex Schofield, Sofia Anastassiou and Yina Dong who fabricated the structure using 11 printers made by 3D Systems.

The printers are located in the College of Environmental Design printFARM (print Facility for Architecture, Research, and Materials), and at Emerging Objects, and produced unique enumerated bricks, with a variegated pattern that allows for varying amounts of light to pass through.

"While there are a handful of people currently experimenting with printing 3D architecture, only a few are looking at 3D printing with cement-based materials, and all are extruding wet cement through a nozzle to produce rough panels," Rael said.

> "This project is the genesis of a realistic, marketable process.

Photos: UCB

"We are mixing polymers with cement and fibres to produce very strong, lightweight, high-resolution parts on readily available equipment; it's a very precise, yet frugal technique. This project is the genesis of a realistic, marketable process with the potential to transform the way we think about building a structure."

Assembled, the bricks create an overall decorative pattern that its creators say is reminiscent of traditional Thai floral motifs along the structure's undulating wall.

The 3D structure is set to be disassembled and shipped to Thailand, where it will be exhibited and remain on display for several months before travelling to various locations around the world.


**POST TENSION DESIGN AND CONSTRUCTION**

**NATIONAL SEMINAR JUN-JUL 2015**

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# POST TENSION DESIGN AND CONSTRUCTION

**Sydney 23 June | Adelaide 24 June | Perth 25 June**
**Brisbane 30 June | Melbourne 1 July | Hobart 2 July**

Post-tensioning has been widely used in Australia for the past 40 years for building and civil engineering structures. During this time, there have been significant advances in design and construction techniques and Australia has been at the forefront of the industry throughout this time.

This National Seminar will provide detailed updates and information in the efficient and economical design of post-tensioned structures, along with an understanding of what is required from a design perspective to ensure good construction practice. It will present some of the latest developments in construction technology, design procedures, and software tools available in Australia.

Our presenters include one of Australia's pre-eminent design experts in post-tension and two leading practitioners who understand the design requirements needed for good construction practice. Held in partnership with the Post-Tensioning Institute of Australia, the Concrete Institute of Australia encourages all designer, contractors and asset owners to attend this full day seminar.

# POST TENSION DESIGN AND CONSTRUCTION

**Sydney 23 June | Adelaide 24 June | Perth 25 June**
**Brisbane 30 June | Melbourne 1 July | Hobart 2 July**

## SEMINAR CONTENT

### Session 1: Post-Tension Design – presented by Peter Dux

- Introduction to Design
- Selection of prestress for determinate members
- Strength limit states
- Selection of prestress for indeterminate members

### Session 2: Post-Tension Construction – presented by Haydn Kirrage and Shaun Sullivan

- Post-Tensioning and Permanent Formwork Systems
- Demolition of Post-Tensioned Structures and the Truncation of Post-Tensioned Tendons
- Grouting in Post-Tensioned Concrete Structures
- Detailing for Restraint
- Waterproofing

### Session 3: Software – presented by Shaun Sullivan

- Software Design

## WHY ATTEND

Course attendees will receive a comprehensive detailed set of notes and reference material including detailed design information.

Attendees will also be able to:

- Find out about the latest developments in post-tensioning systems, its construction practice, and economical advantage.
- Learn and understand the importance of design concepts from first principles.
- Understand how current Standards and other codes impact on design.
- Reduce risk and learn how to avoid costly errors by following accepted design and construction practice.
- Examine the possibilities of using software programs tailored for the design of post-tensioning.

## WHO SHOULD ATTEND

- Structural engineers engaged in concrete and/or post-tensioning design.
- Contractors interested in the construction and design of post-tensioned structures.
- Engineers responsible for the review of post-tensioned designs.
- Academics and students with an interest and background in concrete design.
- Engineers charged with retrofit of post-tensioned buildings.
- Forensic engineers who deal with post-tensioned structures.

## PRICING

Retired and Student CIA Members $295
CIA and PTIA Members $590
Engineers Australia Members $640
Non Members $795
Seminar & 12 Months Individual Membership Package $850

## PRESENTERS

**Peter Dux,** Emeritus Professor, University of Queensland
**Haydn Kirrage,** General Manager, Australian Prestressing Services
**Shaun Sullivan,** Engineering Manager, SRG Limited

To register or to find out more please visit
http://www.concreteinstitute.com.au/posttension

*The Royal Adelaide Hospital under construction.*

# Members and delegates go on site

A number of Institute members and industry delegates have had the opportunity to visit a number of sites in 2015 thanks to our local committees.

The South Australian Branch has conducted two site tours this year – to SA Precast's factory to see the production of high quality precast concrete panels and units, and to the new Royal Adelaide Hospital to inspect the progress being made on this $2 billion project (thanks to HYLC and Wallbridge & Gilbert).

In Tasmania, the committee took delegates on a tour of the Rockwood Hatchery which is undergoing a major expansion of its facility in Ranelagh. The tanks are a composition of curved precast walls with insitu stitch infills to complete the exceptionally large vessels.

The annual Boral Concrete Laboratory tour, conducted by the NSW Branch, was, as always, a great experience for those who attended. A mixture of young and experienced industry delegates enjoyed a very interesting afternoon thanks to the hospitality of Bob Bornstein and his team at Boral.

# There's a change ahead – merging of Bronze and Bronze Plus

Currently the Concrete Institute of Australia has two categories of Single-State Membership – Bronze and Bronze Plus. Following consultation with our members the National Council has approved the merger of these two categories to take effect from 1 July.

These two categories will be merged into the single category – Bronze Membership. The benefits available to members under the new Bronze Membership category remain largely the same as those currently available under the existing Bronze and Bronze Plus Membership categories.

All new members who join on, or after, 1 July will join under the new Bronze category. Existing Bronze and Bronze Plus Members will be converted to the new Bronze Membership category on their first renewal date that falls after 1 July.

The annual membership fee for the new Bronze Membership will be $1350 (inc. GST). This will remain static until at least 1 January 2017.

All existing Bronze and Bronze Plus Members will be contacted prior to their renewal date to advise them of the changes and how the merger will affect them. As with the current Bronze and Bronze Plus categories the new Bronze category is a Single-State Membership. This means that all nominated Representative Members must be from the same state in which the membership is held.

Also, as with the current categories, the Member discount on Institute events applies to all employees of the Company Member attending events held in the state in which the membership is held. If you have any questions about the Bronze/Bronze Plus merger please contact our Membership Services Manager, Duncan Miller, on 02 9955 1744 or <member@concreteinstitute.com.au>.


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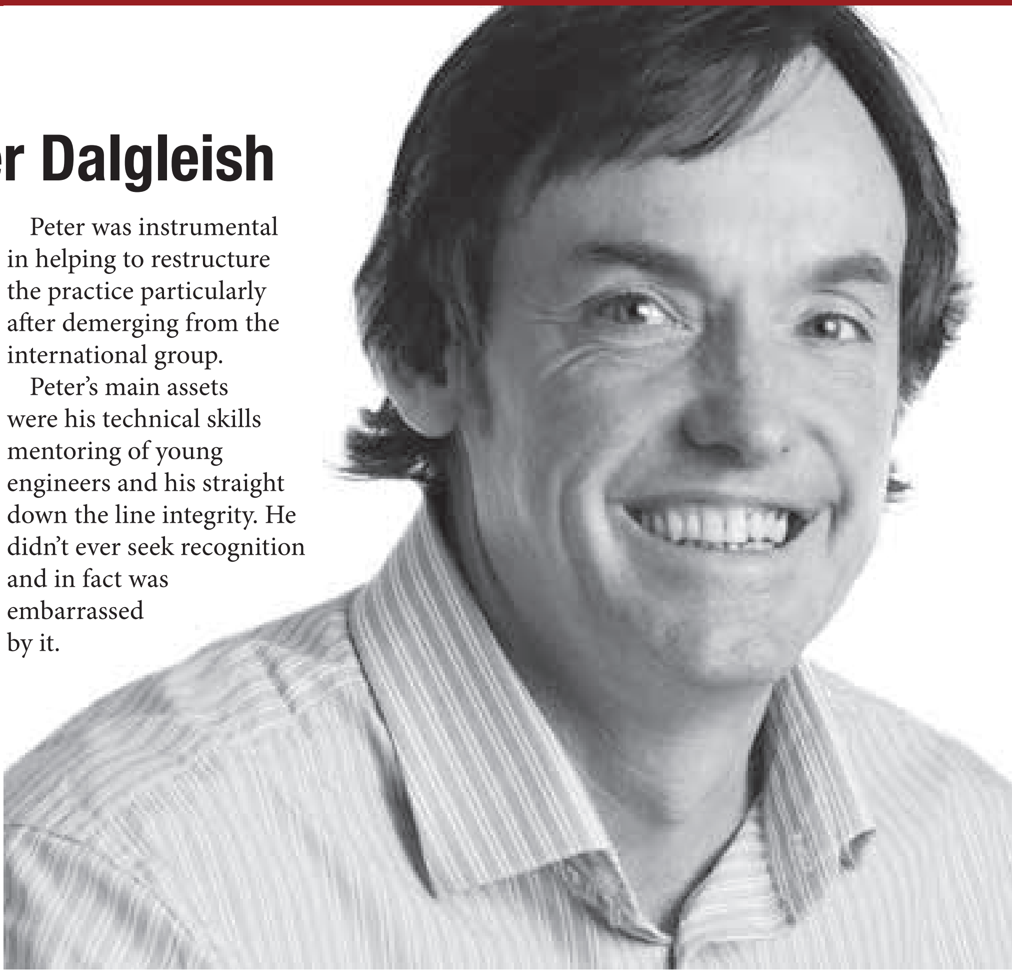
# In memory of Peter Dalgleish



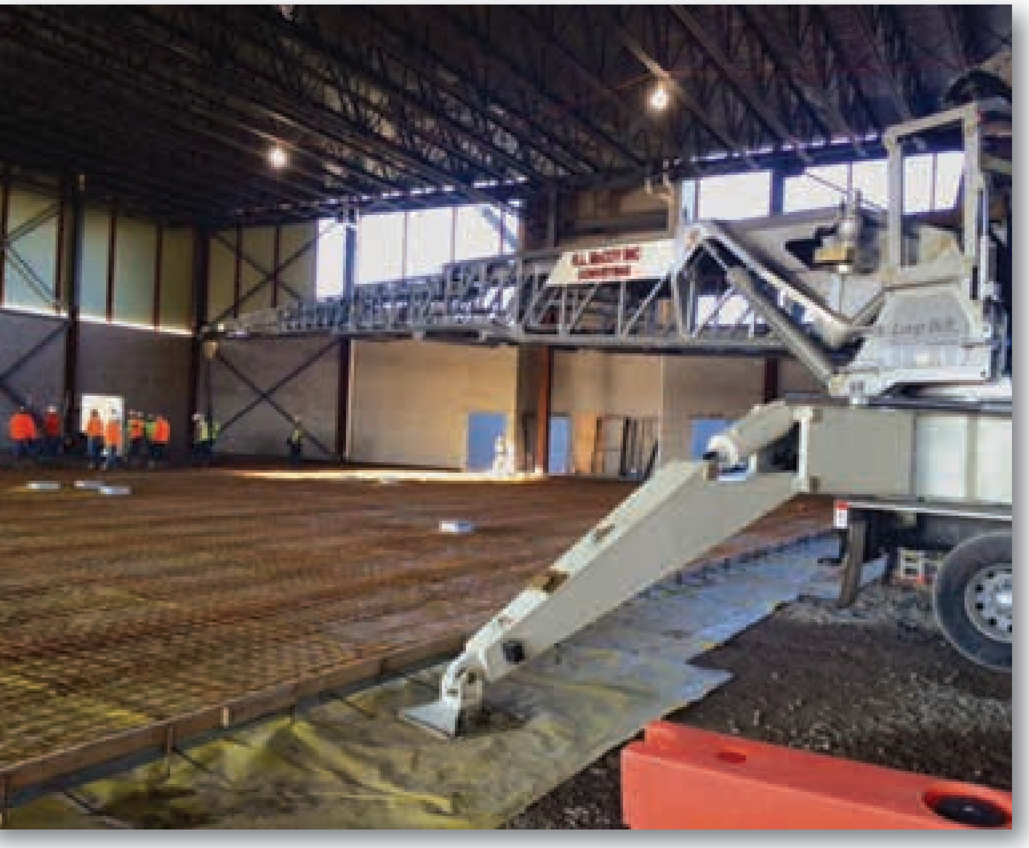
Colleagues in the concrete industry and engineering industry as a whole will be saddened to learn of the passing of Peter Dalgleish in March of this year after a short illness.

Peter's first job was at Minenco in 1982 after graduating from RMIT where he won two prizes for structural engineering in his final year. From 1985 to 1994, Peter worked at Mathieson Crisp under the tutelage of Barry Crisp, another well known engineer who would have taught Peter so much about practice and detailing of concrete and precast in particular.

In 1994, joined Irwin Johnston and Partners, now Irwinconsult, as a project engineer but was promoted to senior engineer almost straight away in recognition of his skill and ability Peter subsequently became a principal engineer, then associate director in 2000 and worked with Irwinconsult until his passing.

Peter was instrumental in helping to restructure the practice particularly after demerging from the international group.

Peter's main assets were his technical skills mentoring of young engineers and his straight down the line integrity. He didn't ever seek recognition and in fact was embarrassed by it.



# World's largest concrete conveyor at work

The world's largest concrete conveyor is being used for the expansion of the Coliseum Conference Center in Fort Wayne, Indiana, in the US, according to *www.wane.com*.

Weigand Construction, the contractor for the project, is using the conveyor to pour concrete in a 12,000 $ft^2$ portion of the expansion. The conference centre at the memorial coliseum will open in January next year, and is set to provide an additional 27,000 $ft^2$ of multi-purpose event space and almost 20,000 $ft^2$ of new or renovated pre-function lobby space.

# Concrete standards remain high

The Concrete Institute of Australia has had a long and distinguished association with Standards Australia and the development of concrete codes and their associated standards. The Institute takes its responsibilities as a nominating organisation very seriously and has established guidelines and put in place policies to select nominated representatives, compose reference groups and establish appropriate committee behaviour and protocol.

At present the Institute is either involved in or supports a number of Australian Standards and committees. These include:

- BD-002: AS 3600 – Concrete Structures
- BD-010: AS 3972 – General Portland Cement
- BD-066: AS 3850 Pts 1 & 2 – Prefabricated Concrete Elements
- BD-090: AS 5100 - Bridge Design (specifically AS 5100.5 – Concrete)
- BD-049: AS 1379 – Specification & Supply of Concrete
- BD-031: AS 3582.1, 2, 3 – Supplementary Cementitious Materials for Use With Portland Cement)
- BD-042: AS 1012 – Methods for Testing Concrete
- BD-084: AS 2425 – Bar chairs in reinforced concrete.

The convenor of the Institute's Standards Committee, Wolf Merretz, notes: "Of the 14 Australian Standards on which the Institute has a participating role with Standards Australia, the above list of eight standards is currently being revised and updated to reflect current state of knowledge and industry practice.

"Our nominated representatives have been selected from the membership of the Institute through a nomination procedure involving review, recommendation and, finally, an approval by the Council of the Institute. These persons are recognised as experts in the relevant fields of representation and are supported by other experts who form a support structure or Reference Group. In this way the Institute is able to maximise its influence at code committee level through writing and review under the management of Standards Australia and its appointed chairpersons.

*Standards Australia's CEO Dr Bronwyn Evans.*

"The Institute has had considerable success in influencing committee decision-making through acceptance of Institute representative knowledge and persuasions being robustly debated and in many instances adopted.

"Nominated representatives currently active and making significant contributions on their respective committees are Linda Lee (Bridge code AS 5100.5), Gil Brock (Concrete Structures AS 3600), Dr Frank Collins (Cement AS 3972), Simon Hughes (Prefabricated Elements AS 3850.1 &2) and Graeme Hastie (Supplementary Materials AS 3582).

"These representatives selflessly provide their time gratis and make expert contributions over extended periods at committee meetings wherever they may be conducted. The Institute is most appreciative of their contribution."

The Institute also recently held its March Council meeting at the offices of Standards Australia. Councillors were given an update on the direction of Standards Australia by National Sector Manager, Alison Scotland, and were also able to express views and thoughts in the company of Standards Australia's CEO, Dr Bronwyn Evans.

# ACI Spring Convention 2015

The American Concrete Institute's Spring Convention for 2015 was held in April in Kansas City. The convention, themed 'Fountains of Concrete Knowledge', saw hundreds of delegates descend upon the US city including the Institute's CEO, David Millar. David was given the opportunity to present at the convention's international forum and gave the delegates an overview of the Institute's strategy and direction. He also highlighted the many global firsts and records that the Australian concrete industry has achieved over its history.

Australia was also represented at the convention by some local concrete experts during the technical sessions including:

- Dr Riadh Al-Mahaidi (Swinburne University of Technology) who presented the paper *A Study of Recovery Stresses Generated by NiTi Shape Memory Alloy Wires in CFRP/SMA Patches*
- Dr James Aldred (AECOM) who presented the paper *Burj Khalifa – A New High for High-Performance SCC.*

# ACMSM23

The 23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23) was hosted by Southern Cross University (SCU) and held in Byron Bay and at the Lismore Campus of SCU in December 2014.

The Concrete Institute of Australia supported the conference along with the Cement Concrete and Aggregates Australia, Ash Development Association of Australia, the Australasian (Iron and Steel) Slag Association and the Amorphous Silica Association of Australia.

The ACMSM conference series has been run biennially since 1967 when it was first held at the University of New South Wales in Sydney. The focus of the conference series was originally:

- the analysis and behaviour of structures under static and/or dynamic loading
- materials, structures and structural element studies in the field of elasticity, plasticity and visco-elasticity as well as creep and fatigue
- the application of computers to the analysis and design of structures, including such topics as computer-aided design and organisation.

The focus has generally stayed the same with the exception of advances in computer based applications. The aim of the conference is to provide a forum for presentation of papers and discussion by authors, researchers and others interested in these fields. It has tended to be been directed more to the academic than the practicing engineers but there is an increasing drive to involve more industry based professionals.

The conference series has grown in stature and reach over the years and brought together key academics in the areas of structures and materials based research. The proceedings of ACMSM23 contains 200 submissions comprising 194 peer reviewed papers as well as six keynote submissions on a variety of topics related to structural mechanics and materials.

Over 180 presentations were delivered at ACMSM23 including six keynotes. The conference was chaired by Prof Scott Smith, Dean of Engineering at SCU, who did a magnificent job in hosting delegates and facilitating discussions in key areas of structures and materials based research.

# Concrete flooring and construction seminar

Concrete Floors Asia Sdn Bhd (CFA), in collaboration with Cement Concrete & Aggregates Australia, Concrete Institute of Australia, and the Concrete Placers Association of NSW, will be holding a seminar in Sydney on 6 July 2015.

Participants can expect comprehensive coverage of the updated best current construction practices, technology and equipment to produce the most appropriate flatness, levelness, durability and longevity in floors.

CFA will continue to bring in leading experts from around the world who specialise in various aspects of concrete flooring and construction. As in the previous seminars, these experts will bring vast knowledge and many years of experience in floor construction activities.

Participants will have firsthand access and practical know-how on the best practices in the process of construction of concrete floors and get to talk to all the leading experts and speakers.

For more information please visit <www.concreteinstitute.com.au/Events/352>.

# Paving the way to the ASCP conference

The Australian Society for Concrete Pavements (ASCP) is conducting its third biennial Concrete Pavements Conference at Coffs Harbour commencing 20 July. The venue was chosen because of its proximity to current Pacific Highway Upgrade projects involving major concrete pavement construction.

Over two days, 25 papers and two keynote addresses will be presented. In addition to papers on the design, construction and performance of concrete road pavements, topics also include concrete airfield, port and tunnel pavements. A site tour to a nearby highway construction project is offered.

The opening address will be presented by Bob Higgins, General Manager, Pacific Highway, Roads & Maritime Services NSW. Overseas presenters include seven Directors of the International Society for Concrete Pavements (ISCP), including President Neeraj Buch who will speak at the Conference dinner.

The ASCP Concrete Pavements Conference attracts a cross-section of the Australian heavy duty concrete pavements industry represented by designers, contractors, client organisations, operators, researchers, and suppliers of materials and equipment. It offers the opportunity to receive up to date information on concrete pavements and to interact with both Australian and overseas practitioners.

The conference is well supported by industry, with sponsors including Acciona Infrastructure Australia, Aurecon, BASF, Boral Cement, BOSFA, Chandler Morrison Geotechnical, Elasto Plastic Concrete, GOMACO Corporation, JK Williams Group, Lend Lease Engineering, and OHL Construction Pacific.

Further information, including the Conference Program and Registrations Brochure, is available from the website at <www.concretepavementments.com.au> under the events section or by emailing <exec@concretepavements.com.au>. Registrations are now open with discounted registration fees available until 20 June.

# Concrete comes to Canberra

In late 2014, an ACT Sub-Branch Committee was formed, thanks largely to the efforts of Dan Rowley (ACRA Past President) who is acting as the committee convenor, and committee members Merv Uren, Aaron Hazelton (Indesco) and Alvin Lau (Sellick Consultants).

The Sub-Branch ran their first seminar in March 2015 on "Cracking in Concrete" and attracted over 50 delegates from Canberra and surrounding NSW regional areas. After such a successful event the committee will look to running more events in the ACT during 2015.

The ACT Sub-Branch is looking for other local members of the Institute to join the committee so that more seminars and events can be put together in Canberra on issues that are topical and of interest to practitioners in the region. Contact <nsw@concreteinstitute.com.au> for more information or to get involved.

# FEA seminar in Melbourne

The Victoria Branch recently presented a half day seminar in Melbourne on FEA modelling that was aimed to increase the understanding of this design process for inexperienced designers or provide a refresher for those who are more familiar with it.

The Branch was fortunate enough to engage the services of two international speakers, through the support of Melbourne based Institute Councillor, Dr David Morris, and the Institute of Structural Engineers (IStructE) from the UK – Steve Rhodes and Stewart Morrison.

# Bamboo as an alternative to steel reinforcement for concrete

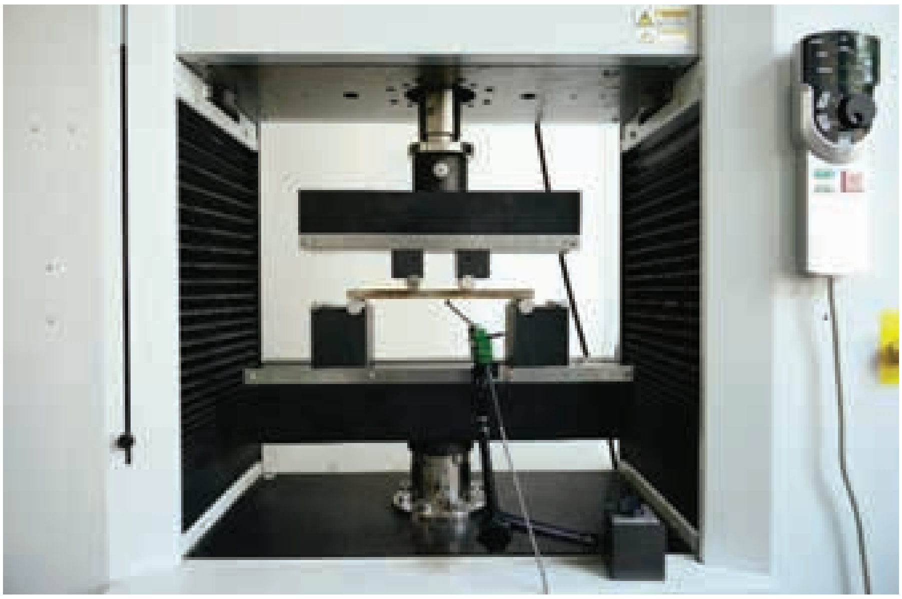
Developing countries use up to 90% of the cement and 80% of the steel which is consumed by the global construction sector, yet steel reinforced concrete as the most common building material worldwide is costly to produce and transport.

Now, the Future Cities Laboratory (FCL) in Singapore-ETH Centre is conducting research which shows that 70% of damage in the built environment is caused by steel corrosion inside reinforced concrete structures. FCL is exploring a bamboo composite material that is free of corrosion, lighter and more cost effective than steel and is derived from a renewable, organic source.

Bamboo is a rapidly growing grass that has been used for centuries in construction and is very resistant to tensile stress. Although bamboo has been used in construction for a long time, new possibilities are being presented by new bamboo composite material developed by FCL, according to Prof Dirk E. Hebel, Chair of Architecture and Construction.

The research is focused on the potential for extracting fibre from natural bamboo, transforming it into a manageable industrial product, and introducing it as a viable building material and an alternative to steel and timber. Given its outstanding tensile properties, replacing the steel reinforcement in reinforced structural concrete with bamboo is becoming of great interest.

However, the natural form of bamboo poses many problems when used as reinforcement in concrete. Despite its strength, bamboo has a range of weaknesses as a construction material. Water absorption, swelling and shrinking behaviour, limited durability, and vulnerability to fungal attacks have limited most applications of bamboo in the past and resulted in its segregation from the concrete environment. But FCL believes it has overcome these issues.



***Testing being conducted at the Advanced Composite Laboratory.*** Source FCL

"Bamboo has long been recognised in many building traditions around the world for its outstanding mechanical and physical properties. Recent concerns for environmental sustainability have seen the material being reassessed for application in mainstream building construction," Alireza Javadian, doctoral researcher from FCL said.

"It has even been described as the super-fibre of the 21st century. Bamboo is the fastest growing plant on earth, is self-regenerative, easy to obtain and therefore is very inexpensive.

"For a common oak or pine tree, a time frame of 30 to 70 years is necessary so that the plant is grown to its full strength before it is cut into any structural elements, while bamboo needs only four to five years to be ready for application for structural purpose."

The recently established Advanced Fibre Composite Laboratory at FCL in Singapore has now extended the range of the research into bamboo to material production, property analysis, chemical composition and micro-imaging.

"Bamboo composite material can be produced in any of the familiar shapes and forms in which steel and timber are produced. Like them, the material can be used to build wall structures for houses or any other buildings. More interestingly, it can be used for specific applications that best take advantage of the material's tensile strength, such as reinforcement systems in concrete or beams for ceilings and roof structures," Javadian said.

The interest in bamboo has been increasing over the last decade with countries like Brazil, Colombia and China already replacing many conventional timber-made products with high quality bamboo.

***Night construction during the build of the Fiona Stanley Hospital.*** PHOTO: BROOKFIELD MULTIPLEX

# Big contracts for Delta

Delta Corporation, a Bronze Member of the Concrete Institute of Australia has been active in its hometown of Perth, Western Australia, having completed contracts on the Perth City Link as well as the Fiona Stanley Hospital.

The $2 billion Fiona Stanley Hospital is a 783 bed, 6300 room development with 150,000 m² of floor space across five main buildings, the equivalent of four city blocks. It also has 3600 basement, ground level and multi-storey car spaces. Construction included the main hospital building, pathology/education centre, central plant building, two multi-storey car parks and a service tunnel to the main hospital.

The developer, Brookfield Multiplex, contracted Delta Corporation for the precast work, with construction requiring architectural walling panels as well as Deltacore Floor Planks for parts of the central plant building and the main hospital building. The panels were wet-cast horizontally using high quality steel moulds.

A total of 994 custom wall panels covering 7151 m² were needed for the main building's podium exterior, internal courtyards and corridor. These panels featured horizontal and vertical grooves, creating a semi-regular pattern. Randomly selected rectangles were also grit blasted for effect, and then to reduce maintenance, the surfaces were treated with a clear waterproof and stain-proof sealer.

For the pathology/ education centre, 103 architectural cladding panels totalling 940 m² were manufactured. A blend of cream and grey cement was used, with a grit blasted finish to expose the granite, diorite and red pebble aggregate, and sealed prior to delivery. Precast was used for two multi-storey car parks. More than 3000 m² of white architectural wall balustrade panels were created using cream cement and white oxide for a high quality finish for this part of the project.

Perth's $360 million rail project was the first stage of the Perth City Link public transport infrastructure project. It involved sinking of the Fremantle Line (between William St and Lake/ King St) to create almost 600 m of a new cut and cover section along the line. Delta Corporation's involvement was to supply the roof of the entire 600 m long tunnel. A total area of 13,750 m² of planks was required, with construction commencing in early 2012 and then supplied over an 18 month period as required.

High capacity precast pre-stressed concrete voided planks were manufactured, ranging from 8500 mm long up to 14,500 mm, to a maximum weight of 24.0 t. The panels were wet cast in steel moulds with structural grey concrete to a class 2 finish. Panel profiles included 2225 mm wide x 450 mm thick (325 No), 1815 mm wide x 450 mm thick (150 No) and 1425 mm wide x 550 mm thick (130 No). Site congestion and difficult ground conditions meant the roof slab could not be constructed using traditional methods.

Perth City Rail Alliance received a Concrete Institute of Australia National Award for Excellence in the projects Engineering Category due to the complex construction of the Fremantle Line Rail Tunnel.


# Research into practice

Concrete 2015, the 27th Biennial National Conference of the Concrete Institute of Australia, will be held in Melbourne at the Pullman Hotel, Albert Park, from 30 August to 2 September 2015. The conference will also be held in conjunction with the 69th Annual RILEM Week.

The Conference Organising Chairman, Professor Jay Sanjayan, invites people from both Australia and the rest of the world, to be part of this historic joint event which will provide delegates with valuable exposure to cutting edge research and development as well as the chance to network in a truly international forum.

Concrete 2015 will focus on the theme ‘Research into Practice’ and is dedicated to bringing together global leaders in the concrete industry, covering all aspects of concrete design improvements, research, construction, maintenance and repair of concrete projects.

The eight keynote speakers, including RILEM’s Robert L’Hermite Medalist, certainly represent this and will present on topics that show how innovative research can be applied to practice. Concrete 2015 will also offer participants from around the world the opportunity to connect face to face and share innovative and interesting ideas on valuable research outcomes and latest construction practices with a wide variety of industry experts.

The Chairman of the Technical Committee, Dr Kwesi Segoe-Crentsil, noted, “We were overwhelmed by the number of abstracts we received, both locally and from overseas. We will only accept quality technical papers for the Conference, but the standard has been extremely high and the program will be prepared to ensure that the delegates get to hear from as many authors as possible”.

The multidisciplinary theme of Concrete 2015 will provide an excellent forum for networking and education and an opportunity to meet and interact with practitioners, engineers, scientists, researchers, academics, practitioners and professionals, and also to engage with international delegates from RILEM technical committees. Whether you attend technical sessions, sit in on multiple committee meetings or network with friends and colleagues this conference will provide you with ample opportunity for professional growth. The Organising Committee and the Concrete Institute of Australia look forward to meeting you at Concrete 2015 in Melbourne.

## Conference details – at a glance

**Delegate registration is open**

Registration for Concrete 2015 is open and can be made via the conference web site <www.concrete2015.com.au>. Early bird registration is available but you need to hurry – this closes on 29 May 2015.

There are many categories of registration available, as well as significant discounts for CIA Members. There are also reduced fee options available to young industry professionals, academics, retired CIA Members and students.

Don’t forget – Early bird registration fees close 29 May – don’t miss out!

# Sponsorship and exhibition opportunities

Sponsorship Chairman Simon Hughes advises that there are still some excellent sponsorship opportunities available for Concrete 2015 for companies seeking exposure to the wide ranging audience from the building and construction industry.

Both large value and smaller value packages are available and special packages can be negotiated. Companies should assess the technical program and the groups to which the conference will appeal in order to gain an appreciation of those topics that will be of value to them and to determine the value of gaining exposure to such an audience.

Concrete 2015 has already got some significant sponsorship support to date from the following companies:

## Conference Partner

### Platinum Sponsor

### Gold Sponsors

### Silver Sponsors

The exhibition has been selling fast for Concrete 2015. At the time of print there were only 8 exhibition spaces left. Many organisations see this conference as not only an opportunity to get exposure to the local concrete design and construction industry, but to also meet the large number of overseas delegates expected due to the RILEM Week of meetings and presentations.

If you are interested in sponsorship or an exhibition space at the conference don't delay. Contact Kirsty Winning, Senior Sponsorship & Exhibitions Account Manager for Concrete 2015 on +61 2 9265 0776 or email <kwinning@arinex.com.au>.

## Awards for Concrete Excellence and Gala Dinner

The Institute received over 50 submissions in the Awards for Concrete Excellence. All of these entries will be striving for the Kevin Cavanagh Medal, the highest accolade available in concrete excellence in Australia, and to join the 2013 winners Rayner Cox Architects for the Age of Australia Dinosaur Museum.

The presentation to the winners of the Institute's Awards for Concrete Excellence will be held at the conference Gala Dinner, to be held on Tuesday 1 September. This prestigious event is one of the highlights of the conference and will recognise excellence in the categories of building projects, engineering projects, technology and international projects. The Institute will also induct any newly elected Life and Honorary Members at the dinner.

*2013 Kevin Cavanagh Medal winner – Age of Australia Dinosaur Museum.*

# 7 reasons to come to Melbourne in 2015

1. **Learn** – The program is incredibly diverse and includes topics that cover a wide range of concrete disciplines. Come and learn more about Australian and international research and how it is put into practice.
2. **Network** – With like-minded people from all parts of the globe and develop contacts that will help you professionally both at home and around the world.
3. **Exposure** – Concrete 2015 will provide exposure for you and your organisation to the concrete industry in the Asia Pacific region.
4. **Representation** – If you are with a local company, university, or industry group, involved in international concrete committees like fib and RILEM, or with an international organisation, represent your constituents in Melbourne and show us what you do.
5. **Reconnect** – Come and catch up with old colleagues from far and wide and reconnect.
6. **Discover** – New and innovative ideas in the world of concrete as well as new markets to explore.
7. **Fun** – Melbourne is a fantastic city and is also gateway to the rest of Australia. Come and enjoy the conference but make the most of your time in one of Australia's most enjoyable places, or if you're travelling from overseas go and explore the rest of the country.

# Keynote Speakers

**Professor Stephen Foster, Head of School, Civil and Environmental Engineering, UNSW, Australia**

Stephen Foster is Professor and Head of School, Civil and Environmental Engineering at UNSW Australia. Professor Foster has more than 30 years of experience in research and over 240 publications. His doctorate research was in the field of reinforced concrete, specifically in the area of analysis and design of reinforced concrete deep beams. He has developed and calibrated a powerful non-linear finite element program, using a number of state of the art numerical techniques, for the analysis of non-flexural concrete elements. His work in the last 13 years has been in SFRC and UHPC. Professor Foster is a Fellow of Engineers Australia, Member of the Concrete Institute of Australia, Member of the Standards Australia Committee BD2 "Concrete Structures", Chairman of Standards Australia Subcommittee BD2/5 "Strength", Chairman of the Standards Australia Subcommittee BD2/8 "Fibre Reinforced Concrete" and has been a Member of the Presidium for the Federation of Structural Concrete (fib) since 2011.

**Dr Yen Lai Voo, Dura Technology Sdn Bhd, Malaysia**

Dr Voo Yen Lei has been setting world records in bridge-building. In 2011, the company that he founded and of which he is CEO and Executive Director, DURA Technology, built the world's longest trafficable bridge using ultra-high performance concrete (UHPC): the Kampung Linsum Bridge in Malaysia. Voo designed, manufactured and built the cutting-edge bridge, which won the Husband Prize from the Institution of Structural Engineers. His company is currently building a 100m single-span bridge using the same technology. Dr Voo completed his B.E in Civil Engineering at the University of NSW where he also finished his PhD. Following this he left Sydney and spent four years developing the ultra-high performance concrete technology, marketing the material, and dealing with regulators and industry bodies. The company has completed 14 bridges for the Malaysian government, 12 more are under construction and 10 others are under tender. Dr Voo is also an adjunct professor at the University Putra Malaysia where he teaches students the technology of UHPC.

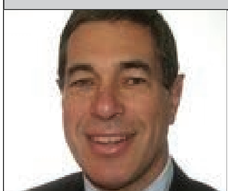
**Professor Karen Scrivener Laboratory of Construction Materials, Switzerland**

Karen Scrivener was born in England and graduated from University of Cambridge in 1979 in Materials Science. She went on to do a PhD on "The Microstructural Development during the Hydration of Portland Cement" at Imperial College, remaining there until 1995 as Royal Society Research Fellow and lecturer. In 1995 she joined the Central Research Laboratories of Lafarge near Lyon in France. In March 2001 she was appointed as Professor and Head of the Laboratory of Construction Materials, Department of Materials at EPFL (Ecole Polytechnique Fédérale de Lausanne), Switzerland. The work of this laboratory is focussed on improving the sustainability of cementitious building materials. She is the founder and co-ordinator of Nanocem, a Network of industry and academia for fundamental research on cementitious materials and Editor in Chief of Cement and Concrete Research, the leading academic journal in the field.

**Professor Jon Provis, Department of Materials Science and Engineering, University of Sheffield, UK**

John L. Provis is Professor of Cement Materials Science and Engineering at the University of Sheffield, United Kingdom, and is an Honorary Fellow at the University of Melbourne, Australia. He was awarded the 2013 RILEM Robert L'Hermite Medal "in recognition of his outstanding contribution to the research and development of geopolymers and other construction materials", and holds funding from the European Research Council (Starting Grant "GeopolyConc"), as well as UK Research Councils, industry, and international sources. He is Chair of RILEM Technical Committee 247-DTA, and Associate Editor of Cement and Concrete Research and Materials and Structures.

**Professor Jannie van Deventer, CEO, Zeobond Group, Melbourne, Australia**

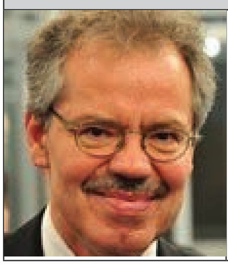


Jannie S.J van Deventer was educated in South Africa and holds doctorates in chemical engineering, mineral processing and business economics. He migrated to Australia in 1995 and served as Dean of Engineering from 2003 to 2007 at the University of Melbourne, where he is currently Honorary Professorial Fellow. He remains active in both mineral processing and cementitious materials, and has commercialised several technologies in the mining industry and construction. His has received several awards, including INNOVIC's national "The Next Big Thing Award" for geopolymer technology in 2008. He is the Chief Executive Officer of Zeobond Pty Ltd in Melbourne, which are commercialising alkali-activated binders.

**Mr K.Sreekumar, Vice President and Head, L&T Construction, India**

Mr. K. Sreekumar is a Vice President of Larsen & Toubro Limited, India, and heads the Buildings & Factories Independent Company (B&F IC) within their Construction Division. The Construction Division of L&T is India's largest construction organization and is ranked among the world's top 30 contractors. Mr Sreekumar's experience includes design of structures, construction methods planning, project management, contracting, construction products manufacturing, and marketing & business development. Mr Sreekumar's interests include adopting innovative technology with achieving efficient design & operational excellence and he has recently been nominated by L&T to serve as a member of Board of the Institute for Lean Construction Excellence (ILCE) in India, which has been specifically established by the Indian Construction industry for popularizing and executing lean construction methods throughout India.

**Dr Harald Muller, Karlsruhe Institute of Technology, Germany**



Harald Müller is a full professor at the Karlsruhe Institute of Technology, a Director of the Institute of Concrete Structures and Building Materials, a Director of the Materials Testing Institute, Karlsruhe, and Managing Partner in the Society of Engineers of Constructions Ltd in Karlsruhe, in Germany. Professor Müller has produced approximately 360 papers on his work related to: Concrete and concrete structures; Life cycle analysis and management of concrete structures; Protection, maintenance, strengthening and repair of structures; Mortars and masonry; Testing methods for concrete; Mechanical behaviour and modelling of concrete; Microstructure and durability of building materials; Temperature and moisture flow in mineral building materials. Professor Müller is also a member of various national and international scientific and technical commissions and associations, in particular the National Science Foundation of Germany (DFG), the International Federation for Structural Concrete (fib) (elected President for 2015-2016), the advisory board of the German Federal Institute of Building Technology (DIBt) and is the Chair of TG 7 "Time dependent effects" within Eurocode 2.

# Concrete 2015 & RILEM Week – Melbourne, Australia

## Construction Innovations – *"Research into Practice"*

Monday, 31 August – Wednesday, 2 September 2015

### Preliminary Conference Program

**Sunday 30th August 2015**

| | |
|---|---|
| 9.00-17:00 | **Optional Workshop:** Cement Chemistry and Hydration |

**Monday 31st August 2015**

| | |
|---|---|
| 09.00-9.45 | Chairman's Welcome & RILEM President's Introduction to Opening Ceremony |
| **9.45-10:30** | **Keynote Presentation 1**<br>Ultra-high performance ductile concrete: the delivery from research into practice<br>*Professor Stephen Foster and Dr Yen Lai Voo* |
| 11:00-13:00 | Concurrent Sessions – Construction Methods; Structures; Technology Applications |
| 14:00-15:30 | Concurrent Sessions – Sustainability Applications; Supplementary Materials; Project Case Studies |
| 16:00-17:30 | Concurrent Sessions –Technology Applications; Analysis and Design; Major Projects |
| 18.00-20.00 | Welcome Cocktail Reception |

**Tuesday 1st September 2015**

| | |
|---|---|
| **8:00 – 10:30** | **Keynote Presentation 2:** Options for the Future of Cement<br>*Professor Karen Scrivener* |
| | **Keynote Presentation 3:** Geopolymer Concrete: Research into Practice of a Low Carbon Technology<br>*Professor John L. Provis and Professor Jannie S.J. van Deventer* |
| | **Keynote Presentation 4:** Global Construction and Engineering Practices – An India Story<br>*Mr K. Sreekumar* |
| 11.00-13:00 | Concurrent Sessions – Concrete Materials Performance; Analysis & Design; Case Studies; Composites |
| 14:00-15:30 | Concurrent Sessions – Durability & Serviceability; Structures; Anchors in Concrete; Admixtures |
| 16:00-17:30 | Concurrent Sessions – Technology Applications; Structural Monitoring & Assessment; Case Studies; Cement Technologies |
| 19.00-23.00 | Conference Gala Dinner & Awards for Excellence |

**Wednesday 2nd September 2015**

| | |
|---|---|
| **9:00 – 10:30** | **Keynote Presentation 5: RILEM Robert L'Hermite Medallist** |
| | **Keynote Presentation 6:** Creep and shrinkage of concrete – from theoretical background and experimental characteristics to practical prediction models<br>*Dr Harald Müller* |
| 11.00-13:00 | Concurrent Sessions – Concrete Durability; FIB Commission 6 – Special Session; Repair & Retrofitting |
| 14:00-15:30 | Concurrent Sessions – Early Age Cracking; FIB Commission 6 – Special Session; Fibres & FRP Application |
| 16:00-17:00 | Concurrent Sessions – Sustainable Construction; Non Destructive Testing; Asset Management |
| 17.00-17.30 | Closing |
| 19.00-24.00 | RILEM Dinner |

**Thursday 3rd September 2015**

| | |
|---|---|
| 9.00-17:00 | Workshop: Precast Concrete – Updates in Design and Standards |

*Program correct as at 12 March 2015 and subject to change.*

# Workshops

Pre- and post-conference workshops have been arranged. These courses are optional and not included in any registration category. Delegates can purchase a seat at these courses via the same online registration form as the conference at <www.concrete2015.com.au>.

**Cement Chemistry and Hydration**
**Date:** Sunday 30 August 2015
**Time:** 09:00 – 17:00
**Venue:** Pullman Albert Park, Melbourne
**Presenter:** Prof Karen Scrivener, Laboratory of Construction Materials in Lausanne, Switzerland

Cement Chemistry and Hydration is a one day course presented by Prof Karen Scrivener, Laboratory of Construction Materials in Lausanne, Switzerland, RILEM Member, and Key Note Speaker at Concrete 2015.

This course is part of a RILEM doctoral course in Nanocem and will take a comprehensive and in-depth look at the chemistry and hydration of cement, as well as looking at the options available for the sustainable development of concrete materials to meet the demands of a changing world.

Topics for the course will be very specific to cement chemistry and will include: clinker production and characterisation, the nature of hydrates in cement and other cementitious materials, thermodynamic prediction of hydration, kinetics and physical structure of cement paste, impact of SCM's on hydration kinetics, and microstructural modelling. This course has been presented around the world by Professor Scrivener and RILEM and is targeted at concrete and cement material technologists, materials specialists, researchers and academics, and anyone with an interest in how concrete works.

**Precast Concrete – Updates in Design and Standards**
**Date:** Thursday 3 September 2015
**Time:** 09:00 – 17:00
**Venue:** Pullman Albert Park, Melbourne

A full day workshop on the latest in design requirements for precast concrete in Australia, in particular, focusing on the new National Precast "Design Guide for Precast". The workshop will also look at changes to Australian Standards that are directly applicable to precast concrete, including AS 3850 "Prefabricated Concrete Elements" Pts 1 & 2 and the impact these will have on design, construction and erection.

Who should come? Design consultants, project managers, contractors, and anyone with an interest in the design and construction of precast concrete elements. The workshop is jointly organised by National Precast Concrete Association Australia and the Concrete Institute of Australia.

## RILEM

RILEM is the International Union of Laboratories and Experts in Construction Materials, Systems and Structures. The name RILEM comes from its French origins and the organisation was founded in June 1947, with the aim to promote scientific co-operation in the area of construction materials and structures.

One of the major outputs from RILEM comes from the technical committees mostly in concrete testing and state of the art reports which serve as authoritative documents. RILEM recently created 14 new committees in addition to the existing 20 active committees, with a further 12 committees recently completing their tasks.

RILEM also publishes a high ranking journal, Materials and Structures, where recent research findings from all over the world are regularly published. The Mission of RILEM is to advance scientific knowledge related to construction materials, systems and structures and to encourage transfer and applications of this knowledge worldwide. This Mission is achieved through collaboration of leading experts in construction practices and science including academics, researchers, testing laboratories and authorities.

The Goals of the Association are:

- To promote sustainable and safe construction, and improved performance and cost benefit for society.
- To stimulate new directions of research and its applications, promoting excellence in construction.
- To favour and promote co-operation at international scale by general access to advance knowledge.

To learn more about RILEM visit <www.rilem.org>.

The Concrete Institute of Australia is proud to host the RILEM Week at Concrete 2015. Many of the RILEM committees will be meeting before and during the conference, as well as attending the conference. The Institute welcomes our RILEM guests with open arms and look forward hosting the 69th annual RILEM Week in Melbourne.

# UHPFRC AS A MATERIAL FOR BRIDGE CONSTRUCTION

## Are we making the most of our opportunities?

*by Stephen J. Foster and Yen Lei Voo*

With the opening of Shepherd's Gully Bridge 150 km north of Sydney in 2005, Australia was among leaders of the world in the utilisation of ultra-high performance (UHPC) for road bridge construction. Ten years on, not one more bridge has been constructed and the uptake of UHPC technologies has been, at best, limited. In contrast, Malaysia's first bridge was opened in 2010 and in the time since a further 40 bridges have been completed, with many more under construction and on the drawing board. Road bridges with spans as little as 12 m and as large as 52 m are operational and spans of 100 m are being built.

Around the globe, UHPC is seeing slow, but steady, take up in many countries with more than 100 operational bridges worldwide. The questions being asked are, "why has Australia gone from leading the world in the application of UHPC technology to watching from a distance?" and "what is the future of UHPC for developing sustainable and resilient infrastructure?" This paper provides examples of two Malaysian UHPC bridges, the 51 m span UHPC-composite deck Rantau Negeri Sembilan Bridge completed in December 2013 and the 100 m span integral deck precast segmental box girder bridge due for completion in mid-2015.

## 1.0 Introduction

One of the major breakthroughs in concrete technology of the 1990s was the development of ultra-high performance fibre reinforced concrete (UHPFRC), also known as the reactive powder concrete (RPC), by Richard & Cheyrezy (1994; 1995). Compressive strengths and flexural strength of over 180 MPa and 40 MPa, respectively, have been reported. Since then, extensive research studies have been undertaken by academics and engineers alike with the view to industrialise this technology as an alternative for sustainable construction.

*Figure 1: Precast UHPFRC 2.5 m high retaining wall segment.*

While its take-up in practice has received gradual acceptance in many countries, this has not been the case in Australia. In the years 2004 and 2005, Australia was among the world leaders in development of UHPFRC for road bridge construction, through VSL Australia and their product Ductal. In the time since, and despite significant potential, the uptake of the technology has stalled, if not stopped in Australia.

The first major structures adopting UHPFRC technology were footbridges. In 1996, the 60 m single span Sherbrooke Pedestrian Bridge was constructed, crossing the river of Magog, province of Quebec, Canada (Lachemi et al, 1998). The walkway deck, serving as the top chord to the truss, consists of 3.3 m wide by 30 mm thin UHPFRC slabs. The web members are of a composite design involving UHPFRC placed in thin walled stainless steel tubing. April 2002 saw the construction of the Seonyu Footbridge (Footbridge of Peace) in Seoul, South Korea (Behloul and Lee, 2003).

Constructed by Bouygues Construction, the bridge is an arch with a 120 m span supporting a 30 mm thick RPC deck. The structure required about one-half of the quantity of concrete that would have been used with traditional construction. At a similar time to the construction of the Seonyu bridge was the 50 m footbridge constructed in Sakata (Sakata-Mirai footbridge), which is located in the north-western region of the island of Honshu, Japan (Tanaka et al, 2011). Other examples from Japan include the 36.4 m span segmental construction Akakura Onsen Yukemuri Bridge (completed in 2004), the 64.5 m span Hikita Footbridge (completed in 2007), the 81.2 m span Mikaneike Footbridge (completed in 2007) (Tanaka et al, 2011, Musha et al, 2013). In the time since the construction of the Seonyu and Sakata-Mirai footbridges, UHPFRC bridges for pedestrian traffic have been constructed in France, New Zealand, Spain, Germany and elsewhere (Toutlemonde & Resplendino, 2011).

Internationally, private and governmental bodies are increasing their attention and initiative towards utilising performance advantages of UHPFRC, together with its being demonstrated as one solution towards more sustainable construction (Ng et al, 2012; Voo & Foster, 2010). UHPFRC is a highly workable material that may be used to form complex shapes, with reduced mass and reduced material. Figure 1 shows a 2.5 m high UHPFRC retaining wall segment; Figure 2 shows the UHPFRC façade elements of the Museum of European and Mediterranean Civilisations, Marseille, France and constructed in 2013.

The first road bridges to be constructed using UHPFRC technology appeared in 2005, with four bridges constructed at around the same time (Voo et al, 2014). One of these was the 16 m span, 21 m wide, precast pre-tensioned I-girder bridge at Shepherd's Gully (Figure 3) located 150 km north of Sydney and constructed by VSL Australia (Foster, 2009; Rebentrost & Wight, 2011). The girders for these bridges were fabricated by VSL using the facilities of the Heavy Structures Laboratory at UNSW Australia.

At this time, Australia was at the cutting edge of research into use of UHPFRC with doctoral theses by Voo (2004), Warnock (2005), Ngo (2005), Malik (2007) and Menefy

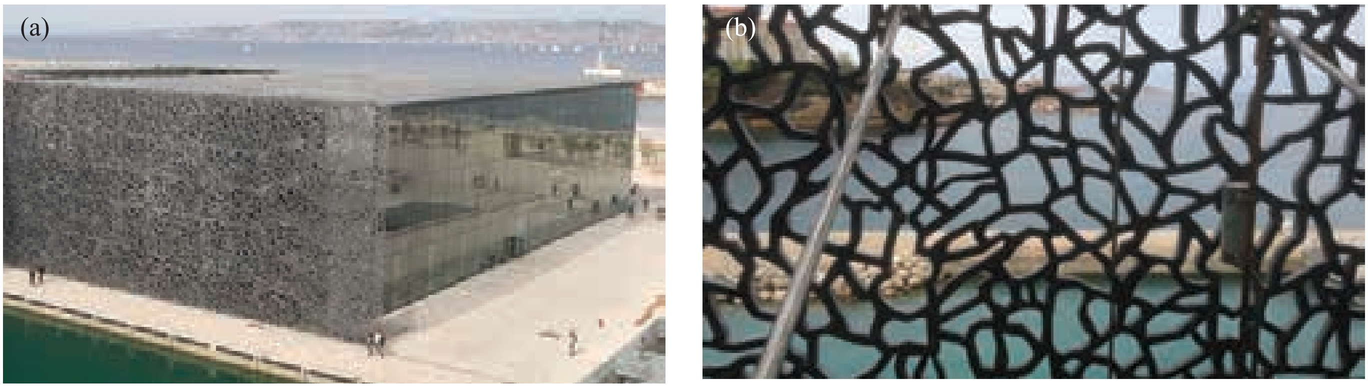



*Figure 2: (a) Museum of European and Mediterranean Civilisations – Marseille, France; (b) UHPFRC façade.*

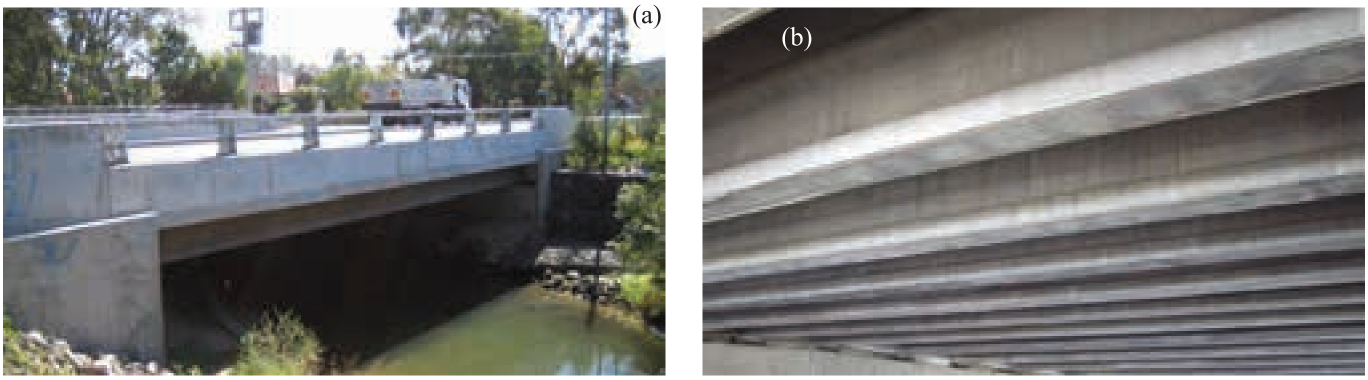



*Figure 3: Shepherds Gully Bridge, NSW, Australia constructed in 2005: (a) 15 metre span 4 lane road traffic bridge (b) underside showing I-girders.*

(2007). The significance of such technology lies not only in the great enhancements in concrete strengths, leading to lighter weight construction and more efficiency of materials, but also in the contribution to sustainability through lower carbon footprints (Voo & Foster, 2010).

In 2008, the world's first segmental UHPFRC composite deck road bridge was constructed; a single-span 46 m ground support equipment (GSE) bridge was built over a road connecting the south and north apron in the extension of the Tokyo International Airport project. At the time, the road bridge was the largest UHPFRC road bridge in the world (Tanaka et al, 2011).

While construction of UHPFRC bridges in Australia has stalled, since 2006 Dura Technology Sdn Bhd (DTSB) has been pioneering research on the optimal uses of UHPFRC in bridge construction in Malaysia. During several years of research and development, DTSB has been collaborating with the Malaysia Works Ministry to design and build UHPFRC bridges, with a particular emphasis for bridges in rural areas where sourcing materials, site access and construction method are major constraints when using the conventional technology.

From 2010 till now, a total of 41 UHPFRC bridges have been completed; a further 13 are in an advanced stage of construction and another 21 are in the early stages of production. By the end of 2015, 75 bridges are due to be completed; 58 of these bridges are of segmental construction and 17 are pre-tensioned girders having spans of less than 22 m.

In most cases UHPFRC precast bridge construction can be demonstrated to realise the following advantages (Voo & Foster, 2010; Voo et al, 2014):

- immediate and life-cycle cost saving
- enhancement in design/service life of structures
- low maintenance due to their high durability
- reduced overall construction time and risk
- reduced consumption of raw material
- lighter superstructure dead weight permitting smaller and lighter substructure and foundations
- reduced man-power and smaller plant
- higher quality than in-situ wet work and precast high performance concrete structures
- lower impact on the construction site due to shorter-duration of temporary works.

In this paper, firstly, the mix design and mix performance properties of the Malaysian UHPFRC are outlined; next, two of the more than 40 bridges that have been completed are briefly discussed, the first the Rantau, Negeri Sembilian bridge, the largest composite deck UHPFRC bridge constructed to date, and the second the 100 m span Batu 6 bridge, due for completion in mid-2015.

## 2.0 DURA Ultra-High Performance Fibre Reinforced Concrete

There are many variations in mix design of UHPFRC with a number of commercial products in the marketplace (e.g. Ductal, BSI, Taktl, myUHPC, Forida, etc). The mix design used in the beams in all bridges designed and constructed

*Table 1: Mix design of standard DURA UHPFRC.*

| Ingredient | Mass (kg/m³) |
|---|---|
| DURA UHPFRC Premix | 2100 |
| Superplasticiser | 40 |
| High strength steel fibres | 157 |
| Free water | 144 |
| 3% moisture | 30 |
| Targeted W/B ratio | 0.15 |
| Total air voids | < 4% |

by DURA is given in Table 1; the material used to produce UHPFRC consists of Type I Ordinary Portland cement, densified silica fume containing more than 92% silica dioxide ($SiO_2$) and with a surface fineness of 23,700 $m^2$/kg and washed-sieved fine sand with a particle size range between 100 µm and 1000 µm. A polycarboxylic ether (PCE) based superplasticiser is used.

Two types of steel fibres are utilised in the mix; both manufactured from 2500 MPa high carbon steel wire. Type I steel fibre are straight in shape and are supplied with dimensions of 20 mm length by 0.2 mm diameter. Type II steel fibre is hooked-end and have dimensions of 25 mm long by 0.3 mm diameter. One percent of each fibre type is used; a total of 2%, by volume. Benchmark values for the specification of the UHPFRC are a 28 day characteristic cube compressive strength of 150 MPa and flexure strength of not less than 20 MPa; heat curing is applied for a period of 48 hours at a temperature of 90 °C. The mechanical properties of the DURA UHPFRC are presented in Table 2.

## 3.0 Rantau, Negeri Sembilan Bridge

The first example presented is the Rantau, Negeri Sembilan Bridge, which on 20 May 2013 became the world's longest single span UHPFRC-composite deck bridge, breaking the record of its predecessor, the 50 m Kampung-Linsum bridge (see Voo et al, 2011). The project cost was MYR6.5 million (AU$2.3 million), which includes the construction of the new four lane road and river protection works, in addition to that of the bridge structure. The four lane wide bridge consists of five DURA UBG1750 beams with a conventional concrete cast in-situ deck (Figure 4).

Being one of the busiest road accesses between the towns of Seremban and Port-Dickson, on the day of launching the existing road and bridge could not be closed to traffic for periods of more than 15 minutes at a time. The seven segments (2 × 5.6 m and 5 × 8.0 m) making up the 51.6 m

*Table 2: Material characteristics of DURA UHPFRC.*

| Characteristics | Standard | Value |
|---|---|---|
| Specific density, $\delta$ | BS1881-Part 114 – 1983 | 2350 – 2450 kg/m³ |
| Cube compressive strength, $f_{cc}$ | BS6319-Part 2 – 1983 | 150 MPa (characteristic)<br>165 MPa (mean) |
| Creep coefficient at 28 days, $f_{cc}$ | AS1012.16 – 1996 | 0.2 – 0.5 |
| Post-cured shrinkage | AS1012.16 – 1996 | < 100 µε |
| Modulus of elasticity, $E_o$ | BS1881-Part 121 – 1983 | 40 – 50 GPa |
| Poisson's ratio, $v$ | | 0.18 – 0.2 |
| Split cyl. cracking strength, $f_t$ | BS EN 12390-6 – 2000<br>ASTM C496 – 2004 | 5 – 10 MPa |
| Split cyl. ultimate strength, $f_{sp}$ | | 10 – 18 MPa |
| Modulus of rupture, $f_{cf,3P}$ | JCI-S-002 – 2003<br>(Three-point test on notched specimens) | 20 – 35 MPa |
| Bending fracture energy, $G_{f,\delta=0.46mm}$ | | 1 – 2.5 N/mm |
| Bending fracture energy, $G_{f,\delta=3.0mm}$ | | 10 – 20 N/mm |
| Bending fracture energy, $G_{f,\delta=10mm}$ | | 15 – 30 N/mm |
| Rapid chloride permeability | ASTM C1202 – 2005 | < 200 coulomb |
| Chloride diffusion coefficient, $D_c$ | ASTM C1556 – 2004 | 0.05 – 0.1 x $10^{-6}$ mm²/s |
| Carbonation depth | BS EN 14630 – 2006 | < 0.1 mm |
| Abrasion resistance | ASTM C944-99 – 2005 | < 0.03 mm |
| Water absorption | BS1881-Part 122 – 1983 | < 0.2 mm |
| Initial surface absorption | BS1881-Part 208 – 1996 | < 0.02 ml/(m²s) (10 min)<br>< 0.01 ml/(m²s) (120 min) |

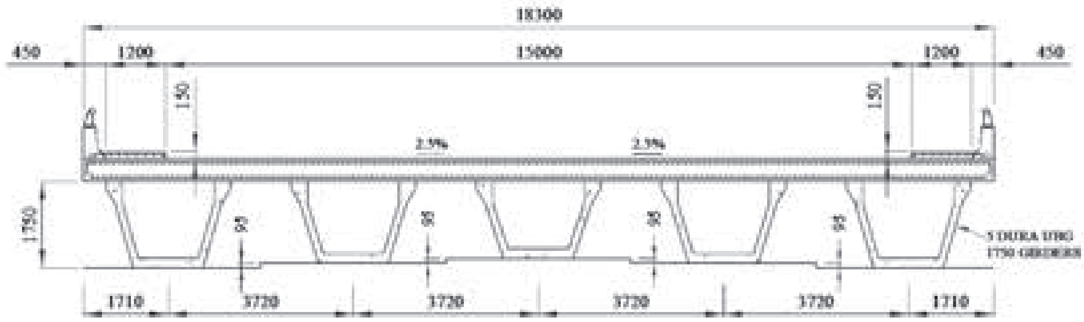



*Figure 4: Rantau-Siliau Bridge cross section.*

*Figure 5: Rantau-Siliau Bridge. U-shaped UHPFRC girder with composite conventional strength concrete deck at different stages of construction: (a) and (b) during launching; (c) and (d) after completion.*

long beams were delivered from the factory to a site adjacent to the construction, where they were assembled and stressed together. The girders were next transported the short distance to the new bridge site, utilising the existing bridge, and were lifted by two 500 t mega cranes in a single lift and placed on their abutments (Figures 5a and 5b). The whole launching process took just five hours to complete. There were no major disruptions to the heavy traffic and by 5 pm normal activity around the site was resumed and launching was complete. The composite deck slab was subsequently cast and the completed bridge is shown in Figures 5c and 5d.

The 18.3 m wide Rantau, Negeri Sembilan Bridge remains the largest single span composite-deck bridge in plan area constructed to date; the longest span is held by the 52 m span single lane Sungai Ara Bridge, completed in December 2013. The largest multi-span bridge is the five span, 200 m long by 17 m wide CFS Bridge, completed February 2015.

## 4.0 Batu 6 Bridge

The second example presented is the 100 m span, integral-abutment box girder Batu 6 Bridge, located at Batu 6, Gerik, Perak, Malaysia. The construction cost was RM6.3 million (AU$2.2 million), which includes the foundation/piling, substructure (included wing-wall and approach slabs), superstructure, temporary works, road furniture, earthwork, 600 m long by 6 m wide approach road works and slope protection. The bridge was due for completion in February 2015; however, on 22 December, just one day before the planned pouring of the first of the integral abutments, the pour that would join the bridge to its foundations, saw the worst floods in Malaysia in decades with more than 100,000 people displaced.

The bridge is constructed of 40 – 4.0 m high precast segments (Figures 6 and 7a), with each segment match-cast in the factory and delivered to site for placement and tensioning.

The thickness of the webs between segment ends is 150 mm; the webs are locally thickened at the matched joints to accommodate the shear keys. The 36 middle segments each weigh 16.5 t, the segments second from the end 18 t and the end segments 20 t. With 26 t of prestressing cable, 52 t for the wearing surface and 20 t for railings and ancillary fixtures, the total weight of the bridge is 770 t.

For construction of the bridge falsework and positioning of the segments, crane access was available from one bank only and required the largest crane available; a 550 t crawler crane with a boom length of 108 m. Even then, the last end segments at Abutment B could not be lifted into position and an innovative strategy was needed. To this end, a rail system was developed on the falsework to locate the precast segments to the accuracy needed for threading of the tendons. Figures 7b – 7d show the placement of the UHPFRC precast box segments. The 40 segments were placed over a period of 18 days (including two rest days). On day 11 of placement, five segments (12.5 m of bridge) were positioned and aligned in a single day.

The stage 1 prestressing work began on day 19 and the bridge was stressed on day 33 (29 November). On days 34 to 38 the strand ends were cut and grouting was completed (Figure 7e); the average prestress on the section (P/A) is 17.1 MPa compression, the stress at the top and bottom of the section at mid-span is 19.3 MPa (compression) and 15 MPa, respectively. The calculated theoretical hog was 34.8 mm; the measured hog was 50 mm. After 7 days, the hog had reduced due to creep by 7 mm to 43 mm, consistent with predictions. Stage 2 stressing will be undertaken after completion of the integral abutment works.

On 29 December 2014, from an unplanned release of water from Bersia Dam, the river Perak rose to a level of 3 m above the soffit of the 4 m tall girder (Figure 7f). This placed an extreme lateral pressure on the member, a load for which it had not been designed. The bridge, which had had its first stage stressing a month before, carried the load without damage but had moved on its abutment 1.2 m downstream, with the edge of the girder moving to within 50 mm of the edge of the abutment, and had tilted by five degrees (Figure 7g); it had come precariously close to toppling into the river. On 20 January 2015, the flood waters had subsided to below the soffit of the girder and planning for restoration works began.

On 12 February, the construction authority gave approval for the proposed remediation plan and work began shortly after. The girder was first lifted using hydraulic jacks and Teflon bearing plates were placed between the girder and the pile cap. The bridge was then repositioned by jacking laterally against a temporary structure that had been constructed around the pile caps for this purpose. The casting of integral Abutment A was undertaken over the days between 30 March and 3 April 2015 (Figure 7h); the casting of Abutment B was planned to begin 13-17 April. When completed mid-2015, the 100 m span Batu 6 Bridge will be the world's longest single span UHPCFRC integral-box road bridge. The story of the Batu 6 Bridge and its completion, together with that of other UHPFRC bridges will be presented at Concrete 2015.

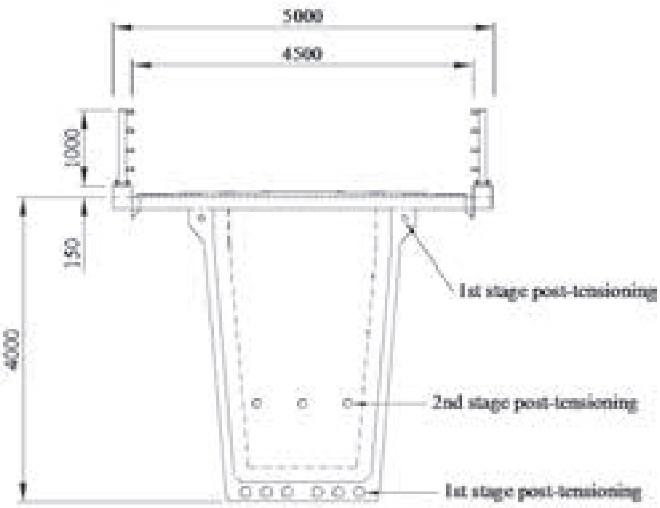



*Figure 6: Batu 6 Bridge cross section.*

## 5.0 Conclusion

With the opening of Shepherd's Gully Bridge near Newcastle, Australia was at the lead of industrialisation of the latest in research in cementitious materials technology and in the utilisation of ultra-high performance concrete for road bridges – 10 years ahead, not one more bridge has been constructed. The question that should be asked is, "where will we be in 2025?"

In contrast, based on research begun in Australia and with Australian research training, Malaysian engineers built their first UHPC bridge in 2010; in the short time since, 40 more bridges, road and pedestrian, have been built. Similarly in other parts of Asia (particularly Japan) and in Europe (particularly France) some remarkable structures are being developed utilising UHPC technology.

In 2005, the German government, through the German Research Foundation, invested €12 million (A$16.7) in a programme that involved 34 research projects at more than 20 research institutes (Schmidt, 2012). Similarly, in 2007 the Korean Institute of Construction Technology (KICT) invested WON$12 billion ($A14 million) into research into UHPC for cable-stayed bridges in their Super 200 program (Kim et al, 2012). The US Federal Highway Administration (FHWA) began investigating the use of UHPC in 2001, with the first structure, the 33 m Mars Hill road bridge in Iowa, constructed in 2006 (Graybeal, 2011). This compares to a general lack of investment in cementitious materials technology research throughout Australia by government, industry and, indeed, universities.

Will we be looking for inspiration from overseas for the years ahead; will Australia again be at the lead or remain a follower? It is time that a new paradigm is found that unlocks the talent invested in Australian research institutions and brings the benefit more directly to Australian industry and the Australian economy. The research discussed in this paper, together with other novel UHPC bridge structures will be presented at Concrete 2015.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

***Figure 7: Batu 6 Bridge: (a) factory cast segments; (b)-(d) placing of segments; (e) after stage 1 stressing; (f) during flood; (g) shifting of girder on abutments downstream; (h) after completion of Abutment A.***

## References

Behloul, M., & Lee, K.C. (2003). "Ductal® Seonyu Footbridge", Structural Concrete, 4(4), 195-201.

Foster, S.J. (2009). "The Application of Steel-Fibres as Concrete Reinforcement in Australia: from Material to Structure", *Materials and Structures,* 42(9), 1209 1220.

Graybeal, B. (2011). "UHPC in US Highway Infrastructure", Designing and Building with UHPFRC: *State of the Art and Development,* Chapter 15, Eds. Toulemonde, F., and Resplendino, J., John Wiley & Sons, Great Britian, 221-234.

Kim, B.-S., Kim, S., Kim, Y-J, Park S.Y., Koh, K-T & Joh, C. (2012). "R&D Activities and Application of Ultra High Performance Concrete to Cable-Stayed Bridges", *Proceedings of Hipermat 2012 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials,* Ed., Schmidt, M., Fehling, E., Glotzbach, C., Fröhlich, S., and Piotrowski, S., Kassel University Press, Kassel, Germany, 865–872.

Lachemi, M., Bastien, J., Adeline, R., Ballivy, G., & Atchin, P.C. (1998). "Monitoring of the World's First Reactive Powder Concrete Bridge", 5th International Conference on Short and Medium Span Bridges, Calgary, Alberta, Canada, July, 10 pp.

Malik, A.R. (2007). "An Investigation into the Behaviour of Reactive Powder Concrete Columns", PhD Thesis, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia.

Menefy, L. (2007). "Investigation of reactive powder concrete and its damping characteristics when utilised in beam elements", PhD Thesis, School of Engineering, Griffith University, Australia.

Musha, H., Ohkuma, H., & Kitamura, T. (2013). "Innovative UFC Structures in Japan", *Proceedings of the RILEM-fib-AFGC International Symposium on Ultra-High Perfomance Fibre-reinforced Concrete (UHPFRC),* October 1-3, Marseille, France, Eds. Toutleemonde, F., and Resplendino, J., RILEM publications S.A.R.L, France, 17-26.

Ng, T.S., Voo, Y.L., & Foster, S.J. (2012). "Sustainability with Ultra-High Performance and Geopolymer Concrete Construction", *Innovative Materials and Techniques in Concrete Construction,* Chapter 5, M.N. Fardis (ed.), Springer, 379 pp.

Ngo, T.D. (2005). "Behaviour of high strength concrete subject to impulsive loading", PhD Thesis, Department of Civil and Environmental Engineering, University of Melbourne.

Rebentrost, M. & Wight, G. (2011). "Perspective on UHPCs from a Specialist Construction Company", Designing and Building with UHPFRC: *State of the Art and Development,* Chapter 13, Eds. Toulemonde, F., and Resplendino, J., John Wiley & Sons, Great Britian, 149-187.

Richard, P., and Cheyrezy, M.H., (1994). "Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength", ACI, SP-144(24), San Francisco, CA, pp: 507-518.

Richard, P., & Cheyrezy, M., 1995. "Composition of Reactive Powder Concretes", *Cement and Concrete Research,* Vol. 25, No. 7, pp: 1501-1511.

Schmidt, M. (2012). "Sustainable Building With Ultra-High-Performance Concrete (UHPC) – Coordinated Research Program in Germany", *Proceedings of Hipermat 2012 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials,* Ed., Schmidt, M., Fehling, E., Glotzbach, C., Fröhlich, S., and Piotrowski, S., Kassel University Press, Kassel, Germany, 17–25.

Tanaka, Y., Maekawa, K., Kameyama, Y., Ohtake, A., Musha, H., & Watanabe, N., (2011). "The Innovation and Application of UHPC Bridges in Japan", Designing and Building with UHPFRC: *State of the Art and Development,* Chapter 12, Eds. Toutleemonde, F., and Resplendino, J., John Wiley & Sons, Great Britian, 149-187.

Toutlemonde, F., & Resplendino, J. (2011). Designing and Building with UHPFRC: *State of the Art and Development,* ISTE, London.

Voo, Y.L. (2004). "An Investigation into the Behaviour of Prestressed Reactive Powder Concrete Girders Subjects to Non-Flexural Actions", PhD Thesis, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia, 313 pp.

Voo, Y.L., Augustin, P.C., & Thamboe, T.A.J. (2011). "Construction and Design of a 50m Single Span UHP Ductile Concrete Composite Road Bridge", *The Structural Engineer,* The Institution of Structural Engineers, UK, 89(15), 24 – 31.

Voo Y.L., & Foster, S.J. (2010). "Characteristics of Ultra-High Performance 'Ductile' Concrete (UHPdC) and its Impact on Sustainable Construction", *The IES Journal Part A: Civil & Structural Engineering,* 3(3), 168-187.

Voo Y.L., Foster, S.J. & Voo, C.C. (2014). "Ultrahigh-Performance Concrete Segmental Bridge Technology: Toward Sustainable Bridge Construction", ASCE, *Journal of Bridge Engineering* [doi: 10.1061/(ASCE)BE.1943-5592.0000704 , B5014001].

Warnock, R. (2005). "Short-term and time-dependent flexural behaviour of steel fibre-reinforced reactive powder concrete", PhD Thesis, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia.

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> "Existing AAR cases are a legacy of inappropriate test methods used in the past.

# Mitigating alkali aggregate reaction

***by Ahmad Shayan***

This special issue of *Concrete Institute of Australia* journal is dedicated to mitigation of Alkali Aggregate Reaction (AAR) in concrete structures. Mitigation, depending on the concept used, can be achieved through two broad pathways; being suppression of the reaction itself, so that AAR does not develop in the concrete, and mitigation of the effects of AAR, i.e., after AAR has developed in given elements. The papers presented in this issue are concerned with the former concept, as it is economically more attractive to avoid AAR than to deal with the management of its effects.

In 1994, the present writer stated in a guest editorial for the *International Journal of Cement and Concrete Composites* (Volume 16, pp. 161-162),
that we were still unsure as to how to tell whether or not an aggregate is reactive.

At the time the existing Australian Standards for alkali aggregate reactivity had just been withdrawn due to their poor performance in detecting the slowly reactive Australian aggregates.

Developments in testing since 1994 have enabled a greater degree of certainty in the identification of reactive aggregates, being through one method or combinations of methods. This is an important achievement, as correct identification of reactive aggregates is a fundamental step in avoiding the harmful effects of AAR in concrete structures.

In fact, existing AAR cases are a legacy of inappropriate test methods used in the past. The next important step concerns management of reactive aggregates should they need to be used in concrete, as has been the case in several situations, in order to suppress the reaction. This aspect has also satisfactorily been addressed in many countries, including Australia.

Given the worldwide achievements in these areas to date, I am grateful to the Concrete Institute of Australia for asking me to prepare this special issue on AAR mitigation. Due to the widespread nature of AAR problems, this issue of the CIA Journal includes papers from counties across the continents (Australia, Japan, Canada and USA, Portugal and, Norway) so that experiences gathered in various countries can be brought together in the same issue of the journal. The writer is grateful to the authors of the articles for their time and effort in preparing their paper for this special issue.

The reader's attention should be drawn to the fact that the nature of the diagnostic tests used is often similar in different countries: most employ similar concrete prism tests conducted at 38°C (CPT) and mortar bar tests conducted at 80 °C (AMBT), ie under similar accelerating conditions.

However, the acceptance criteria adopted are sometimes sufficiently different, to the extent that using test limits from another country may change the reactivity classification of the same aggregate, particularly in the case of slowly reactive ones. The range of rock types tested may have influenced the acceptance limits adopted in each country. In fact, this factor is why the chemical test for AAR detection is still used in Japan.

The paper by Shayan describes the evolution of AAR testing in Australia, where, eventually, new Australian Standard test methods have recently been published for alkali reactivity assessment of concrete aggregate; being AS 1141.60-1for AMBT and AS1141.60-2 for CPT.

The acceptance limits for these tests are < 0.10% expansion at 21 days of testing for AMBT, and < 0.03% expansion at the age of one year for CPT. These tests would detect the great majority of Australian reactive aggregates. It is evident that the acceptance limits of the corresponding ASTM test methods (ASTM C1260 and ASTM C1293) would be too liberal for the Australian aggregates, and would class some of our slowly reactive aggregates as innocuous, which would be an undesirable outcome.

A small number of very slowly reactive Australian aggregates are not detected by these tests and experience shows that the CPT (60°C) would be more efficient for this purpose. Based on testing of 50 Australian aggregates, the acceptance limit of this test has been suggested at < 0.03% at the age of 20 weeks.

This test is similar to the RILEM AAR-4 test method, although the acceptance limit of <0.05% expansion at 20 weeks would be too liberal and inappropriate for the slowly reactive Australian aggregates.

The paper by Fernandes, el al. shows that the AMBT method is not favoured in Portugal; instead, RILEM AAR-4 test method is preferred, but it seems that the test limit has not been decided as yet for the Portuguese aggregates. As Portuguese aggregates seem to be similar to the slowly reactive Australian granitic aggregates, the Australian expansion limit of <0.03% at 20 weeks may apply there too.

The paper by Thomas and Fournier states that in North America there is not a reliable correlation between the results of AMBT and CPT tests, which are the same or similar to the ASTM test methods mentioned above. It would be interesting to check whether this unreliable correlation is partly related to the more liberal limits of these tests compared to the corresponding Australian limits. This paper shows that the testing and mitigation approaches are well established in North America.

The paper by Wigum, et al describes the test methods used in Norway for AAR assessment of aggregates, where modified specimen sizes (40x40x160 mm for mortar bars and 100x100x450mm for concrete prisms) are employed compared to those used in Australia and North America. The larger cross sectional area of the concrete prisms is intended to limit alkali leaching from the interior of the specimen. A petrographic method is also used in the assessment process.

The acceptance criteria for these tests, which have been established for the Norwegian aggregates and specimen sizes, are also different. The effect of concrete specimen size on expansion has been observed elsewhere as well.

Although the larger prisms are more awkward to handle, there may be merit in using the larger size in order to overcome the uncertainty of the results, particularly for slowly reactive aggregates.

The paper by Hashimoto and Torii shows that a variation of the chemical test is performing well in Japan, and is often used for aggregate assessment for reactivity. The authors also employed three test methods, including the AMBT method to confirm the AAR-mitigating effect of 15% classified fly ash or 42% blast furnace slag when used in combination with a river gravel which contained Opal and Cristobalite.

It appears that the Japanese criteria for reactivity classification is more liberal than those in Australia, as their criteria classed the mixture with 15% classified fly ash, which has shown an expansion of about 0.18% in 21 days as non-expansive , whereas this would be classed as slowly expansive by the Australian criteria.

The differences observed in the approaches employed by these countries are probably governed by the material factors available in each locality. Such differences may be inevitable, as the chosen approaches in each country would have been adopted based on a study of several available methods. After all, it may not be possible to have universal methodologies which are applicable worldwide.

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# The current status of AAR in Australia and mitigation measures

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*This paper describes the different stages in the development of research, testing and diagnosis of AAR in concrete structures in Australia. Most AAR cases here are a legacy of using inappropriate overseas test methods and criteria, developed for local aggregates there, and the consequent incorrect classification of reactive aggregates as innocuous. Appropriate Australian Standards for detecting reactive aggregates (AS1141-60.1, AMBT; AS1141-60.2 CPT; and AS1141.65, Petrography) were published in 2014 and early 2015. These, together with existing methods used by road authorities, will help in preventing future cases of AAR-induced damage to concrete structures. AAR mitigation by using suitable supplementary cementitious materials in concrete has been demonstrated in both laboratory testing and in actual structures. The updated Australian AAR guidelines (Handbook HB79) are due for publication in mid-2015. Australia is now well equipped to combat AAR in concrete, although incremental improvements will no doubt be achieved through further research.*

## 1.0 INTRODUCTION AND BACKGROUND

Study of alkali aggregate reaction (AAR) in Australia started soon after the cause of damage to some concrete structures in California was attributed to this mechanism (Stanton, 1940). The initial AAR research, which was very extensive and lasted nearly two decades, was conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and explored several aspects of the AAR mechanism and factors that affected it. Most of the work was conducted by Harold Vivian, who authored 20 out of some 30 publications, and was honoured for his work at the 10th International Conference on AAR, held in Melbourne in August 1996.

Idorn (1996) elaborated on the details of the significant contributions made by Vivian.

In the first three decades since 1940, the AAR work here concerned only laboratory investigations of aggregate reactivity. During this period, and up to 1994, the then current Australian Standards for testing aggregates for AAR were the mortar bar test AS1141-38 and the quick chemical test (AS1141-39), which were copies of ASTM C 227 and ASTM C289, respectively. Incremental developments in AAR testing in Australia were documented by Shayan (1995a) and Shayan (2003) up to these dates.

Field cases of AAR damage to concrete structures in Australia were identified only since early 1980s. Cole et al (1981) reported products formed in an old concrete, which was a case of AAR in a dam structure, but it was not confidently called as such. The first case of AAR in a bridge structure was identified in 1983, but reported later at the 7th Int. Conf. on AAR held in Ottawa, Canada in 1986 (Shayan & Lancucki, 1987). Subsequently, the present writer identified a number of dams and bridges, a very large water storage tank, as well as the majority of one million concrete railway sleepers to be affected by AAR, for example, Shayan (1988; 1999); Shayan & Quick, 1992; Shayan et al, 2000, and Shayan & Grimstad (2006), among many more unpublished cases. These structures are distributed in Victoria, NSW, ACT, Tasmania, Western Australia and Queensland. A large number of AAR-affected bridges were also reported from Queensland (Carse, 1988), as well as a cooling tower (Carse, 1992), the intake tower of a dam (Blaikie, 1996), and Lucinda Jetty sugar terminal in Queensland (Thaulow et al, 1988). A list of some of these structures is presented in the AAR Guidelines (HB79), to be published by mid-2015.

The distribution of known cases of AAR-induced damage to concrete structures is shown in Figure 1. Each location marked on the map of Australia could represent more than one structure. From this map, it is clear that since 1996, when the 10 ICAAR was held in Melbourne, many more cases have been discovered. A number of new cases are currently being

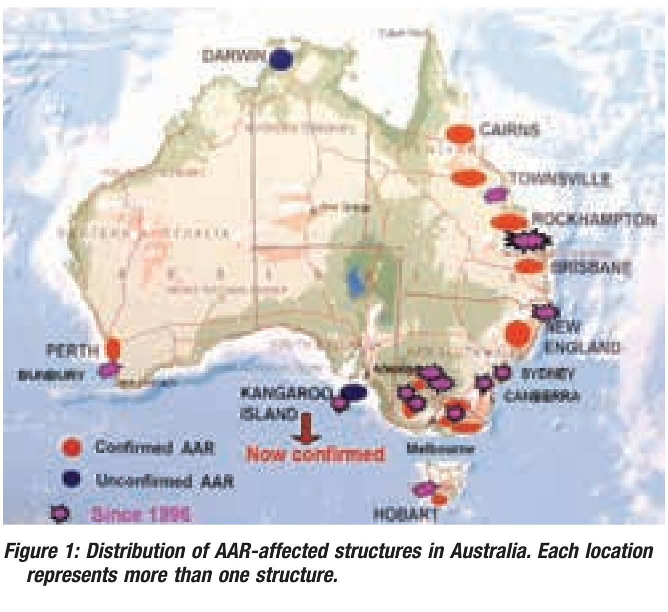


*Figure 1: Distribution of AAR-affected structures in Australia. Each location represents more than one structure.*

investigated in 2015, and no doubt more will surface in the future.

The visual effects of AAR cracking vary depending on the type of element affected and intensity of the reaction. Mass concrete or lightly reinforced elements develop random map-cracking, whereas pre-stressed elements develop cracking parallel to the direction of pre-stress. Figure 2 shows examples of AAR-induced cracking in various elements. The AAR cases in Australia are only of the alkali silica reaction category, i.e. alkali-carbonate reaction, involving de-dolomitisation of dolomitic aggregates, has not been observed in Australia to this date.

AAR can cause serious deterioration in the strength properties of concrete such as compressive and flexural strength and, particularly, elastic modulus of concrete. Moreover, depending on the extent of cracking, the protective function of the cover concrete for the steel reinforcement also deteriorates, which could lead to enhanced corrosion-induced problems, particularly in aggressive environments.

Therefore, development of appropriate test methods for detecting reactive aggregates is essential, so that AAR problems can be avoided or minimised for new structures, either by excluding such aggregates or using them with appropriate precautions.

***Figure 2: Examples of AAR-induced cracking in bridge pylons (top), crosshead end face (middle left), railway sleeper end view (middle right) and body of sleeper (bottom).***

*Table 1: Aggregate reactivity classification based on AMBT method T363.*

| Expansion (E) under storage conditions of 1M NaOH solution at 80 °C | | Classification |
|---|---|---|
| Measured at immersion age: | | |
| 10 days | 21 days | |
| E < 0.10%* | E < 0.10%* | Non-reactive |
| E ≥ 0.10%* | E>>0.10%* | Reactive |
| E < 0.10%* | E ≥ 0.10%* | Slowly reactive |
| * The expansion limit for natural fine aggregates is 0.15% at 21 days | | |

## 2.0 TESTS FOR DETECTING REACTIVE AGGREGATES

As mentioned above, the AAR test methods adopted in Australia since the 1960s were the Australian Standards AS1141-38 (mortar bar test) and AS1141-39 (quick chemical test). The applicability of these tests to the Australian aggregates had not been specifically addressed.

As a result of testing the aggregates that had caused damage to various structures, it was recognised in the mid-1980s (Shayan, 1987) that these tests, which were adopted from ASTM C 227 and ASTM C289, respectively, were inappropriate for the slowly reactive Australian aggregates. This observation led to the withdrawal of these test methods from Australian Standards in 1994. After this date there was no formal Australian Standard for AAR testing of aggregates.

In the meantime, further research on the AAR-affected structures and testing of the culprit aggregates, and other sources, had led to the development of the accelerated mortar bar test and acceptance criteria (Shayan et al, 1988: AMBT; immersion of mortar bars in 1M NaOH solution kept at 80 °C) and a concrete prism test and acceptance criteria (Shayan et al, 1987: CPT; Concrete made at cement content of 410 kg/m$^3$ and cement alkali level of 1.38% $Na_2O$ equivalent, cured at 38 °C, 100% RH).

These new tests were originally adopted in 1992 by the then Roads & Traffic Authority (RTA) of New South Wales under the designations RTA T363 and RTA T364, respectively, and were included in their structural concrete specification B80. These designations have now changed to RMS T363 and RMS T364, due to the change of name of the organisation to Roads & Maritime Services.

Some other Road Authorities later adopted the same tests under their own designations, such as VicRoads test method RC376.03 and RC376.04 in Victoria. Main Roads Western Australia later adopted the AMBT test method as WA 624.11, although Queensland DTMR has adopted a concrete prism test, using 50 °C steam curing temperature (Carse & Dux, 1990).

The applicability of the new tests was demonstrated in at least two studies in which various Australian aggregates with known and unknown field performances were utilised (Shayan, 1992a; Shayan et al, 2003). These studies showed a generally good correlation between the results of AMBT and CPT for the aggregates tested (Figure 3). The reasons for disagreement can often be explained, e.g. where the CPT expansion is high but the AMBT result is low, this could arise from the highly reactive nature of the aggregate, which may exhibit the "pessimum effect" (Shayan, 1992b). In the case of glassy basalts, mortar bars contain fragments of glassy phases and undergo large expansion, whereas concrete prisms would have far less free glass particles and show little expansion. In addition, Shayan & Quick (1989) demonstrated that the nature of the reaction products in these tests were the same, indicating that similar mechanisms are operative in both tests in the expansion processes.

It should be noted that the AMBT test procedures and acceptance criteria used by Road Agencies in Australia are different from those of ASTM C1260. The expansion criteria for ASTM C1260 are given below, and those for RTA T363 are presented in Table 1.

ASTM C1260: < 0.1% @ 14 days: non-reactive; 0.1-0.2% @ 14 days: uncertain or slowly reactive; > 0.2% = reactive

These differences, particularly the acceptance limits can lead to different classifications for the same slowly reactive aggregate,

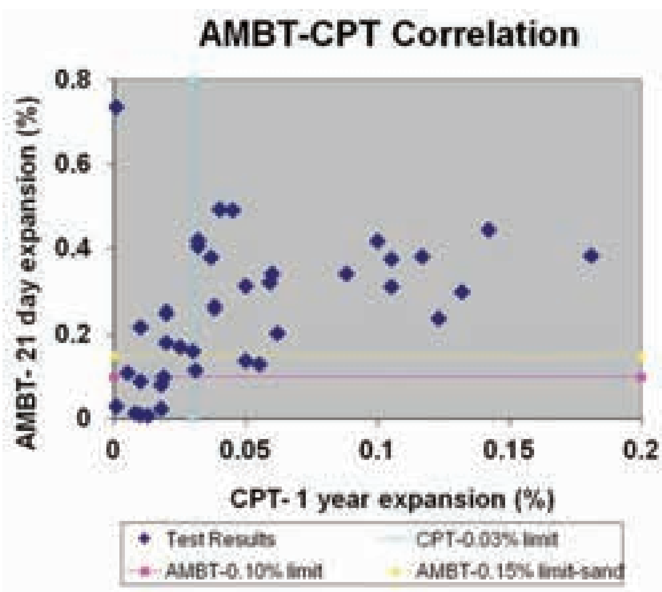


*Figure 3: Comparison of AMBT and CPT results for a large collection of aggregates.*

tested by the two methods. Shayan & Morris (2001) and Shayan (2007) demonstrated that the limits of ASTM C1260 are inappropriate for the slowly reactive Australian aggregates, and would classify some of them as non-reactive.

Similarly, for CPTs, the concrete alkali contents for ASTM C1293 and RTA T364 are 5.25 kg/m$^3$ and 5.66kg/m$^3$, respectively, whereas the expansion limit of ASTM C1293 is 0.04% at one or two years, but 0.03% at one year for RTA T364. The ASTM limit would accept some of the slowly reactive Australian aggregates as innocuous, which is very risky.

For these reasons, the recently published Australian Standards for AMBT (AS1141.60-1) and CPT (AS1141.60-2) have modified procedures compared to their corresponding ASTM methods, but they incorporate the limits of RTA T363 and RTA T364, which were derived based on the performance of the local aggregates. The new standards are now referenced in the Standard Specification for concrete aggregate (AS2758.1), and consequently in AS3600 (concrete structures) and HB79 AAR Guidelines.

In addition to these standard tests, petrographic examination of aggregates (AS1141.65) is also used for assessing the potential of aggregates for AAR. However, it is not always definitive for fine-grained aggregates as it cannot detect very fine-grained reactive components, such as fine silica minerals in aggregates derived from the very old Western Australian metamorphic rocks. Therefore, AS1141.65 is not a pass/fail test, but a useful tool in determining the nature of aggregate mineral phases. However, should sufficient amounts of reactive components be detected in the aggregate, the test can be used to class the aggregate as potentially reactive. Nevertheless, quantitative measurement of expansion caused by the aggregate would be needed for its classification.

### 2.1 Improving the detection of slowly reactive aggregates

The development of the new AAR test methods and their incorporation in the Australian Standards provide the optimism that cases of AAR in new concrete structures would be rare. However, the CPT method, which takes one year to complete, can be made faster and more reliable by increasing the curing temperature from 38 °C to 60 °C (Shayan et al, 2008). The CPT60 test can shorten the one year time that is needed for the CPT38 to 3-4 months. Gogte (1973) appears to be the first researcher who used concrete prisms cured at 60 °C to assess the AAR-susceptibility of aggregates containing microcrystalline quartz, and found the test to be superior to tests which used a lower curing temperature.

For this reason, Shayan (2011) proposed that Road Authorities adopt the CPT conducted at 60 °C (CPT60) rather than the conventional RTA 364, with curing temperature of 38 °C (CPT38). RILEM has also published a concrete prism test method under the designation AAR-4, which employs 60 °C curing temperature. Although work conducted in Canada does not appear to positively support the application of CPT60 (e.g. Fournier et al, 2004; Ideker et al, 2006, among others), the outcomes of the RILEM trials (e.g. Sims & Nixon, 2006, Nixon et al, 2008; Lingard et al, 2010) have been positive and in agreement with the Australian experience.

It should be noted that equilibrating the temperature of the specimens from 60 °C to the measurement temperature of 23 °C need very careful treatment to prevent loss of moisture from the specimens, which would lead to reduced expansion. It is likely that this issue may have resulted in the Canadian tests giving less favourable assessment of the method compared to the RILEM and Australian experiences. Unlike the Canadian results, Gogte (1973); Mullick et al (1986) and Rao & Sinha (1989) all show that increasing the curing temperature from 38 °C to 60 °C increased the expansion of concrete prisms, which is in agreement with the experience in Australia (Shayan et al, 2008).

An example of better performance of CPT60 is given in Figure 4 for slowly reactive quartz gravels, containing strained and microcrystalline quartz, which have caused significant AAR damage to major concrete structures in Australia. Figure 4 shows that CPT60 clearly identified them as reactive, whereas the normal CPT38 failed to detect their reactivity potential, the AMBT results were reasonable. Other examples of failure of CPT38 to detect similar slowly reactive aggregates are given by Shayan (2007). The advantages of CPT60 in its rapid detection and magnitude of expansion are evident.

It is recommended that further studies are undertaken to improve the procedures of CPT60 with the aim of standardising this test, as it would provide significant advantages over the currently used CPT38.

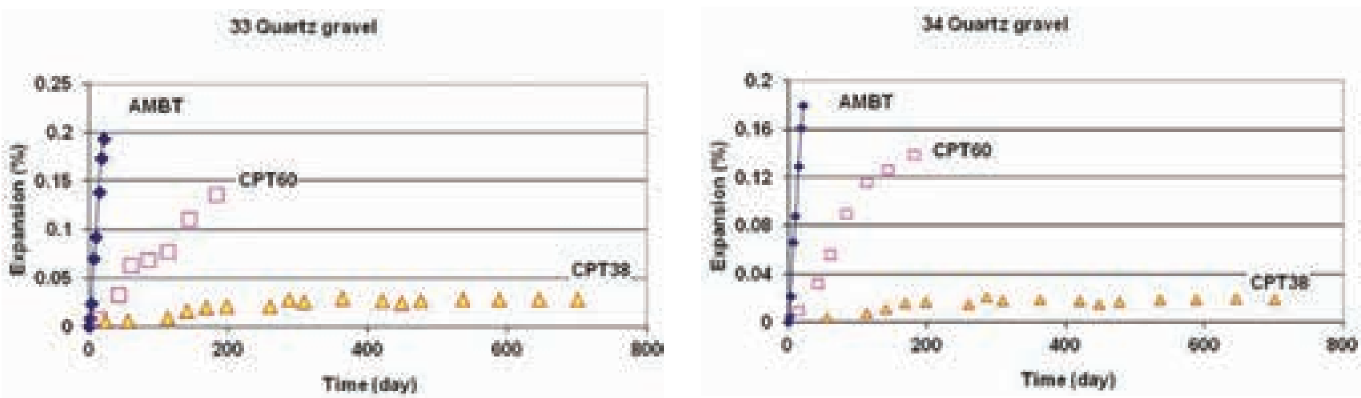


*Figure 4: Expansion trends in the tests indicated for slowly reactive quartz gravels containing strained and microcrystalline quartz.*

## 3.0 MITIGATION OF AAR

The mechanism of AAR requires three essential ingredients i.e. sufficient amounts of reactive components, active alkali and moisture to be present in the concrete at the same time for the reaction to proceed. It would follow that lack of any of the ingredients would suppress the AAR potential in the concrete, and these may be taken as the controlling factors in the mitigation of AAR.

Probably the safest mitigation approach would involve selecting an aggregate which is free of deleterious components. Although this could be achieved using the test methods discussed above, non-reactive aggregates may not be available in all localities. Exclusion of moisture from concrete may prove difficult under field exposure conditions, and limitation of alkali content, to suppress the reaction, may not be feasible if the aggregate phases can release alkali into the pore solution of concrete.

Apart from the use of non-reactive aggregate, the second most reliable method of AAR mitigation is the use of sufficient quantities of appropriate supplementary cementitious materials (SCM) in the concrete formulation. Extensive literature exists on the utilisation of traditional SCMs, such as fly ash, silica fume and blast furnace slag, for the suppression of AAR in concrete, and will not be repeated here. Natural pozzolans and meta-kaolinite have also been used elsewhere for this purpose. Utilisation of chemical compounds such as lithium salts (Stokes, 1996) or lithium-bearing glass (Stokes et al, 2000) are not currently favoured in Australia for suppressing AAR expansion, although original work on lithium salts dates back to the 1950s (McCoy & Caldwell, 1951) and was conducted in Australia. This is because more certain and cheaper alternatives are available.

In Australia, local supplementary cementitious materials, silica fume, low-calcium fly ashes and blast furnace slag have all been effective in suppressing deleterious expansion of reactive aggregate in concrete (Shayan, 1990; 1992; 1995b; Shayan, et al, 1996). The Australian SCMs are required to comply with relevant specifications such as AS 3582.1 (Fly ash), AS 3582.2 (slag) and AS 3582.3 (Silica fume). Shayan & Carse (1992) prepared general guidelines for minimising the risk of deleterious AAR-induced expansion in concrete structures. These guidelines broadly stated the amounts of SCMs (silica fume, low-calcium fly ash and ground blast-furnace slag) required to suppress the AAR potential of reactive agregates to be around 10-15%, 20-30% and >40%, probably 60-65%, respectively.

However, it is well known that factors such as the reactivity of aggregate, the alkali content of concrete, the amount of SCM used, and amorphous silica content of the SCM all influence the effectiveness of the material in suppressing the AAR mechanism (Shayan, 1992; Shayan et al, 1996). The assessment of the efficacy of SCMs can be made by using the same AMBT and CPT methods as used for identifying reactive aggregates, although the test limits may no longer apply.

Examples of laboratory evaluation of some Australian SCMs are presented in Figure 5-Figure 8. The effectiveness of silica fume (Figure 5) was evaluated in concrete prisms, steam cured at 75 °C for 8 hours and stored at 40 °C, 100%RH. This was to represent the bahaviour of actual concrete sleepers that were to incorporate silica fume (10% of binder) as a counter measure against AAR. The alkali contents of different mixes were 2.2 $kg/m^3$ (curves 1 & 2), 4.5 $kg/m^3$ (curves 3 & 4) and 7.2 $kg/m^3$ (curves 4 & 6). Expansion curves 1, 3, and 5 represent concrete mixtures containing plain cement and curves 2, 4, and 6 those with 10% silica fume as cement replacement. The suppressing effect of silica fume, even at the highest alkali level is evident.

Figure 6 shows the effectiveness of 25% fly ash replacement of Portland cement in suppressing the different reactivity levels of two aggregates (a and b). It is shown that the level of alkali in the concrete influences the performance of a given fly ash in suppressing the potential of a given aggregate for deleterious expansion and cracking. Long-term results presented by Shayan, et al showed that the two Australian fly ashes they studied were effective in preventing deleterious AAR damage in concretes with alkali contents as high as 7.0 kg $Na_2O/m^3$, but they produced only a delaying effect in concretes containing 12.5 kg $Na_2O/m^3$. The delay was between two and six years, depending on the type of aggregate. A measureable chemical shrinkage occurred in the first few months in the presence of fly ash in the latter concretes, although some of them later expanded and cracked due to AAR.

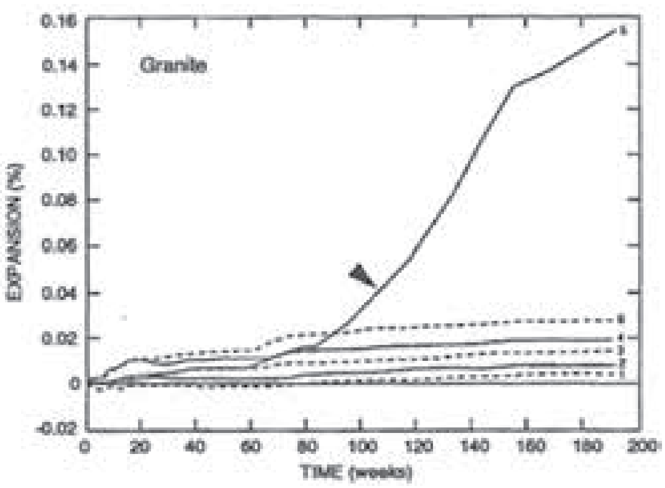


*Figure 5: Concrete prism expansion curves for concrete mixtures made with and without silica fume.*

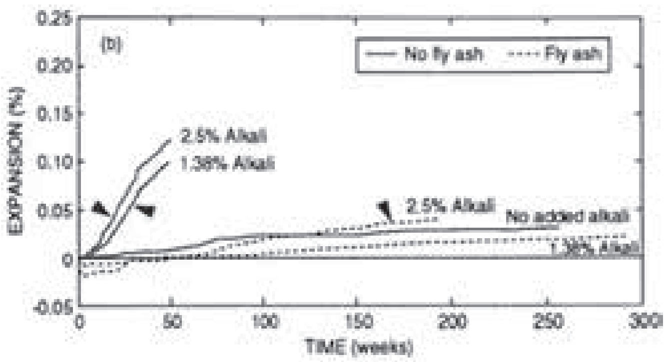


*Figure 6: Expansion curves for concrete prisms made without and with 25% fly ash replacement of cement, at different alkali contents.*

Not only the CPT method, but the faster AMBT method can also be used for the evaluation of the suppressive effects of SCMs on AAR. Figure 7 taken from Shayan (1992) shows the results of AMBTs conducted on mortar bars which incorporated either plain Portand cement or cement with 25% fly ash replacement or a 50/50 blend of cement and ground blast-furnace slag. The results clearly show that the different SCMs have been effective in arresting the AAR-induced expansion. The use of AMBT in evaluationg SCMs for AAR suppression has been reported by other researchers (e.g. Davies & Oberholster, 1987; Berra, 1994; Barringer, 1999; Thomas & Innis, 1999; Thomas et al, 2007). In fact, a modified version of ASTM C1260, i.e., ASTM C1567-08 Standard test method for determining the potential alkali-silica reactivity of combinations of cementitious materials and aggregate (Accelerated mortar bar method) has been in use for this purpose.

In addition to the laboratory results discussed above, the positive effects of fly ash in preventing AAR have also been documented for major dam structures in Australia (Shayan et al, 1997; Shayan & Thomas, 2014).

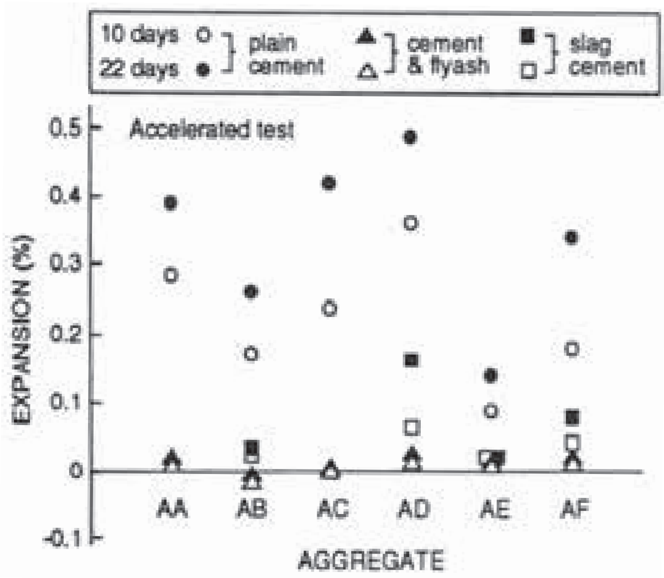


*Figure 7: Use of AMBT in assessing the effectiveness of fly ash and slag in suppressing AAR.*

## 3.1 An alternative to SCMs

In the past 10-15 years, waste glass powder, made from waste bottle glass, has been utilised as an alternative to traditional SCMs to suppress AAR, despite the reactive nature of coarse and sand-sized glass particles and the high alkali content of glass (13.5% $Na_2O$). Through laboratory research (Shayan & Xu, 2004) and field trials (Shayan & Xu, 2006) showed that glass powder (GLP) was effective in suppressing the potential AAR expansion of both natural reactive aggregates and coarser glass aggregate, which is inherently reactive. Therefore, a mixture of glass powder and glass aggregate would perform satisfactorily, without deleterious expansion. Both the above investigations produced very positive and promising results, as shown in Figure 8 and Figure 9. These results show that glass powder was effective in suppressing AAR expansion in long-term laboratory expansion tests. The high alkali content of the glass powder did not appear to cause expansion of a reactive aggregate which was combined with low alkali cement and glass powder, i.e. the large alkali content of the glass powder did not contribute sufficiently to the soluble alkali content of concrete to cause deleterious AAR expansion. It was also found that for a 40 MPa mortar mixture, the strength gain of mortar containing silica fume and glass powder were comparable on the basis of equivalent cement content.

## CONCLUSIONS

This paper has summarised the history of AAR studies in Australia, and the background to development of test methods for aggregate reactivity assessment, leading to the publication of Australian Standards AS1141.60-1 and AS1141.60-2. Examples of AAR-induced damage to various concrete structures have been provided. It has been shown that Australian supplementary cementitious materials are effective in suppressing AAR expansion in laboratory testing and in field structures. Glass powder is also shown to be effective

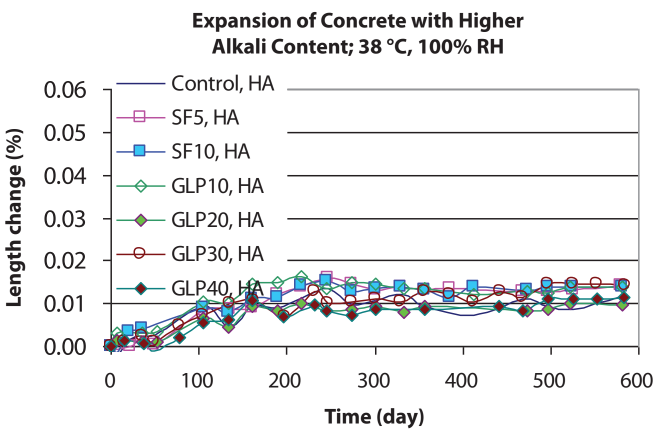


*Figure 8: Concrete expansion curves for the combination of non-reactive aggregate and various amounts of GLP and silica fume in the presence of 5.8 kg $Na_2O$ equivalent/m$^3$ (HA).*

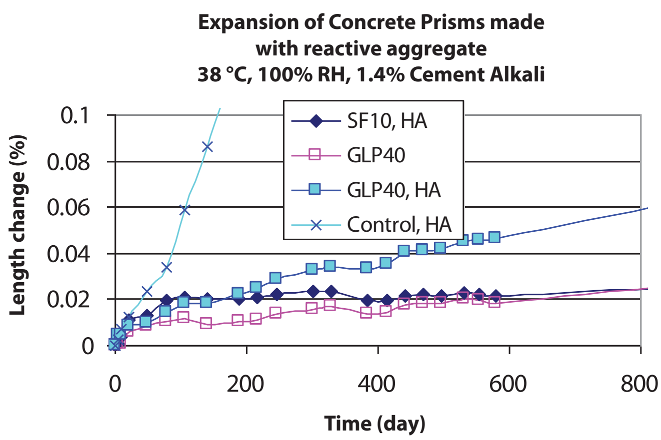


*Figure 9: Expansion curves for concrete prisms containing a very reactive coarse aggregate in combination with the materials indicated. (HA denotes 1.4% cement alkali (HA). GLP 40 denotes mixture with low alkali cement.*

for these purposes, such that a mixture of glass powder and coarser glass particles could be used together without the risk of AAR damage

## REFERENCES

AAR Guidelines HB79, 2014, 'Alkali aggregate reaction: guidelines on minimising the risk of damage to concrete structures in Australia', Cement & Concrete Association & Standards Australia, (in publication).

Barringer, WL 1999, 'Using accelerated test methods to specify admixtures to mitigate alkali-silica reactivity', *Cement, Concrete & Aggregates,* Vol. 21, no. 2, pp. 165-172.

Berra, M 1994, 'Application of the NaOH bath test method for assessing the effectiveness of mineral admixtures against reaction of alkali with artificial siliceous aggregate, *Cement & Concrete Composites,* Vol. 16, pp. 207-18.

Blaikie, NK, Bowling, AJ and Carse, A, 1996. The assessment and management of alkali silica reaction in the Gordon River power development intake tower. *Proc. 10th IAARC* (A.Shayan, editor), Melbourne, Australia, pp. 500-507.

Carse, A 1988. Field survey of concrete structures suffering alkali-silica reaction distress. *Proc. 2nd Australia/Japan Workshop on durability of reinforced concrete structures,* 28-30 Nov. 1988, CSIRO, Highett, Victoria, pp. 2.67-2.82.

Carse, AH & Dux, PF 1990, 'Development of an accelerated test on concrete prisms to determine their potential for alkali-silica reaction', *Cement and Concrete Research,* Vol. 20, pp. 869-74.

Cole, WF, Lancucki, CJ and Sandy, MJ (1981). Products formed in an old concrete, *Cement and Concrete Research,* Vol. 11 (3), pp. 443-454.

Davies, G & Oberholster, RE 1987, 'Use of the NBRI accelerated test to evaluate the effectiveness of mineral admixtures in preventing the alkali-silica reaction', *Cement & Concrete Research,* Vol. 17, no. 1, pp. 97-107.

Fournier, B, Chevrier, R, De Grosbois, M, Lisella, R & Foliard, K 2004, 'The accelerated concrete prism test (60 °C): variability of the test method and proposed expansion limits', *Proceedings of the 12th IAARC,* Beijing, China, pp. 314-23.

Gogte, BS 1973, 'An evaluation of some common Indian rocks with special reference to alkali aggregate reaction', *Engineering Geology,* Vol. 7, pp. 135-53.

Ideker, JH, Folliard, KJ, Fournier, B and Thomas, MDA (2006): The role of "non-reactive" aggregates in the accelerated (60 °C) concrete prism test. Marc-Andre Berube Symposium on alkali-aggregate reactivity in concrete, held in conjunction with the 8th CANMET International Conference on Recent advances in Concrete technology, Montreal, Canada, 31 May- 3 June 2006: 45-70.

Idorn, GM, 1996, Systematic ASR expertise- Australian Research 1940's to 1958, *Proc. 10th ICAAR* (A. Shayan, Editor), Melbourne, Australia, pp. 15-26.

Lingard, J, Nixon, PJ, Borchers, I, Schouenborg, B, Wigum, BJ, Haugen, M and Akesson, U, 2010, The EU "PARTER" Project – European standard tests to prevent alkali reactions in aggregates. Final results and recommendations, *Cement and Concrete Research* Vol. 40, pp. 611-635.

McCoy, W.J. and Caldwell, A.G. (1951). New approach to inhibiting alkali-aggregate expansion. *J. ACI,* Vol. 22 (9), pp. 693-706.

Mullick, AK, Wason, RC, Sinha, SK & Rao, LH 1987, 'Evaluation of quartz and granite aggregates containing strained quartz, in Grattan-Bellew, PE (ed), Concrete alkali-aggregate reactions', Noyes Publications, New Jersey, USA, pp. 428-433.

Nixon, PJ, Lingard, J, Borchers, I, Wigum, BJ & Schouenborg, B 2008, 'The EU "PARTER" Project – European standard tests to prevent alkali reactions in aggregates Final results and recommendations, *Proc. 13th International Conference on AAR,* Trondheim, Norway, pp. 300-309

Roads and Maritime Services, 2012, Guide to QA specification B80: concrete works for bridges, 2nd edn, Roads and Maritime Services, Sydney, NSW.

Shayan, A & Carse, A 1992, *General guidelines for minimising the potential risk of deleterious expansion in concrete structures due to alkali-silica reaction*, technical report TR92/4, CSIRO, Melbourne, Vic.

Shayan, A & Morris, H 2001, 'A comparison of RTA T363 and ASTM C-1260 accelerated mortar bar test methods for detecting reactive aggregates', *Cement & Concrete Research*, Vol. 31, pp. 655-63.

Shayan, A & Quick, GW 1989, 'Microstructure and composition of AAR products in conventional standard and new accelerated testing', *Proceedings of the 8th international conference on AAR,* Kyoto, Japan, pp. 475-82.

Shayan, A 1990, 'Use of fly ash and blended slag cement in prevention of alkali-aggregate reaction in concrete', *Proceedings of the concrete for the nineties conference*, Leura, NSW, Concrete Institute of Australia, Sydney, NSW, 17 pp.

Shayan, A 1992a, 'Prediction of alkali-reactivity of some Australian aggregates and correlation with field performance', *ACI Materials Journal*, no. 1, pp. 13-23.

Shayan, A 1992b, 'The 'pessimum' effect in an accelerated mortar bar test using 1M NaOH at 80 °C', *Cement and Concrete Composites*, Vol. 14, pp. 249-55.

Shayan, A 1995a, 'Developments in testing for AAR in Australia', CANMET/ACI international workshop on alkali-aggregate reaction in concrete, 1995, Dartmouth, Nova Scotia, Canada, Canada Centre for Mineral and Energy Technology and American Concrete Institute, Farmington Hills, MI, pp. 139–52.

Shayan, A 2011, 'Aggregate selection for durability of concrete structures', *Construction Materials Journal,* Vol. 164, pp. 111-121.

Shayan, A and Grimstad, J, 2006. Deterioration of a hydroelectric concrete gravity dam and its characterisation. *Cement & Concrete Research,* Vol. 36, pp 371-383.

Shayan, A and Lancucki, CJ, 1987. Alkali-aggregate reaction in the Causeway bridge, Perth, Western Australia. In: Concrete Alkali Aggregate Reactions (P.E. Grattan-Bellew, editor), Noyes Publications, N.J., USA, pp. 392-397.

Shayan, A and Quick, GW, 1992. Microscopic features of cracked and uncracked prestressed concrete railway sleepers. *ACI Mat.* J., July-August issue, pp. 348-361.

Shayan, A and Thomas, M, 2014. Influence of fly ash in suppressing AAR expansion in a dam wall. *Proc., 36th Int. Cement Microscopy Assoc.,* Milan, Italy April 2014, 18 pp.

Shayan, A, 1987, 'Alkali-aggregate reaction in Australian concrete structures', *Proc. 13th Biennial Conference of the Concrete Institute of Australia,* 1987, Brisbane, Australia, Concrete Institute of Australia, Sydney, NSW, 5 pp.

Shayan, A, 1990. Use of fly ash and blended slag cement in prevention of alkali-aggregate reaction in concrete, *Proc. Concrete for the Nineties Conf.,* Leura, NSW, Australia, Concrete Institute of Australia, Sydney, 17 pp.

Shayan, A, 1995b. Behaviour of precast, prestressed concrete railway sleepers affected by AAR. Real World Concrete. *Proc. Swamy Symposium, 5th Int. CANMET/ACI Conf. on Flyash, Silica Fume, Slag and Natural pozzolans in concrete.* Milwaukee,Wisconsin, 4-9 June, 1995, pp. 35-56.

Shayan, A, 1999. Characterisation of AAR-affected concrete from a dam structure for rehabilitation purposes. *Proc. Int. Conf. On Infrastructure Regeneration and Rehabilitation,* June 1999, Sheffield Univ., U K, pp. 777-787.

Shayan, A, 2003, 'AAR in Australia and recent developments', International seminar on road construction materials, 2003, Kanazawa, Japan.

Shayan, A, 2007, 'Field evidence for inability of ASTM C 1260 limits to detect slowly reactive Australian aggregates', *Australian Journal of Civil Engineering*, Vol. 3, no. 1, pp. 13-26

Shayan, A, Diggins, R, and Ivanusec, I, 1996 Effectiveness of fly ash in preventing deleterious expansion due to alkali-aggregate reaction in normal and steam-cured concrete. *Cement & Concrete Research,* Vol. 26(1), pp. 153-164.

Shayan, A, Diggins, R, Ritchie, DF, and Westgate, P, 1987. Evaluation of Western Australian aggregates for alkali-reactivity in concrete. In: *Concrete Alkali Aggregate Reactions* (P.E. Grattan-Bellew, editor), Noyes Publications, N.J., USA, pp. 247-252.

Shayan, A, Diggins, RG, Ivanusec, I & Westgate, PL 1988, 'Accelerated testing of some Australian and overseas aggregate for alkali aggregate reactivity', *Cement & Concrete Research,* Vol. 18, no. 6, pp. 843–51.

Shayan, A, Landon-Jones, I and Nelson, P, 1997. Case study of fly ash concrete in Tallowa Dam containing alkali-reactive aggregate. *Proc. 4th CANMET/ACI Int. Conf. on Durability of Concrete,* Sydney, Australia, August 1997, Supplementary Papers, pp. 281-293.

Shayan, A, Wark, RE, and Moulds, A, 2000. Diagnosis of AAR in Canning Dam, characterisation of the affected concrete and rehabilitation of the structure. *Proc. 11th Int. AAR Conf.,* June 2000, Quebec City, Canada, pp. 1383 - 1392.

Shayan, A, Xu, A & Andrews-Phaedonos, F 2003, 'Development of a performance measure for durability of concrete bridges', *21st Biennial conference*, Concrete Institute of Australia, Brisbane, Qld.

Shayan, A, Xu, A & Morris, H 2008, 'Comparative study of the concrete prism test (CPT 60 °C, 100% RH) and other accelerated tests', *Proceedings of the 13th IAARC conference,* Trondheim, Norway, 16-20 June *2008*, pp. 412-421.

Shayan, A. (1988). Alkali aggregate reaction in a 60-year-old dam in Australia. *Int. J. Cement Composites and Lightweight Concrete,* Vol. 10, No. 4, pp. 259-266.

Sims, I & Nixon, PJ 2006, 'Assessment of aggregates for alkali-aggregate reactivity potential: RILEM international recommendations', Marc-Andre Berube symposium on alkali-aggregate reactivity in concrete, held in conjunction with the 8th CANMET international conference on recent advances in concrete technology, Montreal, Canada, pp. 71-91.

Stanton, T.E. 1940. Expansion of concrete through reaction between cement and aggregate, *Proceedings of the American Society of Civil Engineers,* Vol. 66 (10), pp. 1781-1811.

Stokes, D.B. (1996). Use of lithium to combat alkali silica reactivity. *Proc. 10th IAARC,* Melbourne, Australia, pp. 862-867.

Stokes, D.B., Thomas, M.D.A. and Shashiprakash, S.G. (2000). Development of lithium-based material for decreasing ASR-induced expansion in hardened concrete. *Proc. 11th IAARC,* Quebec City, Canada, pp. 1079-1087.

Thaulow. N, Holm, J and Anderson, KT, 1988, Petrographic examination and chemical analysis of the Lucinda Jetty prestressed concrete roadway, *Proc. 8th ICAAR* (K.Okada, et al, editors), Kyoto, Japan, pp, 573- 581.

Thomas, MDA & Innis, FA 1999, 'Use of accelerated mortar bar test for evaluating the efficacy of mineral admixtures for controlling expansion due to alkali-silica reaction', *Cement, Concrete & Aggregates,* Vol. 21, no. 2, pp. 157-64.

Thomas, MDA, Fournier, B, Folliard, K, Shehata, M, Ideker, J & Rogers, CA 2007, 'Performance limits for evaluating supplementary cementing materials using the accelerated mortar bar test', *ACI Materials Journal*, Vol. 104, no. 2, pp.115-22.

# The Norwegian regulations to mitigate alkali aggregate reactions in concrete

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*This paper outlines the historical developments in research on Alkali Aggregate Reactions (AAR) in Norway during the past 25 years. Norwegian regulations have proven to be valuable tools for mitigating AAR. A three step test procedure includes; the petrographical analysis, the accelerated mortar bar test and the overruling concrete prism test, the latter also used for the evaluation of binders and concrete compositions. Recent research focus has been on the utilisation of the concrete prism test as a performance test. Test results have shown that the AAR expansion is significantly influenced by the specimen "pre-treatment", the "test conditions" and the "prism crosssection", primarily due to the influence on the rate of alkali leaching during exposure. Further research on these topics, on alkali release from aggregates and on effect of artificial alkali addition (boosting) will be carried out, both by the newly established RILEM TC "AAA" and in a Norwegian R&D project.*

## 1.0 INTRODUCTION

A wide variety of aggregate types in common use across the world, particularly those with a siliceous composition, are vulnerable to attack by the alkaline pore fluid in concrete. This attack, which in wet conditions produces a hygroscopic and hydraulic gel, can cause cracking and disruption of the concrete. The deterioration mechanism is termed Alkali Aggregate Reactions (AAR).

## 2.0 RESEARCH BACKGROUND FOR THE CURRENT NORWEGIAN AAR GUIDELINES

The presence of AAR in Norwegian concrete structures was demonstrated in research activities from 1990 to 1996, in cooperation with the PhD-study of Jensen (1993). It was primarily focused on mapping the occurrence of AAR and the identification of reactive rock types by petrographic examinations of cores; fluorescence impregnated polished half cores and thin sections from structures. It was found that AAR in Norwegian structures was caused by e.g. metamorphosed rhyolites, sandstones, siltstones, argillites (some carbonaceous), greywackes, and phyllites. More uncertain cases of AAR were reported with other aggregates, e.g. hornfels. Cataclastic rocks e.g. cataclasite and mylonite were observed deleterious alkali reactive in about 50% of all the investigated structures.

Furthermore, some research activities emphasised on laboratory test methods for AAR. As a result of these activities, it was introduced in 1992 as an optional arrangement for acceptance and approval of aggregates for concrete by a three step test procedure including petrographic analysis, accelerated mortar bar method and concrete prism method, where critical limits were presented for each test method. The methods were described in Lindgård et al. (1993).

The PhD-study of Wigum (1995a) focused on further improving the method of petrographical assessment towards enhanced quantification of relevant parameters, largely the grain size of quartz, as well as on the effect of adjustments on accelerated mortar bar testing. The study demonstrated that the grain size reduction of quartz, promoted by the process of cataclasis, enhances alkali reactivity by increasing the surface area of quartz grain boundaries available for reaction (Wigum, 1995b). The accelerated mortar bar test was further examined by Wigum et al (1997) where discussions were made about the accuracy of the test, including effects of different mortar bar sizes. Recommendations were made that the volume of molar sodium hydroxide solution to the surface area of the mortar bar should be fixed at a ratio of 4:1 and separate container should be used for each set of bars. These recommendations have later been adapted to the Norwegian accelerated mortar bar test procedures.

In 1996, the Norwegian Concrete Association published a recommendation (NB21) for production of durable non-reactive concrete with use of alkali reactive aggregates. The recommendation provided criteria for the maximum allowable alkali content of bulk concrete, dependant of type of cement (OPC or the Norwegian fly-ash cement produced by Norcem) or use of silica fume. NB21 also described how to deal with

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***Table 1: Classification chart for alkali-reactivity of Norwegian rock types (Norwegian Concrete Association, 2004b ).***

| Class 1.<br>ALKALI REACTIVE<br>ROCK TYPES<br>*(Documented in structures)* | Class 2.<br>AMBIGUOUS<br>ROCK TYPES | Class 3.<br>INNOCUOUS<br>ROCK TYPES |
|---|---|---|
| **1. SEDIMENTARY ROCKS**<br>**Sandstone**<br>**Arkose**<br>**Quartz sandstone**<br>**Claystone** *(including shale)*<br>**Siltstone** *(including shale)*<br>**Marlstone**<br>*(including schistose and/or metamorphic)*<br>**Greywacke**<br>*(also metamorphic)*<br><br>***Sedimentary features should be observed.*** | **5. AMBIGUOUS**<br>*Examples*:<br>**Quartzite/quartz schist**<br>**Rock types with quartz**<br>*(Modal quartz >20vol%)*<br>**Limestone**<br>*(contaminated with dispersed fine grained quartz)*<br>**Hornfels** *(quart-bearing)*<br>**Mylonites** low in free quartz (1-5vol%) | **6. MAFIC ROCK TYPES**<br><br>**Basalt**<br>**Greenstone**<br>**Gabbro**<br>**Amphibolite**<br><br>***All types of variations of the rocks, also metamorphic*** |
| **2. MYLONITE/ CATACLASITE**<br>**(Containing free quartz)**<br>**Mylonites**<br>**Cataclasites**<br>**Mylonite gneiss** | *All quartz-containing rock types could be potentially reactive. This however depends on petrological parameters such as grain size of quartz, degree of deformation and other microstructural features.*<br><br>*Various types of quartzites have reacted in concrete.*<br><br>*Microcrystalline quartzite (quartz grains <60 µm) should be classified as alkali reactive.*<br><br>*Quartzite with quartz grains <130 µm, should be classified as ambiguous.*<br>*Quartzite with quartz grains > 130 µm, should be classified as innocuous, even if the quartzite contains "strained" quartz.* | **7. ROCK TYPES CONTAINING QUARTZ**<br><br>**Granite/Gneiss**<br>**Quartzite/quartz schist**<br>**Mica schist** |
| **3. ACIDIC VOLCANIC ROCKS**<br>**Rhyolite**<br>**Quartz keratophyre** | | **8. FELDSPATHIC ROCK TYPES** |
| **4. OTHER ROCK TYPES**<br>**Microcrystalline quartzite**<br>**Phyllite**<br>**Quartz schist** | | **9. OTHER/ UNIDENTIFIED**<br>**Limestone** *(pure)* and **marble**<br>Other non-reactive *(also single crystals)*<br>Porphyry<br>Quartz-free mylonites |
| **Typical grain size of quartz; < 60 µm**<br>**Exception: Sandstone** | **Typical grain size of quartz; < 130 µm** | **Typical grain size of quartz; > 130 µm, or quartz not present** |

blends of aggregate. In this recommendation, a classification chart for alkali-reactivity of Norwegian rock types was included. An updated version of this chart, with details of alkali reactive rock types, ambiguous and innocuous rock types, is presented in Table 1. In 1999 detailed petrographic atlas with micrographs of the various rock types was published (NORMIN-2000, 1999). An online version of the atlas is available at: www.farin.no. To pursue research into these matters, a nationwide forum known by the acronym FARIN (Forum on Alkali-Reactions In Norway) was established in 1999.

A three year project comprising quantitative measurements on drilled cores from about 50 concrete structures (mainly bridges) was completed in 2003 (Lindgård & Wigum, 2003; Lindgård et al, 2004a). The aims of the project, where about 160 concrete structures were surveyed in field, were to:

- Use experience from concrete structures in the field, together with quantitative measurements of concrete cores (environment, type of aggregates and mix design of concrete), to carry out an assessment of the current critical limits given by the Norwegian petrographical method and the accelerated mortar bar test.
- Find correlation between type of structures, local environment (humidity) and degree of damage in the field, with the ambition of obtaining more competent guidelines

for production of non-reactive concrete.
- Make suggestions for revision of the current guidelines for production of durable concrete (NB21) given by the Norwegian Concrete Association in 1996.

The project succeeded in developing a technical and economical feasible method for separating the sand and coarse aggregate fractions from the drilled cores, and thus made it possible to perform petrographical analyses in a similar way as for "virgin material" (Haugen et al, 2004). It was also possible to "link" most of the aggregates to geological areas and known deposits. Results were used to strengthen the petrographic method for "virgin materials".

It was concluded that the Norwegian petrographic method appeared to be appropriate as a screening engineering tool in order to classify alkali reactive aggregates (Wigum et al, 2004). The degree of variation in the method was set to ± 5vol%-point. However, recommendations were made for further development and strengthening of the method, including advanced image analysis systems.

The project also succeeded in characterising the degree of damage in the drilled cores by introducing a so-called "Crack Index" (CI), based on counting of three crack parameters in the plane polished sections (Lindgård et al, 2004b). This method is similar to the Damaging Rate Index (DRI)-method, but is more simplified and adjusted to the Norwegian experience with our late expansive aggregates. A good correlation was found between the "Crack Index" in the plane polished sections, the degree of water saturation and the presence of AAR.

These findings were also verified by statistical analyses. A reasonable correlation was found between the content of reactive rock types in an aggregate and the "Crack Index". It seemed likely that coarse aggregates lead to more damage (i.e. is more severe) than the sand fractions. Thus, more strict requirements were suggested to a coarse aggregate compared to sand aggregate. The overall experience gained in the research project was that the results obtained with the three Norwegian laboratory test methods correlate satisfactorily with field experience, under supposition that some of the critical limits were revised. Thus, based on the results from the research project, specific suggestions were given for revision of the Norwegian guidelines for production of durable concrete given by the Norwegian Concrete Association, NB21 (1996). These guidelines were updated in 2004 (see later).

## 3.0 CURRENT AAR GUIDELINES

Until 2001, the NB21 publication – published by the Norwegian Concrete Association – enjoyed the status of an industry standard but was by then formally referred to by the concrete construction standard.

Based on the referred national research and some international research work, a revision of the NB21 publication started late in 2002 and was finalised in 2004 (Norwegian Concrete Association, 2004a). In addition, the Norwegian test methods along with requirements to laboratories were published in a new publication, NB32 (Norwegian Concrete Association, 2004b). An English summary of the NB21 publication has been presented by Dahl et al. (2004).

Both these publications are now available in English translations. The updated NB21 publication has a formal status as a harmonised normative reference document to the new concrete materials standard, NS-EN 206:2013+NA:2014 (Norwegian Committee for Standardization, 2013), and is considered as a key element in the Norwegian system for preventing AAR.

### 3.1 Current test methods and critical limits

Evaluation of material parameters regarding effect of AAR in Norway is since 2004 based on three different test methods; 1: the Norwegian petrographic analysis, 2: the Norwegian accelerated mortar bar test and 3: the Norwegian concrete prism test (Norwegian Concrete Association, 2004a).

**1. The Norwegian petrographic analysis** – This method is a compulsory first step to evaluate the reactivity of aggregate types. The test is carried out by sieving a sand sample into two fractions (1/2 mm and 2/4 mm), respectively by crushing and sieving a coarse aggregate sample into one fraction (2/4 mm). The sieved samples are embedded in an epoxy resin, which allows the preparation of thin sections for petrographic examination. Two thin sections (25 x 35 mm) are made with particles in the fraction 2/4 mm and one in the fraction 1/2 mm. Approximately 1000 points are counted in each fraction. The volume percentage of alkali reactive rock types, ambiguous rock types and innocuous rock types (see Table 1) is obtained by calculating an average of the results from both fractions.

The critical reactive component in an aggregate is the summation of alkali reactive rock types and ambiguous rock types. According to the method description, the reactivity of the particles as a whole is evaluated. However, there are some exceptions from this procedure, e.g. if a mylonite zone occurs in a granite grain. Then the mylonite zone is counted as a mylonite, while the rest of the particle is counted as granite. The petrographic analysis should be performed by an experienced and approved petrographer (Norwegian Concrete Association, 2004b). This is important, because Norwegian rocks are very varied and hence often difficult to identify and classify correctly.

The Norwegian petrographic method is in agreement with the RILEM AAR-1 method (Jensen and Lorenzi, 1999; RILEM, 2003). The accuracy of the method has been examined by Wigum et al (2004). In order to make judgment regarding AAR of the aggregates tested by the petrographic analysis, some recalculations of the results are required according to NB21 (Norwegian Concrete Association, 2004a). A comparative value, *Sv*, is calculated. The calculation includes:

- Use of a "serial factor", i.e. a weighted average is obtained from all the six last individual petrographic analyses.
- In order to take into account the fact that coarse aggregates have proven to be more harmful than sand aggregates, a "grain size factor" is applied. For fine aggregates (0/4 mm and 0/8 mm) the factor is 1.0, while for coarse aggregate (8/16 mm and 16/22 mm) the factor is 2.0. For fine coarse aggregate (2/8mm and 4/8mm) the factor is 1.5.
- Finally a safety margin is added in order to take into account the number of analyses that form the basis for the weighted average value.

If the calculated *Sv* is less than the critical limit (see Table 2), no further documentation is required, i.e. the aggregate is considered to be non-reactive and may be used in any concrete mix.

**2. The Norwegian accelerated mortar bar test** – The test is carried out using mortar bars (40·40·160 mm) exposed in 1N NaOH at 80 °C for 14 days. The method is mostly in agreement with the RILEM AAR-2 method, but European standards (NS-EN) are followed for sieving, conditioning and moulding. The method can be used for testing single aggregates or blends of aggregates. However, as a standard aggregate grading is used, the method is not able to evaluate the reactivity of different aggregate fractions. The experience is that a sand and a coarse aggregate from the same deposit give similar expansion values. Since the coarse aggregates have proven to be more harmful than sand aggregates in field, a lower limit is thus applied for coarse aggregates (see Table 2).

**3. The Norwegian concrete prism test –** The test is carried out using concrete prisms with dimension 100·100·450 mm (400 kg OPC cement and 5.0 kg of alkalis/$m^3$). The prisms are stored in 100% RH at 38 °C in small containers, similar as described in the Canadian standard CSA A23.2-14A, and in the American standard ASTM C1293.

The critical expansion is measured after one year. The test may be used for testing of a sand, a coarse aggregate or a combination of both. When a potential reactive fine or coarse aggregate is tested, it shall be combined with a specified non-reactive coarse or fine aggregate, respectively; in a 60/40 mix representing the practical "worst case", i.e. 60 % of the potential reactive aggregate shall be applied.

The critical limits presented in Table 2 are based on the assumption that the concrete prism test is capable to take into account the effect of different reactivity of various grain sizes. Consequently, the same limit is applied for fine and coarse aggregates (0.040% after one year of exposure). However, for blends of aggregates a slightly higher critical limit is specified (0.050% after one year of exposure). The reason for this is that in real life an aggregate classified as "non-reactive" may give a certain contribution to the overall expansion.

### 3.2 Performance testing

The alkali-reactivity of various types of aggregates, binders and concrete recipes can be documented by performance testing using the Norwegian concrete prism method. Binders shall be tested in concrete with a specified "reference" highly reactive Norwegian aggregate (Norwegian Concrete Association, 2004b). The acceptance criteria for different types of binders and concrete recipes are presented in Table 3. A performance test shall be based on one or more batches normally varying the alkali content by adding (some) extra alkali (boosting) and keeping the binder composition and w/c-ratio constant. The motivation is to take into account possible alkali content variation of the product(s). If based on more than one batch, test results shall be plotted in an expansion versus alkali content-diagram as illustrated in Figure 1. By assuming a linear relationship between concrete prism expansion and alkali content, a limit of maximum accepted alkali content

***Table 2: Overview of critical limits for the three Norwegian test methods for documentation of alkali-reactivity of single aggregates or blends of aggregates (Norwegian Concrete Association, 2004a).***

| | Critical limits for the three Norwegian laboratory test methods[1] | | |
|---|---|---|---|
| **Documentation of** | **Petrographic analysis, Sv (adjusted results)[2]** | **Accelerated Mortar bar method[3]** | **Concrete prism method[4]** |
| Fine aggregate and blend of fine | 20.0% | 0.14% | 0.040%[5] |
| Coarse aggregate and blend of coarse | | 0.08% | 0.040% |
| Fine coarse aggregate | | 0.11% | n/a |
| Blend of a fine- and coarse aggregate, where the fine or coarse is alkali-reactive | 20.0%[6] | 0.11% | 0.050% |

[1] A single aggregate or a blend of aggregates shall be classified as innocuous if the values obtained are lower than the specified critical limits.
[2] Sv shall be compared with the critical limit.
[3] The measured expansion after 14 days of exposure shall be compared with the critical limits.
[4] The measured expansion after 1 year of exposure shall be compared with the critical limits.
[5] A fine aggregate or a blend of fine shall be tested with a coarse non-reactive reference aggregate. A coarse aggregate or blend of coarse shall be tested with a fine non-reactive reference aggregate. The binder used shall have an alkali content of 5.0 kg/$m^3$ $Na_2O$ eq.
[6] A maximum of 15% of the calculated value is allowed to come from the coarse aggregate.

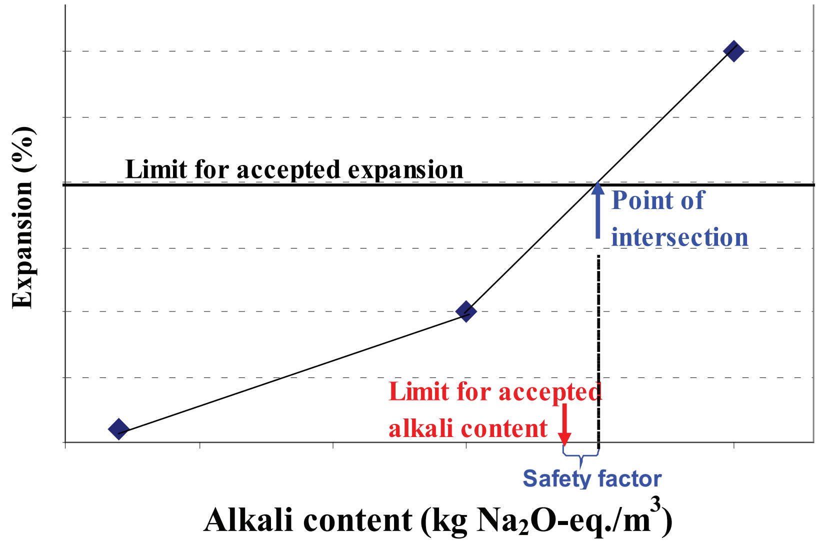


*Figure 1: Principle diagram for determination of acceptable critical alkali limit based on critical limit for accepted expansion and results from performance testing of three concrete mixes with different levels of alkalis. (Norwegian Concrete Association, 2004a).*

can be obtained. A safety factor of 0.2 kg $Na_2O$ eq./$m^3$ is required to be subtracted to obtain the critical alkali limit. The observed alkali leaching during accelerated laboratory testing (Lindgård, 2013 – see later) was not an issue when the level of this safety factor was agreed.

## 4.0 THE PATH FORWARD

In Norway, the aggregate, cement, and concrete industries are aware of the potential problems related to AAR. With the revised AAR regulations (NB21, 2004) and the revised test methods (NB32, 2005), suitable tools have been established to perform the required tests for the industry on a regular basis, and according to European standards, where NB21 gives the Norwegian national requirements for handling the AAR-problem.

However, AAR is complicated, and in Norway, with all the many variations in the aggregate materials due to the complex geology, we still need research to fully understand the mechanisms. The petrographic method has proven to be a cost and time efficient screening tool for various types of aggregates. A possible further development of the current method may however in the future make the method able to distinguish better between the reactivity of different rock types.

Assessments and testing by new advanced techniques could provide clarification in more detail about micro structural properties of reactive minerals and rock types. The PhD-study of Castro (2012) was an important step in this direction. This prospective new knowledge, along with automated image analysis, might be a path forward for strengthening and consolidating the petrographic method.

During the last years, the research focus has been on the

*Table 3: Maximum permitted expansion values for the Norwegian concrete prism test (Norwegian Concrete Association, 2004a).*

| Documentation of | Concrete containing pozzolanes or slagg? | Time of exposure | Maximum permitted expansion value after one year of exposure |
|---|---|---|---|
| CEM I binders, CEM II/A-V and CEM II/A-D, in addition to potential added silica fume and concrete recipes with these binders | No | 1 year | < 0.050% |
| | Yes | 1 year | < 0.030% |
| All other types of binders and concrete recipes with these other types of binders | Yes and No | 1 year | <0.030% |
| | Yes and No | 2 years | <0.060% |

utilisation of the Concrete Prism Test (CPT) as a performance test. The PhD-study of Lindgård (2013) was performed in cooperation with the international "performance testing" task group of RILEM TC 219-ACS. His results clearly show that parameters of importance for the development of AAR are significantly influenced by the specimen "pre-treatment", "AAR exposure conditions" and prism cross-section.

It was documented that in general a high fraction of the in-mixed alkalis are leached out of the concrete prisms during the AAR exposure. In fact, the rate of alkali leaching during the first weeks of exposure is the parameter found to have the highest impact on the development of the ultimate AAR expansion, in particular when exposed to 60 °C. Fortunately, due to the relative large prism cross-section of the Norwegian concrete prisms (100·100 mm), the Norwegian CPT showed less alkali leaching compared with all the other CPTs included in the study and consequently the highest expansions (Lindgård, 2013).

Norwegian scientists have recently taken the chair of the newly established RILEM Technical Committee (TC) "AAA" (2014-2019). The purpose of this TC is to develop and promote a performance based testing concept for the prevention of deleterious AAR in concrete. In connection to the development of performance tests, an assessment of the correlation between field structures versus laboratory results will be carried out.

The challenges of potential alkali release from certain types of aggregates will also be addressed. Strong emphasis will be put on the implementation of the RILEM methods and recommendations as national- and international standards. The activities in RILEM will be in cooperation with a recently established Norwegian R&D project (2014-2018) dealing with many of the same topics. The issues of implementation of aggregate alkali release on the alkali threshhold limits and limitation of alkali boosting are two vital research areas considered critical for future adoption of CPT for performance testing.

In addition, to improve the current test methods, the current critical acceptance limits need to be available for revision. It is the intention to initiate a new revision of NB21 in the near future. However, it is important to always bear in mind that the reality always has to be found in real concrete structures, and critical acceptance limits should always attempt to echo these conditions.

## REFERENCES


Castro, N., 2012: *Alkali-Aggregate Reactions in Concrete. Study of the relationship between aggregate petrographic properties versus expansion tests.* Thesis for the degree of Philosophiae Doctor, Trondheim, November 2012. Norwegian University of Science and Technology. Faculty of Engineering Science and Technology. Department of Geology and Mineral Resources Engineering.

Dahl, P.A., Lindgård, J., Danielsen, S.W., Hagby, C., Kompen, R., Pedersen, B. and Rønning, T.F., 2004: *Specifications and guidelines for production of AAR resistant concrete in Norway*, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 499-504.

Haugen, M., Skjølsvold, O., Lindgård, J. and Wigum, B.J., 2004: *Cost effective method for determination of aggregate composition in concrete structures*, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 907 – 911.

Jensen, V., 1993: *Alkali Aggregate Reactions in Southern Norway*, Doctor Technical Thesis, The Norwegian Institute of Technology, University of Trondheim, 1993, 262 pp + Appendices.

Jensen V. and Lorenzi G., 1999: *RILEM petrographic method for analysis of alkali reactive concrete aggregates.* In: Pietersen, HS, Larbi, JA, and Janssen, HHA (editors): Proceedings of the 7th Euroseminar on Microscopy Applied to Building Materials, 1999, pp. 143-153.

Lindgård J., Dahl P.A., Jensen V., 1993: *Rock composition – reactive aggregates: Test methods and requirements to laboratories*, SINTEF report no. STF70 A93030, Trondheim, 1993, (in Norwegian). 9 pp.

Lindgård, J. and Wigum, B.J., 2003: *Alkali Aggregate Reaction in Concrete – Field experiences*. SINTEF report STF22 A02616, 2003, (in Norwegian). pp 127 + appendices.

Lindgård, J., Wigum, B.J., Haugen, M., Skjølsvold, O., 2004a: *Field experience from investigation of more than 100 Norwegian bridges with respect to Alkali Aggregate Reactions (AAR)*, Nordic Concrete Research, Publication No. 32, 2004, pp. 114-128.

Lindgård, J., Haugen, M., Skjølsvold, O., Hagelia, P. and Wigum, B.J., 2004b: *Experience from evaluation of degree of damage in fluorescent impregnated plane polished sections of half-cores based on the "Crack Index Method",* Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 939 – 947.

Lindgård, J., 2013: *Alkali-silica reaction (ASR) – Performance testing.* Thesis for the degree of doctor philosophiae. Trondheim, October 2013. Norwegian University of Science and Technology. Faculty of Natural Sciences and Technology. Department of Materials and Science Engineering

NORMIN-2000, 1999: *Alkali Aggregate Reaction in Concrete – Petrographic Atlas* (in Norwegian). Edited by B.J. Wigum, 1999, Oslo, 14 pp. [English version available at www.farin.no].

Norwegian Committee for Standardization, 2013: NS-EN 206:2013+NA:2014. *Concrete – Specification, performance, production and conformity.*

Norwegian Concrete Association, 1996: *Durable concrete containing alkali reactive aggregates*, NB21, 1996, 5 + 27 pp including appendices. (in Norwegian).

Norwegian Concrete Association, 2004a: *Durable concrete containing alkali reactive aggregates*. NB21, 2004, 22+12 pages including appendices, (in Norwegian).

Norwegian Concrete Association, 2004b: *Alkali aggregate reactions in concrete. Test methods and requirements to laboratories*, NB32, 2004, (in Norwegian).

RILEM TC 191-ARP, 2003: RILEM Recommended Test method AAR-1: Detection of potential alkali-reactivity of aggregates – Petrographic method, *Materials and Structures, Vol. 36,* 2003, pp. 480-496.

Wigum, B.J., 1995a: *Alkali-Aggregate Reactions in Concrete; Properties, Classification and Testing of Norwegian Cataclastic Rocks*. PhD. thesis 1995:98, 1995, Inst. for Geologi og Bergteknikk, NTNU, Trondheim 1995, 227 pp.

Wigum, B.J., 1995b: Examination of microstructural features of Norwegian cataclastic rocks and their use for predicting alkali-reactivity in concrete. *Engineering Geology (40)* 1995: pp 195-214.

Wigum, B.J., French, W.J., Howarth, R.J. & Hills, C., 1997: Accelerated Tests for Assessing the Potential Exhibited By Concrete Aggregates for Alkali-Aggregate Reaction. *Cement and Concrete Composites, Vol. 19*, 1997, pp 451-476.

Wigum, B.J., Haugen, M., Skjølsvold, O. and Lindgård, J., 2004: *Norwegian Petrographic Method – Development and Experiences During a Decade of Service*, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 444 – 452.

# AAR in North America: Recommended practices for testing aggregates and selecting preventive measures

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*Stanton documented the first discovery of alkali-silica reaction (ASR) in California in the USA in1940, and Swenson reported the occurrence of alkali-carbonate reaction (ACR) in Ontario, Canada, in 1957. Since these pioneering works, extensive research has been conducted in both countries to elucidate the mechanisms of the reactions, determine factors that influence them, develop test methods for identifying reactive aggregates, evaluate various preventive measures and assess strategies for controlling damage in AAR affected structures. Both countries now have comprehensive guidelines and/or standard practices for minimising the risk of reaction in new construction. The approaches are similar and involve characterisation of the aggregates, estimation of the risks and consequences of reaction based on aggregate reactivity, exposure condition and the nature of the structure, and identifying appropriate preventive measures. This paper describes the development of these protocols and related test methods, and provides a summary of strategies used for preventing deleterious reaction with potentially reactive aggregates.*

## 1.0 INTRODUCTION

Two types of alkali-aggregate reaction (AAR) are currently recognised; these are alkali-silica reaction (ASR) discovered by Thomas Stanton in the late 1930s in the United States (Stanton, 1940) and alkali-carbonate reaction (ACR) first observed by Ed Swenson in Canada almost 20 years later (Swenson, 1957). Both phenomena involve chemical reactions between the alkali hydroxides (NaOH and KOH) in the pore solution of the concrete and the aggregate, and can lead to expansion and cracking of concrete.

With ASR, it is certain silica minerals in the aggregate that react and these include opal, chert, cristobalite, tridymite, volcanic glass and some forms of microcrystalline, cryptocrystalline and strained quartz; these minerals are abundant and present in a great many rock types although not always in sufficient quantity to cause deleterious expansion of concrete.

ACR appears to be confined to certain types of argillaceous dolomitic limestones with a specific texture characterised by small dolomite rhombs floating in a matrix of clay minerals, micrite and silica; on exposure to alkali hydroxides, there rocks undergo "dedolomitisation" producing calcite and brucite. Also, alkalis are recycled into the concrete pore solution through ACR, thus explaining why deleterious expansion occurs at low cement alkali contents. Cases involving ACR are relatively rare compared to ASR. It has been disputed (Katayama, 1992; 2010) that ACR is a form of ASR and that it is a reaction of the fine-grained silica in the reactive rocks that causes problems. Regardless of the precise mechanism, aggregates that are currently classified as alkali-carbonate reactive and exhibit dedolomitisation need to be distinguished from other alkali-reactive carbonate aggregates as expansion cannot be readily controlled by the "traditional and proven" preventive measures for ASR, which include controlling the alkali content of the concrete, use of suitable supplementary cementing materials (SCM) and, for some alkali-silica reactive materials, the use of lithium-based admixtures (Thomas et al,, 2013).

Much research has been conducted on AAR, particularly ASR, including studies to (i) determine the mechanisms of reaction and expansion, (ii) isolate contributing factors, (iii) establish effective preventive measures, (iv) develop test methods for identifying reactive aggregates (including the type, ASR or ACR, and severity of reactivity) and/or for evaluating the efficacy of preventive measures, and (v) appraise methods for mitigating expansion and damage in existing AAR-affected structures.

In Canada and the United States, similar testing protocols or "standard practices" have been established to minimise the risk of damage due to AAR (ASR and ACR); these are (i) in Canada, CSA A23.2-27A (CSA, 2014a) first developed in 2000 and updated in 2004, 2009 and 2014, and (ii) in the USA, AASHTO PP 65 (AASHTO, 2011) and ASTM C 1178 (ASTM, 2014).

These protocols involve a suite of testing including petrographic examination and expansion testing of aggregates to determine the nature of the reactivity and then, depending on the structure in question (e.g. exposure condition, service-life requirements, type of structure, etc.), provide guidelines for selecting appropriate preventive measures; the level of prevention is either prescribed or may be determined by performance testing (Standard Practice CSA A23.2-28A in Canada) (CSA 2014b).

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This paper describes the test methods used to identify both alkali-reactive silica and carbonate rocks, and the approaches for selecting appropriate levels of prevention.

## 2.0 TESTING AGGREGATES FOR REACTIVITY

### 2.1 Alkali-silica reaction (ASR)

The standard practices in North America allow aggregates to be evaluated using field-performance history, petrographic evaluation and/or expansion testing in mortar or concrete; the sequence of testing is shown in Figure 1. A certain risk is implied using field performance as the mineralogy of the aggregate within a given pit or quarry, or the composition of the cementing materials used, might change with time. There is also a risk that petrography will fail to identify the presence of reactive silica if it is present in finely-divided form that cannot be resolved by optical microscopy. Consequently, the practices recommend expansion testing wherever possible. The following two test methods (see Test Methods table opposite) are included in these practices:

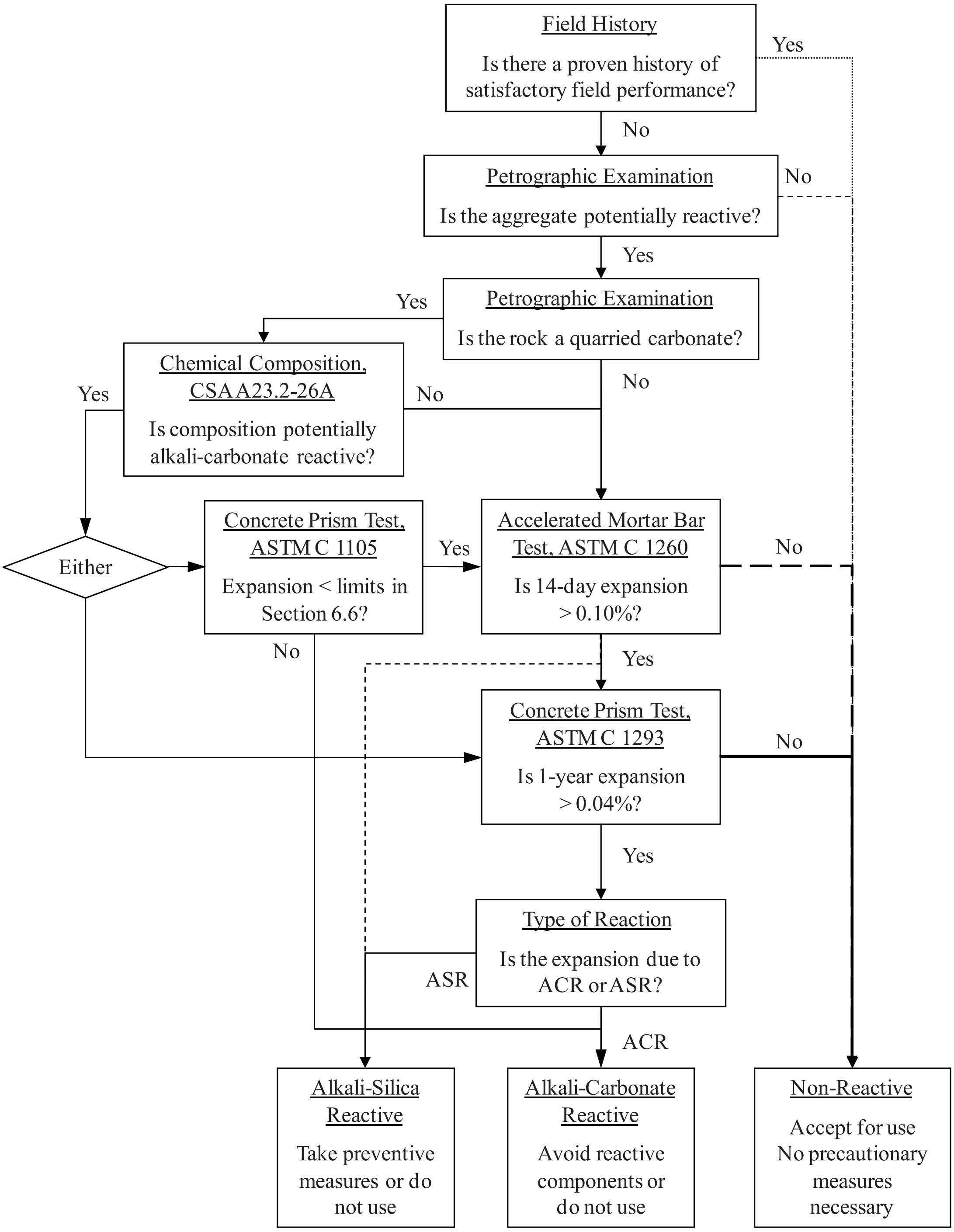


*Figure 1: Flowchart showing sequence of tests and possible outcome – from AASHTO PP65.*

| Test Methods | |
|---|---|
| Accelerated mortar-bar test (AMBT) | AASHTO T 303, ASTM C1260, CSA A23.2-25A: mortar bars (25 x 25-mm cross-section x 250-mm gauge length) stored in 1M NaOH at 80 °C for 14 days. |
| Concrete-prism test (CPT) | ASTM 1293, CSA A23.2-14A: concrete prisms (75 x 75 cross-section x 250-mm minimum gauge length) stored in sealed containers over water at 38 °C for 1 year. |

The aggregate is classified as being non-reactive, moderately-reactive, highly-reactive or extremely-reactive depending on the expansion recorded in these tests. In the event that results are available from both tests, the results from the CPT prevail.

Unfortunately, there is NOT a reliable correlation between the results of the two test methods; this is shown in Figure 2 using data for control mixes (without preventive measures) from various published and unpublished sources (Thomas et al, 2012). It is generally recognised that the CPT is more reliable as it usually compares well with observations from the field performance.

It is well known that the AMBT is unduly harsh and frequently produces "false positives" indicating aggregates to be reactive when performance in concrete tests or in the field gives no indication of reactivity; however, perhaps of more concern, is the growing number of cases where the AMBT produces "false negatives" by failing to correctly identify known reactive aggregates (Thomas et al, 2012; 2013). The justification for continuing to include the AMBT in the repertoire of ASR tests is the need for a rapid test. The CPT is not without problems; it has been reported by a number of workers, most recently Lindgård et al, (2013), that significant leaching of alkalis occurs during the test, which necessitates the augmentation of alkalis when producing the concrete.

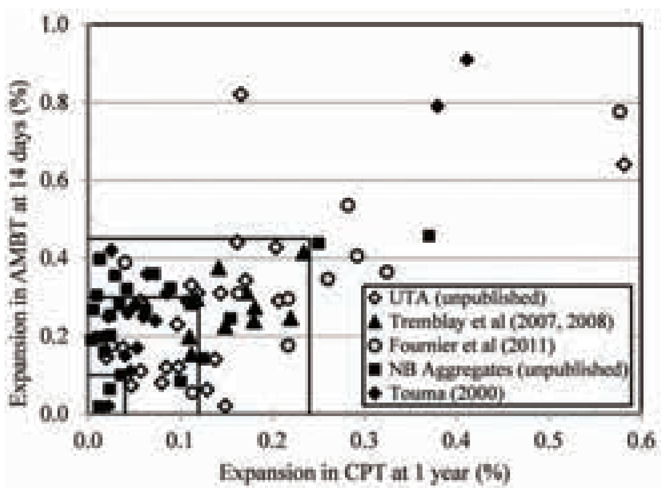


*Figure 2: Relationship between expansion in AMBT and CPT (from Thomas et al, 2012).*

## 2.2 Alkali-carbonate reaction (ACR)

Quarried carbonate rocks require special consideration as the potential for ACR must be addressed (see Figure 1). Limestones and dolostones are first evaluated using chemical composition and plotting the results on a plot of CaO:MgO ratio versus $Al_2O_3$ (from Rogers, 1986). If the composition falls in one of the zones designated "Aggregates considered non-expansive due to ACR", the aggregate is then tested for ASR potential using the suite of tests described above. However, if the composition indicates "Aggregates considered potentially expansive due to ACR", the aggregate must be tested using one of two approaches; these are:

- Standard CPT. If there is no damaging expansion (≤ 0.040%), then the aggregate is considered to be non-reactive. If the expansion is > 0.040%, then further (petrographic) investigation is required to determine if the expansion is due to ASR, ACR or both.
- Modified CPT following ASTM C 1105 using an alkali loading of 1.8 $kg/m^3$ $Na_2Oe$. If deleterious expansion occurs, the aggregate is assumed to be alkali-carbonate reactive and must be rejected. If deleterious expansion is not observed, the aggregate is considered to be non-alkali-carbonate reactive and can be tested for ASR using the suite of tests outlined in the previous section.

## 3.0 PREVENTIVE MEASURES

Aggregate testing (described above) results in one of three outcomes; these are described in Table 1 with the appropriate actions. Aggregates that are demonstrated to be non-reactive require no further consideration with regards to these practices and may be used without preventive measures. Aggregates that are identified as being alkali-carbonate reactive (either with or without a contribution from ASR) must be rejected for use in concrete as there are no universally-accepted preventive measures for ACR[1]. Aggregates that are alkali-silica reactive (with no evidence of ACR) can still be accepted for use in concrete provided an appropriate preventive measure is adopted. The type and level of prevention may be prescribed (prescriptive approach) or determined by testing (performance approach).

[1] Note: this action does not preclude beneficiation and retesting of the aggregate.

*Table 1: Possible outcomes and appropriate actions following aggregate testing.*

| Outcome for aggregate | Action |
|---|---|
| Non-reactive[1] | Accept aggregate: no prevention required |
| Alkali-silica reactive (no ACR detected) | Implement appropriate preventive measures |
| Alkali-carbonate reactive (with or without ASR) | Reject aggregate |

[1] Care should be exercised because some aggregates, for instance some granites, granitic gneisses, siliceous sandstones, may generate low expansion in the accelerated mortar bar test while being reactive in the field or in the concrete prism test.

*Table 2: Example showing range of preventive measures (from CSA A23.2-27A).*

| Preventive Measure | Prevention Level[1] | | | | |
|---|---|---|---|---|---|
| | W | X | Y | Z[2] | ZZ |
| Maximum alkali from PC (kg/m$^3$ $Na_2Oe$) | 3.0 | 2.4 | 1.8 | 1.2 | Use maximum PC alkali and minimum SCM for Level Z |
| Minimum Class F fly ash[3] level (%) | 15 | 20 | 25 | 35 | |
| Minimum slag level (%) | 25 | 35 | 50 | 60 | |

[1] Level ranges from V for "no prevention required" (not shown) through W for "mild prevention" to ZZ for "exceptional prevention".
[2] For prevention level Z, it is permitted to use a combination of the maximum PC alkali and minimum SCM for level Y.
[3] Requirements shown for fly ash with alkali < 3.0% $Na_2Oe$.

### 3.1 Prescriptive Approach

The prescriptive approach can be used to determine the level of prevention required using any of the following measures:

1. Controlling the alkali content of the concrete (only the alkalis contributed by the portland cement component of the concrete are included in the calculated alkali content).
2. Incorporating a sufficient level of the following SCM: Class F fly ash, slag, silica fume or blends of these materials (i.e. for use in ternary and quaternary cements).
3. A combination of 1 and 2 above.

The prescriptive approach can NOT be used to determine the level of prevention when the following measures are being considered:

4. Use of a lithium-based admixture.
5. Use of natural pozzolans.
6. Use of Class C fly ash.
7. Use of Class F fly ash, slag or silica fume with atypically high alkali contents.

When these materials (4 to 7 above) are being considered, the appropriate level of prevention must be determined by performance testing (see below).

The prescribed level of prevention depends on a number of factors; these being (i) the reactivity level of the aggregate, (ii) the exposure condition and (iii) the nature of the concrete element being constructed including size, design life and (in the case of AASHTO and ASTM) the consequences of ASR. For example, if the preventive measure being contemplated is the use of Class F fly ash, the minimum level of fly ash required will be greatest when extremely reactive aggregates is used in massive structures exposed to moisture, where the structure has a design life of 75 years or more and the consequences of ASR are severe. In all three practices, the minimum level of silica fume required also varies with quantity of alkali contributed by the portland-cement component of the concrete; increased alkali requiring an increased level of prevention. The CSA, AASHTO and ASTM practices also allow a reduction in the level of fly ash or slag required when low-alkali (< 0.70% $Na_2Oe$) cement is being used and impose an increase for high-alkali (> 1.00% or 1.15% $Na_2Oe$, depending on the reactivity level of the aggregate) cement.

In all three practices, the level of prevention ranges from Level V (no prevention) through W (mild prevention, X (moderate prevention), Y (strong prevention), Z (very strong prevention) to ZZ (exceptional prevention). Table 2 shows how the maximum alkali content and minimum SCM (Class F fly ash and slag shown) replacement level change with the level of prevention required. The values shown are for the Canadian practice, CSA A23.2-27A (CSA 2014a); the same or, in some cases, similar values are used in the AASHTO and ASTM practices.

The supporting evidence used to select the maximum alkali contents and minimum SCM replacement levels that are prescribed in the three practices can be found in the literature; in the case of AASHTO PP-65, the data underpinning the practice was summarised and documented in Thomas et al, (2012).

### 3.2 PERFORMANCE APPROACH

The performance approach, as described in the three Standard Practices, can be used to determine the level of prevention required using any of the following measures:

1. Using SCM including those incorporated in and those not covered by the prescriptive approach (e.g. Class F and C fly ashes, slag, silica fume, metakaolin and other pozzolans).
2. Using a lithium-based admixture (specifically a solution of lithium nitrate).

The performance approach CANNOT be used to determine the level of prevention when the following measures are being considered:

3. Controlling the alkali content of the concrete.

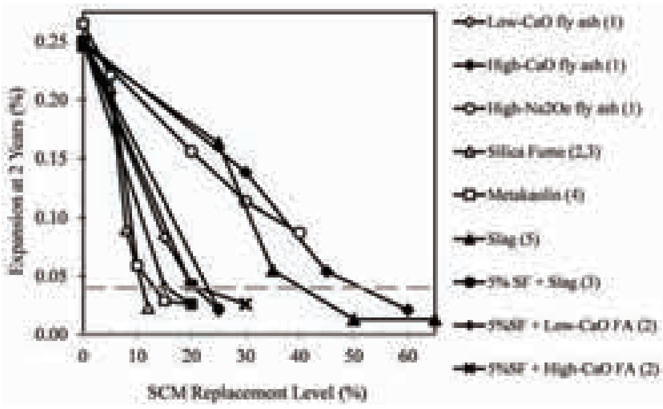


***Figure 3: Effect of SCMs on two-year expansion of concrete containing siliceous (Spratt) limestone (1;2 – Shehata & Thomas, 2000; 2002; 3 – Bleszynski, 2002; 4 – Ramlochan et al, 2000; 5 – Thomas & Innis, 1998).***

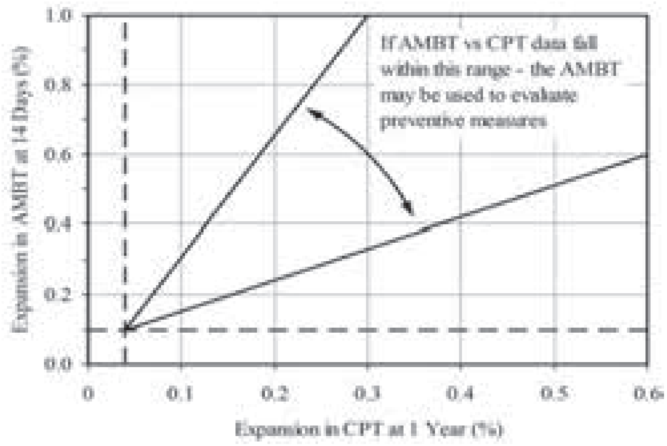


***Figure 5: Relationship used to determine the "reliability" of the AMBT by comparison with CPT data for the same aggregate (from AASHTO PP 65).***

In determining the minimum amount of SCM required to control expansion with a certain aggregate, the three practices recommend the use of the CPT, applying the limiting expansion criterion after a 2-year test duration (rather than the 1-year test used for evaluating potential reactivity of aggregates), but also permit the use of the AMBT using the expansion measured after 14 days in the NaOH solution.

When using the AMBT, both AASHTO and ASTM specify the use of ASTM C 1567, which is basically ASTM C 1260 modified to allow the evaluation of SCM and blended cements. The practices suggest that tests are run with the specific aggregate in question and a range of SCM replacement levels in an attempt to bracket the minimum level required to meet the expansion limits (0.040% at 2 years for CPT and 0.10% at 14 days for AMBT).

An example of data collected using the Spratt aggregate (a highly-reactive siliceous limestone) and a wide range of SCMs at different replacement levels is shown in Figure 3; the two-year concrete prism expansion results are plotted against the replacement level. As observed in Figure 2 for tests on aggregates in control mixes (without SCM), the correlation between the results of the AMBT and CPT for concrete containing preventive measures is also poor as shown in Figure 4 (from Thomas et al, 2006; 2007); the data shown are from

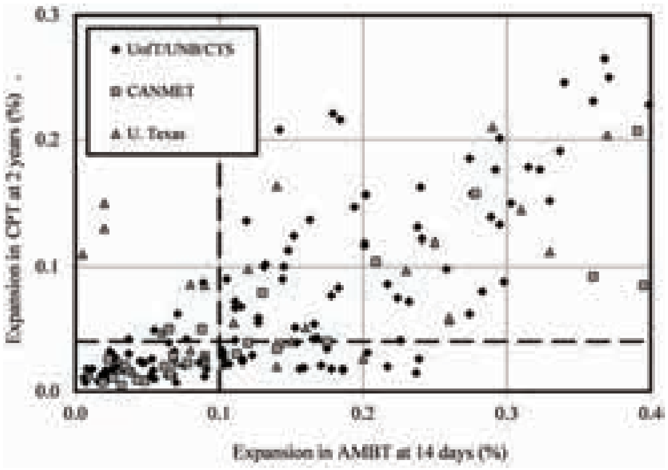


***Figure 4: Relationship between expansion in CPT and AMBT for mixtures with and without SCM and a wide range of aggregates (Thomas et al, 2006; 2007).***

five different laboratories and include mixtures with a wide range of aggregates and different SCMs.

For some aggregates, there is a good agreement between the results from the AMBT and CPT for mixtures with and without SCM. However, the AMBT has been shown to produce many "false positives" and a lesser but increasing number of "false negatives". In response to this, both AASHTO PP 65 and ASTM C 1178 recommend that, before using the AMBT for evaluating the efficacy of SCM with a specific aggregate, the two tests are conducted using the aggregate without SCM and the results compared (see Figure 4). The AMBT should only be used to evaluate SCM if the results from mortar and concrete tests without SCM are in good agreement (i.e. the data plot in the range shown in Figure 5).

## 4.0 DISCUSSION

The three practices described here essentially follow the same approach and produce very similar guidelines regarding preventive measures. The CSA standard practice, CSA A23.2-27A (CSA, 2014) was first published in 2000. PP 65 (AASHTO, 2011) was closely based on the CSA practice and, in turn, formed the basis for C 1178 (ASTM, 2014).

The intent of the practices is to provide a uniform approach to testing aggregates and selecting preventive measures while allowing the user some degree of flexibility in selecting options. It is expected that the practices will continue to evolve as further data become available to validate the prescriptive options and as new test methods are developed.

At this point in time, perhaps the greatest need for improving the practices is the development of a test method that is reliable, rapid and capable of testing "job mixtures" (that is testing the specific combinations of materials that will be used in a construction project, including low alkali systems). Neither the CPT nor the AMBT is indeed capable of determining the true impact of the alkalis in a concrete mixture on the resulting expansion. The AMBT uses a soak solution of NaOH and, hence, provides an inexhaustible supply of alkalis for the reaction; these alkalis "swamp" the system and mask the impact of the alkalis contributed by the components of the mixture (e.g. the portland cement alkalis, high alkali SCM). On the other hand, the alkalis in the CPT decrease during the test due to leaching. Consequently, the alkali content of the CPT must be increased to compensate for alkalis lost during test and this again makes it difficult to determine the effective alkali contribution from the ingredients. One way forward is the development of test methods that prevent alkali leaching but still provide additional moisture to the concrete; several such tests are currently being investigated.

## REFERENCES


AASHTO, 2011. "Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction." AASHTO pp. 65-11, American Association of State and Highway Transportation Officials, Washington, D.C.

ASTM, 2014. "Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete", ASTM C 1178 (successfully balloted in 2014, scheduled for publication in 2015).

Bleszynski, R.F. 2002. "The performance and durability of concrete with ternary blends of silica fume and blast-furnace slag", PhD Thesis, University of Toronto.

CSA, 2014a. "Standard practice to identify degree of alkali-reactivity of aggregates and to identify measures to avoid deleterious expansion in concrete." CSA A23.2-27A, Canadian Standards Association, Mississauga, Canada.

CSA, 2014b. "Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete." CSA A23.2-28A, Canadian Standards Association, Mississauga, Canada.

Katayama, T. 1992. "A critical review of carbonate rock reactions – is their reactivity useful or harmful ?" *Proceedings of the 9th International Conference on Alkali-Aggregate Reaction in Concrete* (ICAAR), A.B. Poole (Ed.), London, UK, pp. 508–517.

Katayama, T. 2010. "The so-called alkali-carbonate reaction (ACR) – Its mineralogical and geochemical details, with special reference to ASR." *Cement and Concrete Research,* Vol. 40, pp. 643-675.

Lindgård, J., Thomas, M.D.A., Sellevold, E.J., Pederson, B., Andic-Cakir, O., Justnes, H., Ronning, T.F. 2013. "Alkali-silica reaction (ASR) – performance testing: influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion." *Cement and Concrete Research,* Vol. 53, pp. 68-90.

Ramlochan, T., Thomas, M.D.A. and Gruber, K.A. 2000. "The effect of metakaolin on alkali-silica reaction in concrete", *Cement and Concrete Research,* Vol. 30 (3), pp. 339–344.

Rogers, C. A. 1986. "Evaluation for the Potential for Expansion and Cracking of Concrete Caused by the Alkali-carbonate Reaction", *Cement, Concrete and Aggregates,* Vol 8 (1), pp. 13–23.

Shehata, M.H. and Thomas, M.D.A. 2000. "The effect of fly ash composition on the expansion of concrete due to alkali-silica reaction, *Cement and Concrete Research,* Vol. 30 (7), pp. 1063–1072.

Shehata, M.H. and Thomas, M.D.A. 2002. "Use of ternary blends containing silica fume and fly ash to suppress expansion due to alkali-silica reaction in concrete, *Cement and Concrete Research,* Vol. 32 (3), pp. 341–349.

Stanton, T.E. 1940. "Expansion of concrete through reaction between cement and aggregate", *Proceedings of the American Society of Civil Engineers,* Vol. 66 (10), pp. 1781-1811.

Swenson, E.G. 1957. "A reactive aggregate undetected by ASTM tests", *Proceedings of American Society for Testing and Materials,* Vol. 57, pp. 48-51.

Thomas, M.D.A. and Innis, F.A. 1998. "Effect of slag on expansion due to alkali-aggregate reaction in concrete", *ACI Materials Journal,* Vol. 95 (6), pp. 716–724.

Thomas, M.D.A., Fournier, B., Folliard, K.J., Ideker, J.H. and Shehata, M.H. 2006. "Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete." *Cement and Concrete Research,* Vol. 36 (10), pp. 1842–1856.

Thomas, M.D.A., Fournier, B., Folliard, K.J., Shehata, M.H., Ideker, J.H. and Rogers, C.A. 2007. "Performance Limits for Evaluating Supplementary Cementing Materials Using Accelerated Mortar Bar Test." *ACI Materials Journal,* Vol. 104 (2), pp. 115-122.

Thomas, M.D.A., Fournier, B., Folliard, K.J. 2012. "Selecting Measures to Prevent Deleterious Alkali-Silica Reaction in Concrete: Rationale for the AASHTO PP65 Prescriptive Approach". Report No. FHWA-HIF-13-022, Federal Highway's Administration, Washington, D.C.

Thomas, M.D.A., Fournier, B., Folliard, K.J. 2013. "Alkali-Aggregate Reactivity (AAR) Facts Book." Report No. FHWA-HIF-13-019, Federal Highway's Administration, Washington, D.C.

Touma, W.E., Fowler, D.F. and Carrasquillo, R.L. 2001. "Alkali-silica reaction in portland cement concrete: testing methods and mitigation alternatives". Report ICAR 301-1F, International Center for Aggregates Research, Austin, Texas.

Tremblay, C., Bérubé, M-A., Fournier, B., Thomas, M.D.A., and Folliard, K.F. 2007. "Effectiveness of lithium-based products in concrete made with Canadian reactive aggregates." *ACI Materials Journal,* Vol. 104 (2), pp. 195-205.

Tremblay, C., Bérubé, M.A., Fournier, B., Thomas, M.D.A., Folliard, K.J. & Nkinamubanzi, P.C. 2008. Use of the AMBT to evaluate the effectiveness of $LiNO_3$ against ASR – Part 2: Comparison with results from the Concrete Prism Test. *Journal of ASTM International,* Vol. 5 (8).

# The assessment on ASR of aggregates and ASR mitigation effect by fine fly ash

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*In the Hokuriku district in Japan, large numbers of concrete structures have been suffering from a combined damage caused by the ASR and/or the chloride-induced corrosion of reinforced concrete structures. In this district, two approaches have been applied in relation to ASR problems; one is to prolong the life of the structure by appropriate repair and strengthening, and the other by employing countermeasures against ASR, such as using fine fly ash of 8 μm in average particle size. This paper describes work in which the reactivity of aggregate was assessed by the chemical method according to JIS A1145, the method of test for "Alkali-Silica Reactivity of Aggregates", and the assessment outcome of aggregate classification was 'deleterious', which was also confirmed by the petrographic method. The latter was also applied to three types of mortar bar methods to investigate and confirm the mitigating effect of fine fly ash on ASR.*

## 1.0 INTRODUCTION

In the Hokuriku district in Japan, large numbers of bridges and tunnels have been suffering from the combined damage caused by the chloride-induced corrosion of steel reinforcement and/or ASR (Torii, 2010). On the whole, in the West region in Japan, the chloride attack is related to the use of sea sand or sea gravel in concrete (so-called internal salt attack), but in the Hokuriku district, the chloride attack is related to both the northwest monsoon from the Sea of Japan especially in winter, and the increased scattering of de-icers on road surfaces in the winter season (so-called external salt attack). On the other hand, this district is also located within some huge volcanoes, as shown in figure 1, in the upstream section of main rivers, prompting the outflow and spreading of volcanic rocks such as the andesite and rhyolite stones, which are the main reactive aggregates causing the ASR damage in the entire area. Figure 2 shows the deteriorated ASR bridges map in the Hokuriku district and figure 3 shows the examples of seriously deteriorated bridge piers by ASR.

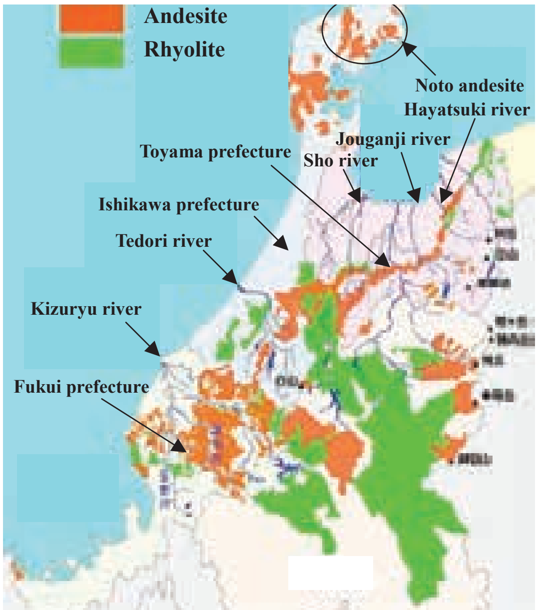


*Figure 1: Outflow and spreading of volcanic rock (andesite, rhyolite) in Hokuriku district.*

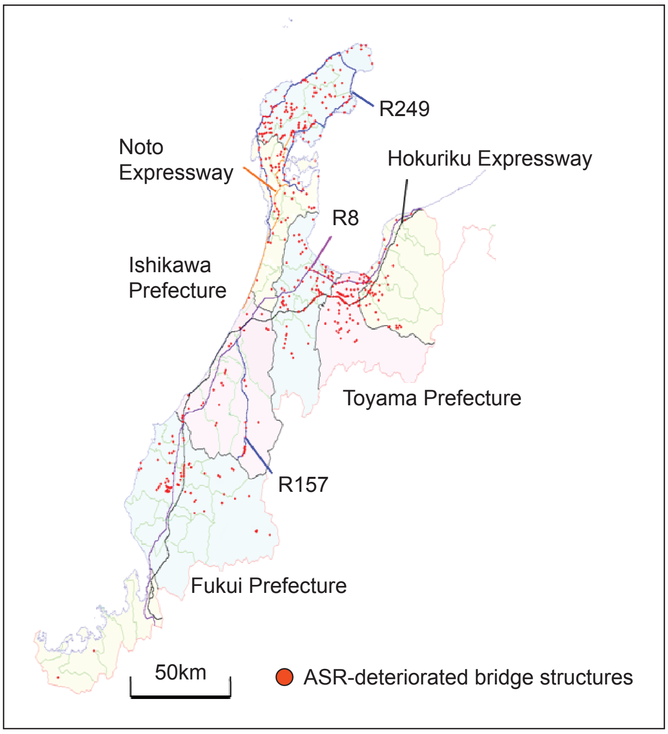


*Figure 2: Distribution map of ASR deteriorated bridges in Hokuriku district.*

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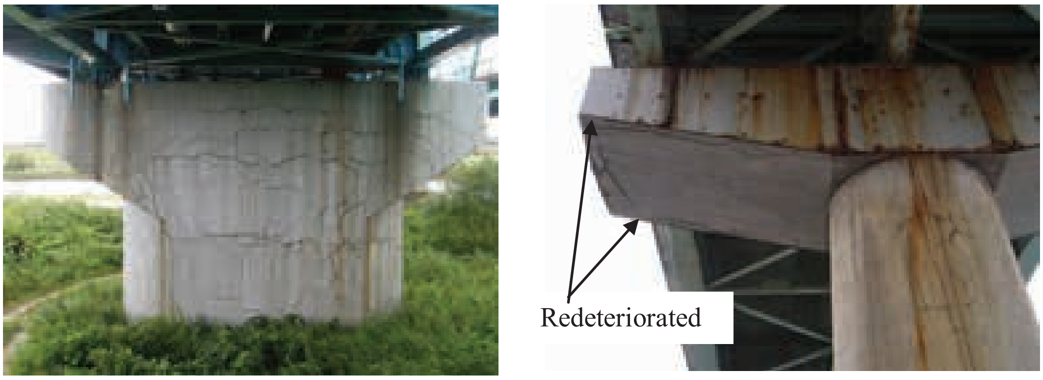
*Figure 3: Overviews of ASR-deteriorated bridge piers used with Joganji River gravel.*



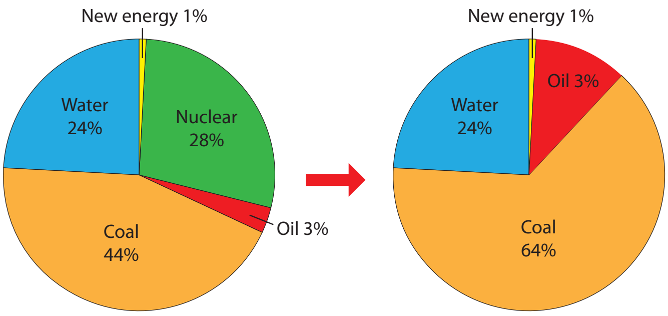




*Figure 4: The share of electrical production source in Hokuriku district before or after the 2011 Tohoku Great Earthquake (Left: in 2010, Right: in 2012).*

In order to produce the highly durable concrete structures especially against ASR problems, the standard use of a good-quality fly ash cement with the replacement of more than 15% has been recommended by one of the authors, which is now proposed in all ready-mixed concrete mixtures from the economical and environmental point of view in this region (Sannoh & Torii, 2008). For the achievement of this inevitable target, a joint-collaborative industry-academia-government research committee on "the promotion of effective utilisation of fly ash concretes in the Hokuriku district", which is chaired by Prof. K. Torii at Kanazawa University, has also been set up in January 2011. On the approach of a promotive work, it can be pointed out that both the supply of a good-quality fly ash from the coal burning power plant and its quality assurance are essential in the production of concrete mixtures. In the Nanao-Ohta coal burning power plant in the Ishikawa Prefecture, the production technique of very fine particles has successfully been established, where two processes are adopted; one is the selection of original fly ash from only the bituminous coal from Australia, the other is its mechanical separation of ultra-fine particles less than 20 µm by a centrifugal machine with the air flow. The physical and chemical properties of fine fly ash produced are almost well satisfied with the quality standard of the highest level "Class I" according to JIS A6201.

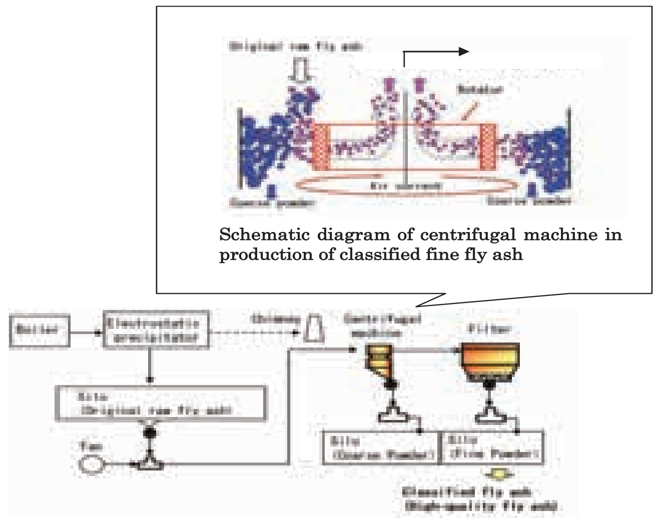



*Figure 5: Production process of classified fly ash in Nanao-Ohta coal burning power plant in Ishikawa Prefecture.*

Furthermore, on the trial test in ready-mixed concrete plants, it has been confirmed that in the fly ash concretes with the replacement of 15% by classified fine fly ash, the water content of concrete can, on average, be reduced by 5 kg/m$^3$ to 10 kg/m$^3$, and the compressive strength of concrete can be almost equal to the OPC concretes even at 28 days, and it can be greater than them at 56 days.

Additionally, the share of electrical production source in the Hokuriku district drastically changed after the 2011 Tohoku Great Earthquake and Tsunami disaster, as shown in figure 4. Because most of nuclear power plants have been shut down, and there is no plan in sight for their immediate operation. This resulted in the growing importance of the coal burning power plant and the effective utilisation of fly ash especially in the Hokuriku district.

In this paper, firstly both the supply system and the quality assurance of classified fine fly ash are introduced, secondly the assessment of alkali silica reactivity of Joganji River gravel in the Hokuriku district is introduced, which is considered to be the most reactive one in Japan, finally the mitigating effect of classified fine fly ash on ASR by three types of mortar bar tests for Joganji River gravel is introduced (Hashimoto & Torii, 2013).

## 2.0 SUPPLY SYSTEM AND QUALITY ASSURANCE OF CLASSIFIED FINE FLY ASH AS ADMIXTURE FOR CONCRETE

In January 2011, a joint-collaborative industry-academia-government research committee on "the promotion of effective utilisation of fly ash concretes in the Hokuriku district" was set up. It has started the standardisation of the use of fly ash concrete and consultations on the definition of a sustainable

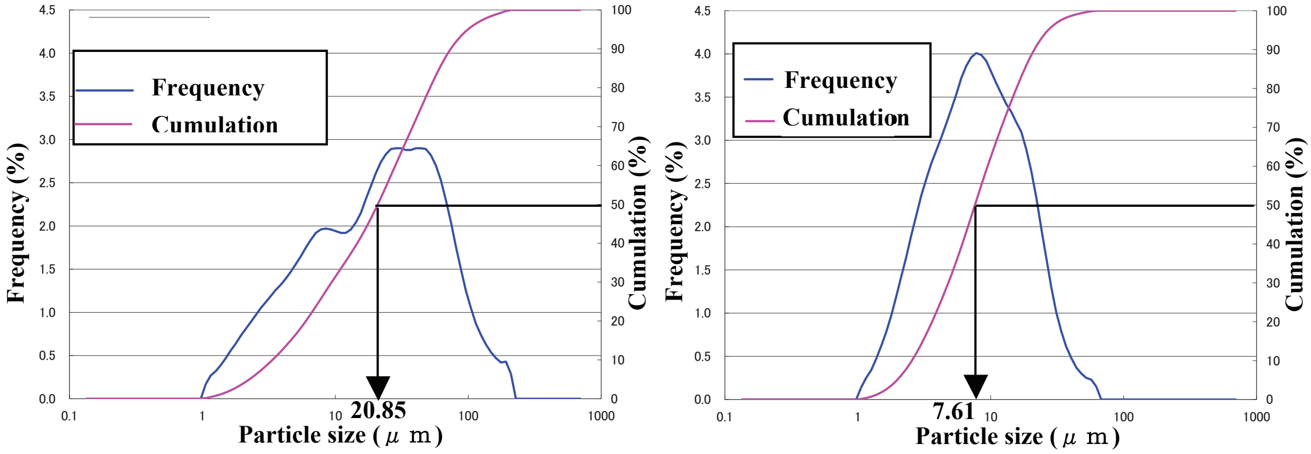



*Figure 6: Comparison in particle size frequency of original and classified fly ash (left: original fly ash, right: classified fly ash).*

*Table 1: Comparison in physical and mineralogical properties of original and classified fly ash.*

| Fly ash type | Physical properties | | Mineralogical properties (%) | | | | |
|---|---|---|---|---|---|---|---|
| | Density (g/cm$^3$) | Blaine fineness (cm$^2$/g) | Quartz | Mullite | Magnetite | Lime | Glass |
| Original | 2.36 | 3390 | 5.4 | 26.7 | 2.0 | 0.8 | 65.1 |
| Classified | 2.43 | 4780 | 5.0 | 20.6 | 1.0 | 0.2 | 73.2 |

and effective supply system in the Hokuriku district. In the Toyama, Ishikawa and Fukui Prefectures, there is one coal burning power station respectively, but those from where good quality fly ashes can be steadily supplied, judged from relationship between the type of boiler and its burning temperature, are the Nanao-Ohta coal burning power plant in the Ishikawa Prefecture and the Tsuruga coal burning power plant in the Fukui Prefecture.

For this reason, it has been decided that both the Toyama and Ishikawa Prefectures have been supplied from the Nanao-Ota coal burning power plant, while the Fukui Prefecture will be supplied from the Tsuruga coal burning power plant in September 2012, thus covering all the entire Hokuriku district area, through the distribution terminals suitably located in the network of supply system, in which the 30,000 t/a of a classified fine fly ash can be supplied from both Nanao-Ohta and Tsuruga coal burning power plants respectively. Furthermore, at the following stage, the fly ash will be directly transported to the cement factories at the Itoigawa City in the Niigata Prefecture or at the Tsuruga City in the Fukui Prefecture for the production of fly ash cement type B (fly ash replacement ratio of 10% to 20% by mass), as the supplying system is being taken under consideration. When this system becomes operational, it is more expected that cement transportation costs within the designated area can be largely reduced, including other advantages.

On the other hand, in regard to the quality assurance of fly ash, as shown in figure 5, the production technique of very fine particles and the small variations in the physical and chemical properties at the Nonao-Ohta coal burning power plant has successfully been established, where two processes are adopted; one is the selection of original fly ash from only the bituminous coal from Australia, the other is its mechanical separation of ultra-fine particles less than 20 µm by a centrifugal machine.

Furthermore, it has been confirmed that the variations in the physical and chemical properties of fly ash itself by a centrifugal machine can significantly improve the pozzolanic activity. Physical properties of fly ash can be improved from 21 µm to 8 µm at the average particle size, as shown in figure 6, and chemical properties of fly ash can be improved that the glassy phases of fly ash, which is mostly composed of silica glass, are

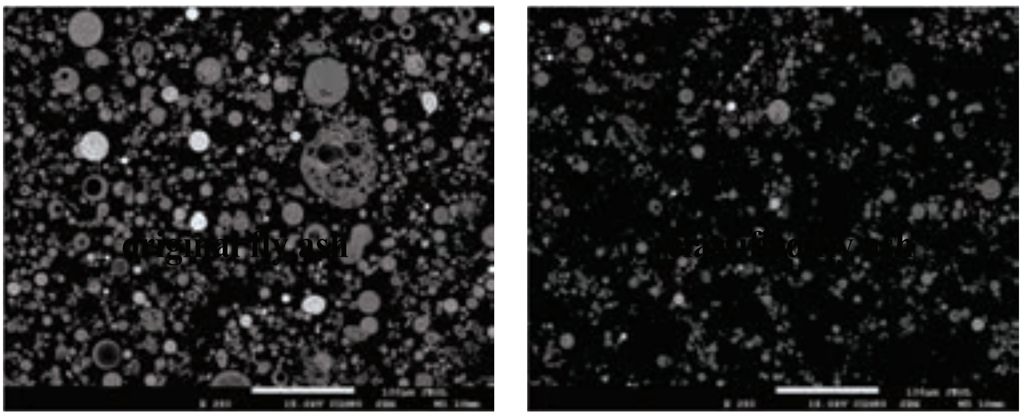


*Figure 7: Comparison in size and shape of original and classified fly ash particles (left: original fly ash, right: classified fly ash, scale bar: 100 µm).*

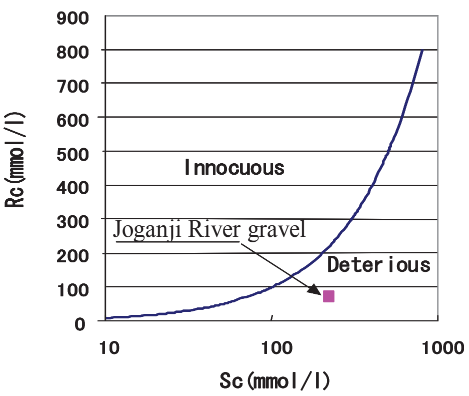



*Figure 8: Results of chemical test method (JIS A1145) for Joganji River gravel.*

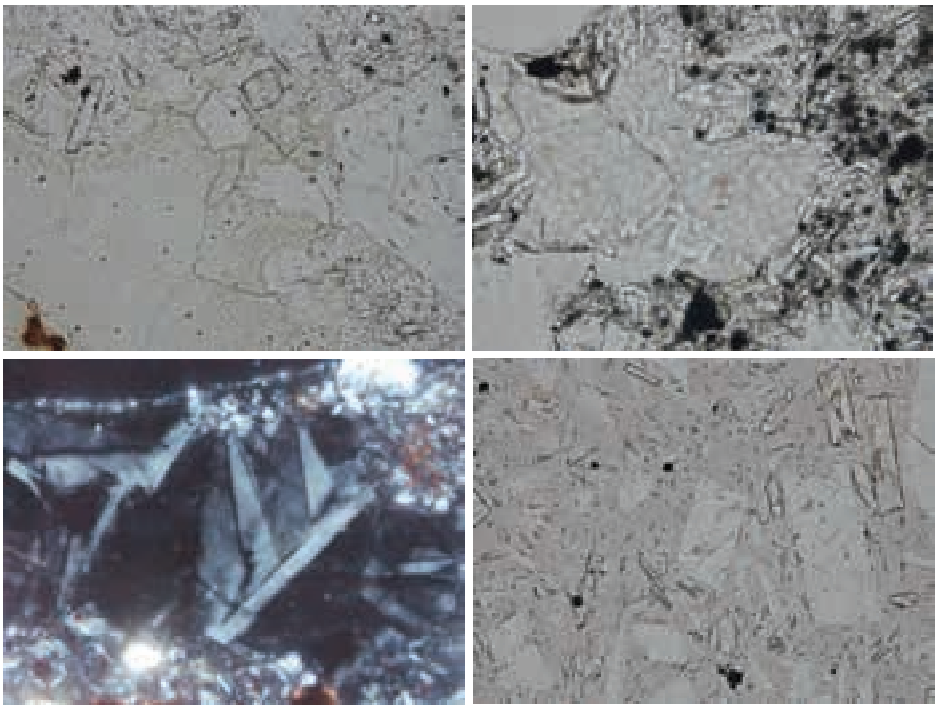


*Figure 9: Photomicrographs of reactive minerals and others in the Joganji River gravel used in this study by polarising microscope observation.*

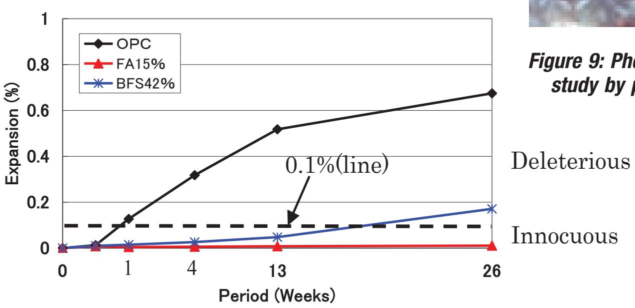



*Figure 10: Expansion behaviours of OPC,BFS 42% and FA 15% mortars in JIS A1146 test method in fog container at 40 °C.*

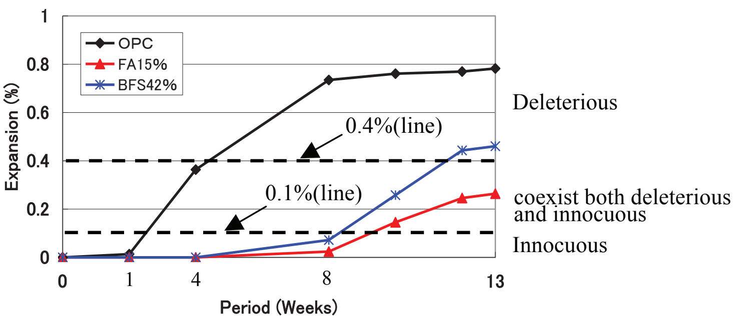



*Figure 11: Expansion behaviours of OPC, BFS42% and FA15% mortars in Danish test method immersed in saturated NaCl sol. at 50 °C.*

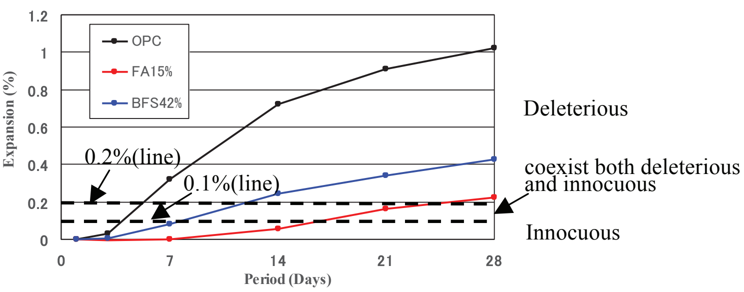



*Figure 12: Expansion behaviours of OPC, BFS42% and FA15% mortars in ASTM C1260 method immersed in 1N NaOH sol. at 80 °C.*

*Table 2: Lithology of gravel in Joganji River used in this study determined by petrographic observation.*

| Rock type | | Vol. % | Main constituents |
|---|---|---|---|
| Rock fragment | Granitic rocks | 39 | Plagioclase, Quartz, Hornblende, Biotite, Alkali feldspar, Chlorite, Epidote, Sphene, Prehnite, Opaque mineral, Pyroxene |
| | Andesite | 36 | Plagioclase, Cristobalite, Tridymite, Volcanic glass, Pryoxene, Opaque mineral, Quartz, Opal, Smectite, Biotite, Hornblende, Olivine, Apatite |
| | Basalt | 2 | Plagioclase, Pyroxene, Volcanic glass, Opaque mineral, Cristobalite |
| Mineral fragment | | 23 | Plagioclase, Quartz, Alkali feldspar, Biotite, Pyroxene, Hornblende, Chlorite |

*Table 3: Chemical compositions of OPC, FA and BFS used in this study.*

| Material | LOI | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | MnO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OPC | 2.67 | 20.10 | 5.31 | 2.97 | 64.70 | 0.82 | 2.09 | 0.21 | 0.38 | – | – | – |
| FA | 2.00 | 53.60 | 28.93 | 6.74 | 3.20 | 0.77 | 0.22 | 0.30 | 0.72 | 1.39 | 0.98 | 0.09 |
| BFS | 0.97 | 33.14 | 14.19 | 0.33 | 42.96 | 5.29 | 1.97 | 0.25 | 0.28 | 0.53 | 0.01 | 0.28 |

*Table 4: Petrographic classification observed under a polarising microscope.*

| | OPC | FA 15% | BFS 42% |
|---|---|---|---|
| JIS A 1146 | IV | I | III |
| Danish method | IV–IV | II–IV | III–IV |

Danish method: Core–Rim

[Evaluation of ASR deterioration degrees by polarising microscope proposed by Dr T. Katayama]

| Stages | The progress of ASR |
|---|---|
| I | The formation of reaction rims and exudation of ASR sol/gel around the reacted aggregate. |
| II | The formation of ASR gel-filled cracks within reacted aggregate. |
| III | The propagation of ASR gel-filled cracks from the reacted aggregate into surrounding cement paste. |
| IV | The formation of ASR gel-filled cracks network and the migration of ASR gel into air voids. |

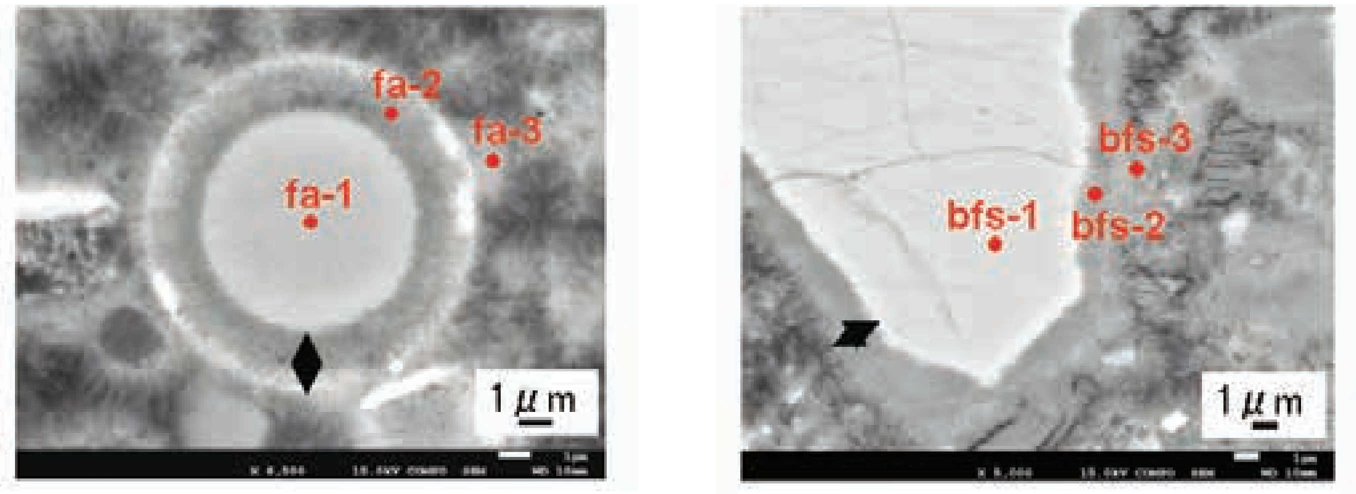
increased from 65% to 73% since the crystal phases such as quartz, mullite, magnetite and lime are reduced compared with the original raw fly ash, as presented typical sample data in table 1. This is a very successful process in the improvement in both physical and chemical properties of fly ash for concrete. Figure 7 shows the size and shape of fly ash particles. As it can be seen, this type of good-quality fly ash consists mainly of spherical and uniform particles with the average particle size of 8 µm, where those deformed, irregular-shaped particles containing many voids are not observed. Concerning the quality improvement of the fly ash, amongst other properties, the ignition loss is almost constant below 2%, the pozzolanic activity index on compressive strength of fly ash mortar with replacement of 25% by fly ash is increased to over 90% at 28 days and over 100% at 91 days aged, respectively, thus fulfilling all requirements of the quality standard of the highest level "Class I" according to JIS A6201 only excepting for the fineness of more than 5000 $cm^2/g$.

## 3.0 THE ASSESSMENT OF ALKALI SILICA ACTIVITY OF RIVER GRAVEL IN HOKURIKU DISTRICT

The river sand and gravel of Joganji River in Hokuriku district, which is considered to be the most reactive one in Japan, was assessed by chemical method (JIS A 1145) and the outcome of aggregate classification was 'deleterious', as shown in figure 8. It was mainly constituted of granitic rocks and andesite, and the reactive minerals in andesite were Cristobalite and/or Tridymite, Opal, volcanic glass, as shown in table 2. The composition ratio of 36% on andesite was roughly equivalent to the pessimum content gained by mortar tests of andesite in Joganji River. Thus, it has become clear that the most reactive river sand and gravel in Joganji river contains Opal of the most reactive minerals and andesite of the pessimum content. The photomicrograph of reactive minerals and others in the Joganji River gravel used in this study was shown in figure 9.

## 4.0 ASSESSMENT OF ALKALI SILICA REACTIVITY OF THE JOGANJI RIVER GRAVEL BY MORTAR BAR TESTS AND ASR MITIGATION BY CLASSIFIED FINE FLY ASH

Concerning the mitigating effect of classified fine fly ash on ASR, table 3 shows chemical compositions of OPC, FA and BFS, and figures 10 to 12 show the results of the accelerated mortar tests of specimens using the Joganji river gravel, which is considered to be the most reactive one in Japan. In JIS A1146 standard mortar bar test cured in a relative humidity 100% box at 40 °C for 26 weeks (specimen size : 40 × 40 × 160mm), OPC and BFS 42% mortars expanded with the curing time to a significant extent since FA 15% mortar did not expand at all. This is mainly attributable to the CSH layer with the low Ca/Si atomic ratio of 0.9 formed around fly ash particles on the process of their active pozzolanic reaction because this type of CSH can easily absorb the alkali ions in its texture, leading to the reduction of the alkali level in the pore solution to a significant extent, as shown in figure 13 (Hong & Glasser, 1999; Hirono &Torii, 2012; Hirono &Torii, 2013). Furthermore, both in the Danish test (Chatterji, 1978; Chatterji, 1979) immersed in a saturated NaCl solution at 50 °C for 13 weeks (specimen size: 40 × 40 × 160mm) and in the ASTM C1260 immersed in a 1N NaOH solution at 80 °C for 14 days (specimen size: 25 × 25 × 285 mm), the OPC mortar bars without fly ash expanded considerably, but




| | fa-1 | fa-2 | fa-3 |
|---|---|---|---|
| Ca/Si | 0.05 | 0.88 | 1.64 |

| | bfs-1 | bfs-2 | bfs-3 |
|---|---|---|---|
| Ca/Si | 1.39 | 1.47 | 1.58 |

*Figure 13: Ca/Si ratio of CSH formed around inner and outer areas of fly ash particle after JISA1146 mortar bar test (SEM-EDS, Left: FA15% mortar, Right: BFS42% mortar).*

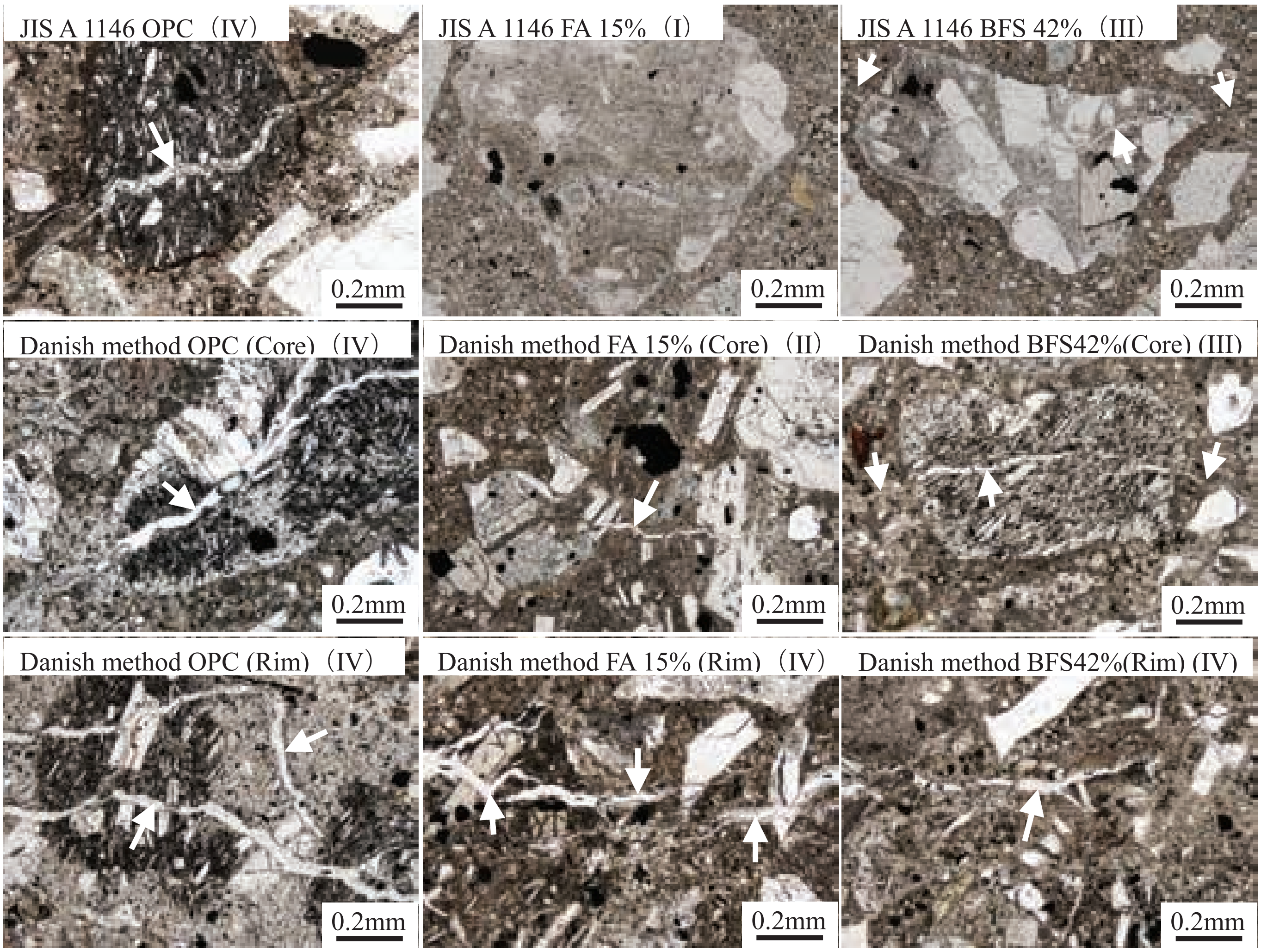



*Figure 14: Photomicrographs of the mortar texture (ASR gel-filled cracks) under plane polarised light.*

also very little in the FA15% mortar bars, it became very clear that total ASR expansion of mortars was controlled over a long term by using classified fine fly ash. On the basis of these results, the use of fly ash concrete using classified fine fly ash has been now recommended in order to solve the ASR problem in the Hokuriku district, which is in agreement with findings of Shayan et al (1996) in Australia, and Lee et al (2000) in Taiwan in a different manner.

On the other hand, in Australia, it is pointed out that the ASTM limits give uncertain reactivity for expansion at 14 days, and they should be assessed at 21 days (Shayan, 2007; 2010). However, in Japan, further research and discussion of this point are needed because reactive aggregates in Japan such as mainly volcanic rocks are different from mainly slowly reactive aggregates in Australia such as mainly metamorphic varieties of both sedimentary and igneous rocks.

After the accelerated mortar tests, we observed the thin section of mortar textures by polarising microscope under plane polarised light, and assessed the petrographic classifications of ASR deterioration stages based on the evaluation proposed by Dr. T. Katayama (Katayama et al, 2008). Table 4 shows the results of the petrographic classifications observed under a polarising microscope, and figure 14 shows photomicrographs of the mortar texture under plane polarised light. In the stage II of the petrographic classifications, it was confirmed that there were large numbers of expansion cracks in the aggregate particle.

In the stages III and IV of the petrographic classifications, it was confirmed that there were extended expansion cracks toward cement paste, and their crack width was observed corresponding to the stage of progress. Also, in the stage IV of the petrographic classifications, it was confirmed that there were extended expansion cracks far from the reactive aggregate particle in figure 14, and immediate voids were filled with ASR gel. In table 4, the stage of FA15%, BFS42% and OPC in JIS A1146 and Danish method were observed corresponding to figures 10 and 11 respectively. Thus, the mitigating effect by using classified fine fly ash became clear in addition.

## 5.0 CONCLUDING REMARKS

In this paper, it was confirmed that the mitigating effect of classified fine fly ash on ASR was clear by the results of three types of the accelerated mortar bar methods using the Joganji river gravel, which contains Opal and Cristobalite of the most reactive minerals in andesite, and FA15%, BFS 42% and OPC were more effective on ASR in good order. In the Hokuriku district, the efforts toward the production of highly durable concrete mixtures using classified fine fly ash from the Nanao-Ohta and Tsuruga coal burning power plants, has just started. At the present time, when ASR deterioration phenomena are still progressing in some areas in the Toyama and Ishikawa Prefectures after the ASR countermeasures according to JIS A5308 in 1989, the use of fly ash concrete is the most recommended in order to solve the ASR problem, based on the strong ethic.

## REFERENCES


Chatterji, S., (1978). "An accelerated method for the detection of alkali-aggregated reactivities of aggregates." *Cement and Concrete Research,* Vol. 8, pp. 647-650.

Chatterji, S., (1979). "The role of $Ca(OH)_2$ in the breakdown of Portland cement concrete due to alkali-silica reaction." *Cement and Concrete Research,* Vol. 9, pp. 185-188.

Hashimoto,T. and Torii, K., (2013). "The development of highly durable concrete using classified fine fly ash in Hokuriku district." *J. of Advanced Concrete Technology,* Vol. 11, pp. 312-321.

Hirono, S. and Torii, K., (2012). "The alkali-silica reactivity of representative andesite aggregates produced in Hokuriku district and its mitigation mechanisms by fly ashes." *Cement Science and Concrete Technology,* No. 66, pp. 249-256 (in Japanese).

Hirono, S. and Torii, K., (2013). "An assessment on mitigation effect of ASR in fly ash-bearing mortars with andesite stones by ASTM C 1260." *Journal of the Society of Materials Science,* Japan, Vol. 62, No. 8, pp. 498-503 (in Japanese).

Hong, S.Y. and Glasser, F.P., (1999). "Alkali building in cement pastes Part I. The C-S-H phase." *Cement and Concrete Research,* Vol. 29, pp. 1893-1903.

Katayama, T. et al. (2008). "Late-expansive ASR due to imported sand and local aggregates in Okinawa Island, southwestern Japan." *Proceedings of the 13th International Conference on Alkali-Aggregate Reaction in Concrete,* Trondheim, Norway, pp. 862-873.

Lee, C., Shieh.,W.K. and Lou, I.J., (2000). "Evaluation of the effectiveness of slag and fly ash in preventing expansion due to AAR in Taiwan." *Proc. of 11th Inter. Conf. on Alkali-aggregate Reaction in Concrete,* pp. 703-712.

Sannoh, C. and Torii, K., (2008). "Suppressing effect of various mineral admixtures on combined deterioration caused by ASR and chloride attack." *Proc. of 13th Inter. Conf. on Alkali-aggregate Reaction in Concrete,* pp. 1166-1175.

Shayan, A., (2007). "Field evidence for inability of ASTM C1260 limits to detect slowly reactive Australian aggregates." *Australian Journal of Civil Engineering,* Vol. 3, No. 1, pp. 13-26.

Shayan, A., (2010). "Aggregate selection for durability of concrete structures." *Construction Materials,* ICE publishing, pp. 1-11.

Shayan, A., Diggins, R. and Ivanusec, I., (1996). "Long-term effectiveness of fly ash in preventing deleterious expansion due to alkali-aggregate reaction in concrete." *Proc. of 10th Inter. Conf. on Alkali-aggregate Reaction in Concrete,* pp. 538-545.

Torii, K., (2010). "The characteristic feature of fracture of steel reinforcement in ASR-deteriorated concrete structures." *J. of Corrosion Engineering,* 59 (4), pp. 59-65.

# The effectiveness of expansion tests on slowly reactive aggregates

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*Cases of alkali-silica reaction were reported for the first time in Portugal in the 1990s, mainly associated with granitic aggregates used in large dams. A research project was developed aiming at the determination of the most effective laboratory test for the identification of the alkali reactivity of this type of aggregates. The laboratory tests followed the RILEM recommendations on Alkali-Silica Reaction, namely the petrographic method and the concrete prism tests at 38 °C and 60 °C. Accelerated mortar bar tests were also performed. The results obtained show the importance of the variability of the rocks at the quarries' scale and the need to quantify the occurrence of microcrystalline quartz. It could be confirmed that the accelerated mortar bar test is ineffective for granitic aggregates. The concrete prism test at 60 °C proved to be more effective than at 38 °C to identify a larger number of slowly reactive granitic aggregates. The results are discussed according with two different criteria.*

## 1.0 INTRODUCTION

Since alkali-aggregate reactions (AAR) were identified in 1940s in the USA, research has been developed worldwide in order to understand the mechanisms involved and, mainly, to prevent the occurrence of such deterioration mechanisms in new constructions. The most common type of AAR involves different forms of silica such as micro and cryptocrystalline quartz, opal, chalcedony, volcanic glass and is called alkali-silica reaction (ASR).

Many standards about preventive measures regarding ASR are published and used on a national/regional basis. The prevention of ASR in these standards and guidelines is based on the need to avoid the presence of at least one of the three ASR conditioning factors (alkali reactive aggregates, high content of alkalis and humidity/available water). Theoretically, the easiest measure to be taken would be to reject the use of potentially reactive aggregates.

However, this is not always possible as is the case for large constructions built in remote areas for which the aggregates available in the vicinity have to be used. The assessment of aggregates for ASR follows a methodology that involves two types of tests (e.g. CCANZ, 2003; CUR Recommendation 89, 2008; AFNOR FD P 18-464, 2014):

- Visual study by petrographic method
- Accelerated expansion tests of mortar and/or concrete specimens.

Petrography provides an indication of the likelihood of ASR to occur with a given aggregate by identifying alkali-reactive phases. It constitutes a relatively fast method with negligible costs comparing to the expenses related to diagnosis and rehabilitation of damaged structures (Blight & Alexander, 2011). The laboratory expansion tests can be carried out as assessment tests to evaluate the reactivity of aggregates when subjected to extreme conditions of alkalinity, temperature and relative humidity or as performance tests (Lindgård et al, 2012). Also, different concrete mixes can be prepared in order to study the concrete mix combination to be applied on a specific project, including the evaluation of the effect of the SCMs (e.g. silica fume, fly ash, ground granulated blastfurnace slags (ggbs), metakaolin) and lithium salts in preventing or controlling the expansion due to ASR (Folliard et al, 2007; Thomas, 2011).

In general, the most recent ASR international recommendations, as well as the Portuguese Specification LNEC E 461 (2007), define the principles to be followed in order to prevent ASR. This specification defines different levels of prevention based on the type of structure (or structural element), the risk associated with the occurrence of ASR and also the environmental conditions of exposure of the structure (Table 1).

It therefore defines three preventive levels. According to this classification, dams are in the "especial precautions level". The preventive measures pointed out by this specification are as follows:

- P1, no measures are needed.
- P2, apply one of the following measures:
  - Control the alkalinity of the concrete pore solution
  - Avoid the use of a critical content of reactive silica

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*Table 1: Selection of the level of prevention regarding the type of structure and the environmental classes of exposure.*

| Environmental class / Structure category | A1 Concrete protected from external humidity | A2 Concrete exposed to external humidity | A3 Conditions as A2 aggravated (e.g. freeze-thaw, maritime conditions) |
|---|---|---|---|
| I Low or acceptable risk | P1 | P1 | P1 |
| II Low tolerance to risk | P1 | P2 | P2 |
| III Unacceptable risk | P2* | P3 | P3 |

* For very massive structures, level P3 must be considered.

– Control the humidity and keep the concrete in a relatively dry state
– Modify the composition of the alkali-silica gel so that it is not expansive.

• P3, apply at least two of the above referred measures.

In the last four years, about 40 samples of Portuguese granitic aggregates were studied regarding potential alkali reactivity by using different test methods, as recommended in RILEM AAR-0 and in the Portuguese Specifications LNEC E 461, 2007. Some of these aggregates are being used in new large constructions such as dams. In the present work, the five most reactive samples were selected and the results of the research are presented and discussed.

## 2.0 MATERIALS AND METHODS

### 2.1 Selected aggregates

The research included five samples of granite from different areas in Portugal, corresponding to those which were classified as showing the highest potential reactivity by petrographic analysis and/or by expansion laboratory tests. In Figure 1 the main petrographic characteristics of these samples are presented (Ramos, 2013).

The features of most interest in these samples are related with the manifestations of deformation. In this context, the occurrence of stretched quartz, locally in ribbons and usually with subgraining is the main characteristic in GR-A. This is the most deformed rock of the selected group. Subgraining is also present in GR-C where sutured boundaries and bulging are quite common. In this sample, there are abundant microcracks crossing the main minerals, namely the quartz.

Samples GR-D and GR-E are characterised by the presence of microcrystalline intergrowths and inclusions of quartz. Both samples also show abundant microcracks. The most different is GR-B which is a fine grained granitic rock with very variable sizes. Microcrystalline quartz occurs in the groundmass and as inclusions. The boundaries of the crystals are locally serrated.

During the preparation of the thin sections it was realised that there was some variability in the characteristics of the rock fragments of some samples. This variability was due to the occurrence of fault zones and dykes generating strong deformation features or finer grain rocks. Several thin sections were prepared in order to adequately characterise each sample.

### 2.2 Expansion tests

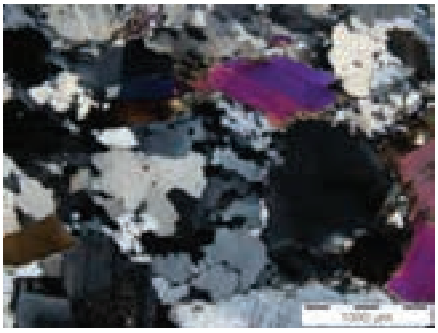
According to the Portuguese Specification LNEC E 461 (2007), the granitic rocks are classified as Class II (potentially reactive) independently of the results of the petrographic assessment. The recommended expansion tests are mainly those prepared in the scope of RILEM activities. Although, neither RILEM AAR-2 nor ASTM C1260 are recommended in Portugal for the evaluation of the alkali reactivity of granitic aggregates, these accelerated mortar bar tests were used in this work. This was due to the need of comparison between the results of mortar bar and concrete prism tests. Concrete prism tests were prepared for AAR-3 and AAR-4.1 expansion tests. The aggregate's sizes were obtained by crushing in a jaw crusher in laboratory. The sizes of the aggregate particles and the parameters of the mixtures used in the expansion laboratory tests are presented in Table 2.

#### *2.2.1 Accelerated mortar-bar test at 80 °C (ASTM C1260)*

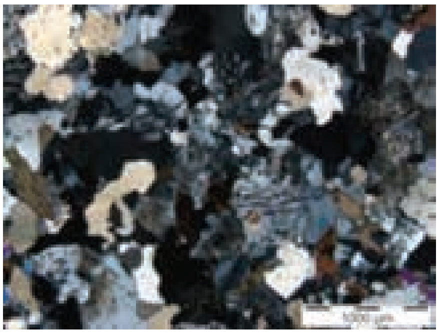
The accelerated mortar-bar test is based on the South African National Building Research Institute (NBRI) mortar-bar test (Oberholster & Davies, 1986) and it has been widely used for determining the potential alkali-silica reactivity of aggregates (Fournier et al, 2006). In this test the mortar bars are submerged in 1 N NaOH solution at 80±2 °C for 14 days during which at least three measurements are taken. After 14 days, expansions of less than 0.10% are indicative of non-reactive cement-aggregate combination; expansions over 0.20% indicate potentially deleterious behavior; expansions between 0.10% and 0.20% are considered ambiguous and additional confirmatory tests should be performed. In order to evaluate the long term performance of the aggregates and the tendency of the expansion curve with time, the tests were extended to 28 days and, further, maintained for 364 days (12 months).

#### *2.2.2 Concrete prism test at 38 °C (RILEM AAR-3)*

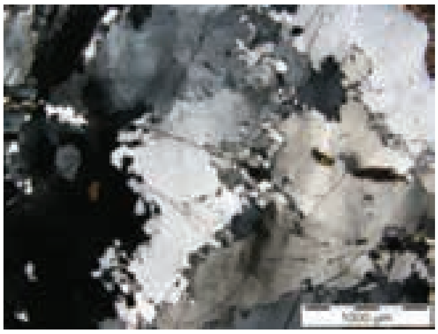
The RILEM AAR-3 concrete prism test was also used for testing the potential alkali-reactivity of the aggregate. The concrete prims were prepared with fine and coarse aggregate of the same composition and reference cement with a high alkali content of 0.89% to 1.2% $Na_2O_{eq}$. The specimens were stored in a closed plastic bag over water at 38±2 °C in containers for maintaining high relative humidity condition (HR> 95%). Measures were taken at periodic intervals, during



**GR-A** Evidence of intense deformation with preferred orientation of minerals; sutured borders and bulging of the boundaries of the crystals of quartz; subgraining.

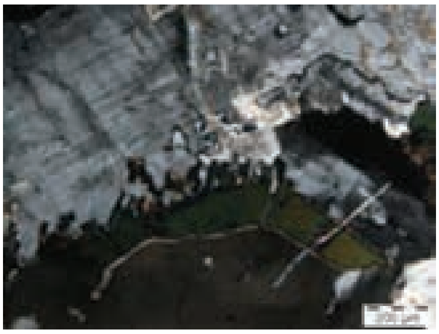


**GR-B** Fine grained granite. No evidences of deformation. Microcrystalline quartz also as inclusions and in micrographic texture.



**GR-C** Evidences of intense deformation; sutured borders and bulging; subgraining. Microcracks are abundant.

**GR-D** Quartz grains show straight, serrated or even sutured boundaries. The larger grains present deformation lamellae and frequent intra- or intercrystalline microcracks. Myrmekites are frequent.



**GR-E** Quartz occurs in variable sizes, including microcrystalline quartz (up to 35 μm) and myrmekites. Intra- and intercrystalline microcracks are frequent.

***Figure 1: Characterisation of the granitic samples by petrography. The features presented are related with deformation, the occurrence of microcrystalline quartz and microcracks.***

364 days (12 months), and then the tests were extended to 728 days (24 months) in order to evaluate the tendency curve obtained. Although the criteria for the interpretation of the results of RILEM AAR-3 have not yet been finally agreed, it was assumed that results of expansion of less than 0.05% at 12 months were likely to indicate non-expansive materials, while results exceeding 0.10% indicate expansive materials. For results in the intermediate range 0.05% to 0.10% it is still not possible to give a definitive interpretative guidance. In the absence of additional local experience, aggregates yielding in this range will need to be regarded as being potentially alkali-reactive. There is some evidence that a lower criterion at twelve months (perhaps 0.04% or even 0.03%) might be applicable for some slow reactive aggregates (Santos Silva et al, 2014).

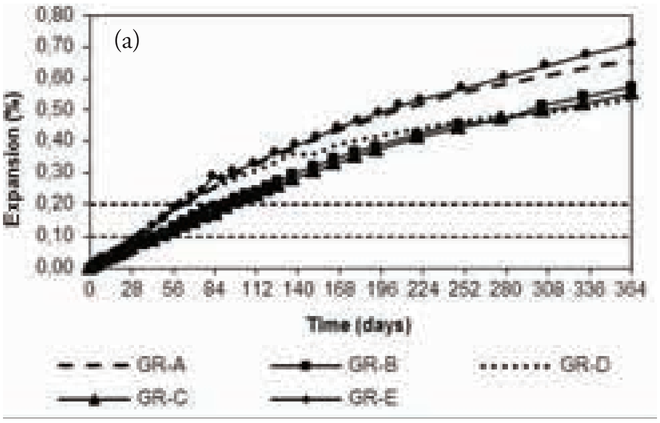
### *2.2.3 Accelerated concrete prism test at 60 °C (RILEM AAR-4.1)*

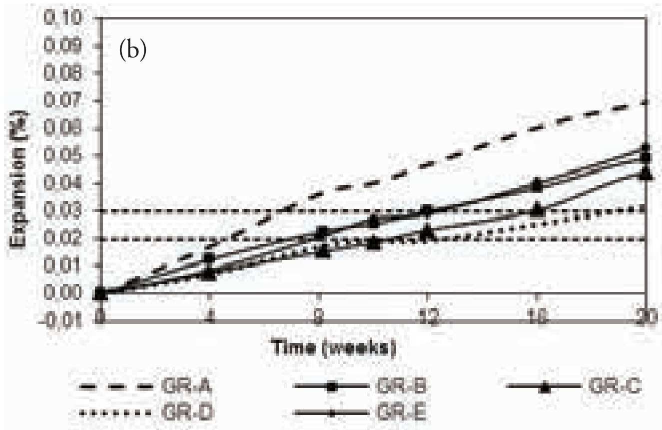
The accelerated concrete prism method at 60 °C (RILEM AAR-4.1, 2013) is an accelerated version of RILEM AAR-3 concrete prism test for evaluating the reactivity of an aggregate combination. The concrete prisms had the same dimensions as in AAR-3 and the cement composition was also the same. The prisms were sealed in containers over water which were stored in a reactor generating constant temperature of 60±2 °C and relative humidity as close as possible to 100%. Periodic measurements were made during twenty weeks.

The criteria for the interpretation of the results are still a matter of dispute. In this work two different criteria were considered:

- According to the Portuguese Specification LNEC E 461 (2007), results above 0.02% at twelve weeks are sufficient to consider the aggregate as potentially reactive to alkalis.
- According to Lindgård et al (2010) aggregates are classified as potentially reactive for results above 0.03% at 20 weeks.

Besides the expansion value in percentage, it would be expected that the expansion would have ended or the rate of expansion reduced close to the end of the test, resulting in a curve that would tend to flatten.



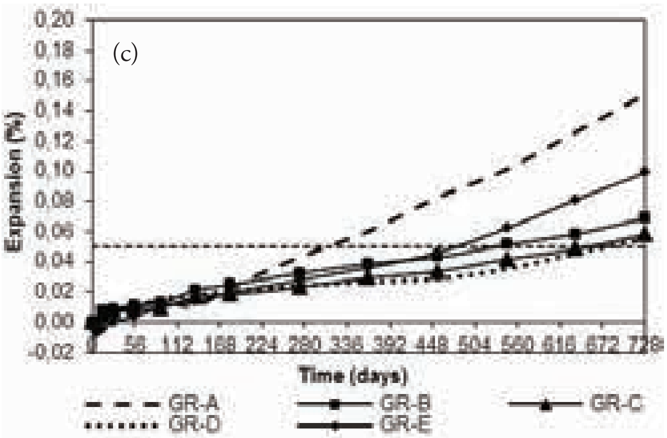




***Figure 2: Results of the expansion tests. (a) mortar bar (ASTM C 1260); (b) concrete prism test (RILEM AAR-4.1); (c) concrete prism test (RILEM AAR-3). The curves maintain a positive slope suggesting that the reaction did not stop until the end of the tests.***

## 3.0 RESULTS

The results obtained by the mortar bar expansion test are presented in Figure 2. The results of all the granitic samples in mortar bars after 14 days of test show that none of the aggregates can be considered as potentially reactive. In fact, they are far below the threshold of 0.10% expansion. The same happens for the 28th day considering the limit of 0.20%. All the aggregates show a positive slope of the trend curves which keeps the same rate until after the 84th day.

The curves which reflect the higher values of expansion at one year correspond to GR-A and GR-E with a final expansion of about 0.65 and 0.71%, respectively. The lower values of expansion are obtained for GR-B and GR-D with values of 0.57 and 0.55%, respectively. GR-C shows a different behavior as it is close to the lines of GR-A and GR-E until the 140th day after which the expansion slows-down and by the end of the test the curve tends to flatten and is even below (0.54%) the results obtained for GR-D. For the other four aggregates, the expansion slightly slows-down after the 84th day, although maintaining a constant rate. The stability is, however, never reached until the end of the test (364 days).

The results of expansion obtained for RILEM AAR-3 are below the threshold limit of 0.05 at 12 months for all the aggregates except GR-A (0.06%), which reaches the limit very close to the end of the first year of testing. This is the aggregate which curve shows an almost constant expansion rate, ending up with a value of 0.15% at 24 months. For the other aggregates the trend curves are flatter until the 280th day and then they start to show a slight positive slope.

However, it is just after the 448th day that the curves reflect an accelerated expansion and by the end of two years of testing all the aggregates show an expansion higher than 0.05% (GR-A-0.15%; GR-B-0.07%; GR-C and GR-D-0.06%; GR-E-0.10%). Stabilisation of the curves was not reached, on the contrary, the slope is stronger, suggesting that the potential for further reaction still exists. However, there are challenging exceptions between the 168th and the 448th days for the expansions of GR-C and GR-D, exhibiting flatter curves in this period. The expansion of GR-C, GR-D and GR-E accelerates after the 448th day maintaining a constant rate until the end of the tests. The only aggregate showing a constant trend throughout the test is GR-A.

In what concerns the results of the RILEM AAR-4.1 test all the curves representing the expansion of each aggregate show a positive slope, suggesting ASR progression. The two criteria of interpretation of the results (0.02% at 12 weeks or 0.03% at 20 weeks) show that all the aggregates are potentially reactive. There is no stabilisation of the curves, which indicates further potential for alkali-silica reaction.

## 4.0 DISCUSSION

One of the objectives of the research regarding ASR is to find the laboratory test method which best simulates the field performance of the aggregates. All the tests applied in the present study have advantages and drawbacks and it is common to find discrepancies between the results of the accelerated mortar-bar test and the concrete prism test (e.g. Feng & Clark, 2012). It must be taken into account that the test conditions of the accelerated mortar-bar test (AMBT) are considered very severe and not representative of those encountered by concrete in service (e.g. Bérubé et al, 1992; Grattan-Bellew, 1997; Fournier et al, 2006; Zollinger et al, 2009; Fertig & Tanner, 2012). The main advantage of the AMBT is to be quick, relatively simple to carry out and a good screening test, according to some authors (Shayan, 2007; Lindgård et al, 2010).

Results that have raised discussion were reported by Shayan (2007) with granitic aggregates and by Hooton & Rogers (1992), Shayan & Morris (2001) and Shayan (2007) for granitic gneisses. Suggestions have been made in the literature for extending the testing period and/or lowering the detection limits for the accelerated mortar-bar test (e.g. Shayan et al, 1988; Hooton & Rogers, 1992; Santos Silva & Braga Reis, 2000; Shayan & Morris, 2001; ASTM C 1260, 2007).

For Portuguese aggregates, and excluding granites, Santos Silva & Braga Reis (2000) proposed that if after 14 days the expansion was larger than 0.10% the test should be extended to 28 days and the aggregate should be considered ambiguous if the expansion was less than 0.20% after this period of time.

In Lindgård et al (2010), the test RILEM AAR-2 (similar to ASTM C 1260) is said to be effective in classifying European slow reactive aggregates. However, the slow reactive aggregates tested were quartzite, sandstone, rhyolite and mylonite which show mineralogical and textural features different from the granitic rocks used in the present study.

One of the basic differences between the mortar-bar and the concrete prisms tests is related to the size of the aggregate particles. The crushing and grinding actions to obtain the required grain size curve should not affect the characteristics of the aggregate (Lu et al, 2006a; 2006b) and therefore the characteristics of the coarse grain and the fine grain samples should be the same. The influence of the size of the particles used in the tests has been analysed e.g. by Zhang et al (1999) who state that the aggregate grading can affect the ASR expansion: when there are larger aggregates in the specimen, the expansion is smaller at early ages, but will increase continuously at later ages. Multon et al (2008; 2010) concluded that the aggregate size causing the highest ASR expansion is dependent on the nature and composition of the aggregate. Important conclusions can be found in Barisone & Restivo (2000) and Lu et al (2006a) stating that the use of very fine aggregates can destroy the original microstructure characteristic of the rocks, and thus under-estimate the alkali reactivity of the rocks in AMBT.

Fournier et al (2006) found ultimate expansion values in a concrete prism test at 60 °C (similar to RILEM AAR-4.1) considerably lower than the ones for the concrete prism test at 38 °C (similar to RILEM AAR-3). The authors justified this difference by a higher extent of alkali leaching from the concrete prisms at more elevated temperatures and changes in pore solution. Ideker et al (2010) showed their concern about the use of concrete prisms similar to RILEM AAR-4.1 since a significant reduction in expansion was observed in comparison to tests similar to RILEM AAR-3, which may lead to inaccurate predictions concerning aggregate reactivity. This fact was attributed to the influence of storage conditions on the rate extent of alkali leaching of aggregates and the contribution of alkalis of the "non-reactive" fine aggregate used for testing coarse reactive aggregates. On the contrary, Shayan et al (2008) concluded that RILEM AAR-4.1 clearly identified slow reactive aggregates as reactive in opposition to the concrete prism test at 38 °C (similar to AAR-3).

The results of the three tests performed in the present study were plotted in x-y charts considering different test periods in order to find possible correlations between the tests (Figure 3).

It can be concluded that the charts with ASTM C1260 results show large dispersion of the values and that the correlations with both AAR-3 and AAR-4.1 are very weak. The best fit line occurs for ASTM C1260 at 364 days and RILEM AAR-3 at 728 days ($r^2$=0.51). This result is not very encouraging in trying to use ASTM C1260 for this type of slow reactive aggregates. It was verified that the expansion is not yet stabilized at 364 days test, and therefore the main advantage of the tests (14 or 28 days) is not valid for granitic rocks.

The reactivity limit of 0.20% was attained after 61 days for GR-E, after 63 days for GR-A and GR-C, after 91 days for GR-B and after 98 days for GR-D (Figure 2). This conclusion suggests that the limit should probably be lowered for slow reactive rocks, assuming that a short term test such as the AMBT is accepted as effective for these rocks. The reduction of the reactivity limit to 0.08% was indicated by Shayan (2007) for slow reactive aggregates. The extension of the test until at least 90 days is also a possible solution, as already suggested by Alaejos et al (2014) for slow reactive Spanish aggregates. Santos Silva et al (2014) by analysing a larger number of samples from Portuguese aggregates suggest that the mortar bar test is extended to 100 days with the same limit of 0.20%, as this is the value with better correlation with both petrography and field concrete performance.

In case the option of extending the duration of the test is accepted, then the advantage of performing the AAR-4.1 seems to be highlighted as this test might be used also as a performance test, using the concrete mixture to be applied in the future constructions. In fact, the test AAR-4.1 is the one which works in the most conservative way by identifying a larger number of aggregates as potentially reactive. This method shows excellent correlations with the AAR-3 test both for 12 and 20 weeks. The perfect correlation ($\chi^2$=1.0) is obtained when comparing the results after 12 weeks with the results after 364 days of AAR-3. The weaker correlation occurs for 20 weeks and 728 days ($\chi^2$=0.84).

In what concerns the possible correlation between the results of each test and the petrographic characteristics of the aggregates, it could be expected that the most deformed samples (GR-A and GR-C) showed the highest values of expansion. Although this is verified for GR-A, it is not correct for GR-C, rising again the possible limitations of petrography in the identification of the features which originate ASR. In literature there are examples of the correlation between deformation features and expansion test results such as in Kerrick & Hooton (1992), Monteiro et al (2001), Wenk et al (2008) and Locati et al (2010) who tested deformed rocks and concluded there is a relationship between the aggregate microstructure and the mortar expansion. However, GR-E shows higher results of expansion than GR-C which might be explained by another factor observed under microscope: the abundant microcracks which allow the access of the pore fluids to the interior of the grains, as also suggested in Velasco-Torres et al (2010). Another parameter to be considered is the variability of texture and grain size features observed in the samples, indicating the need of collecting representative samples for testing and, as far as possible, to quantify at the scale of the quarry the volumes

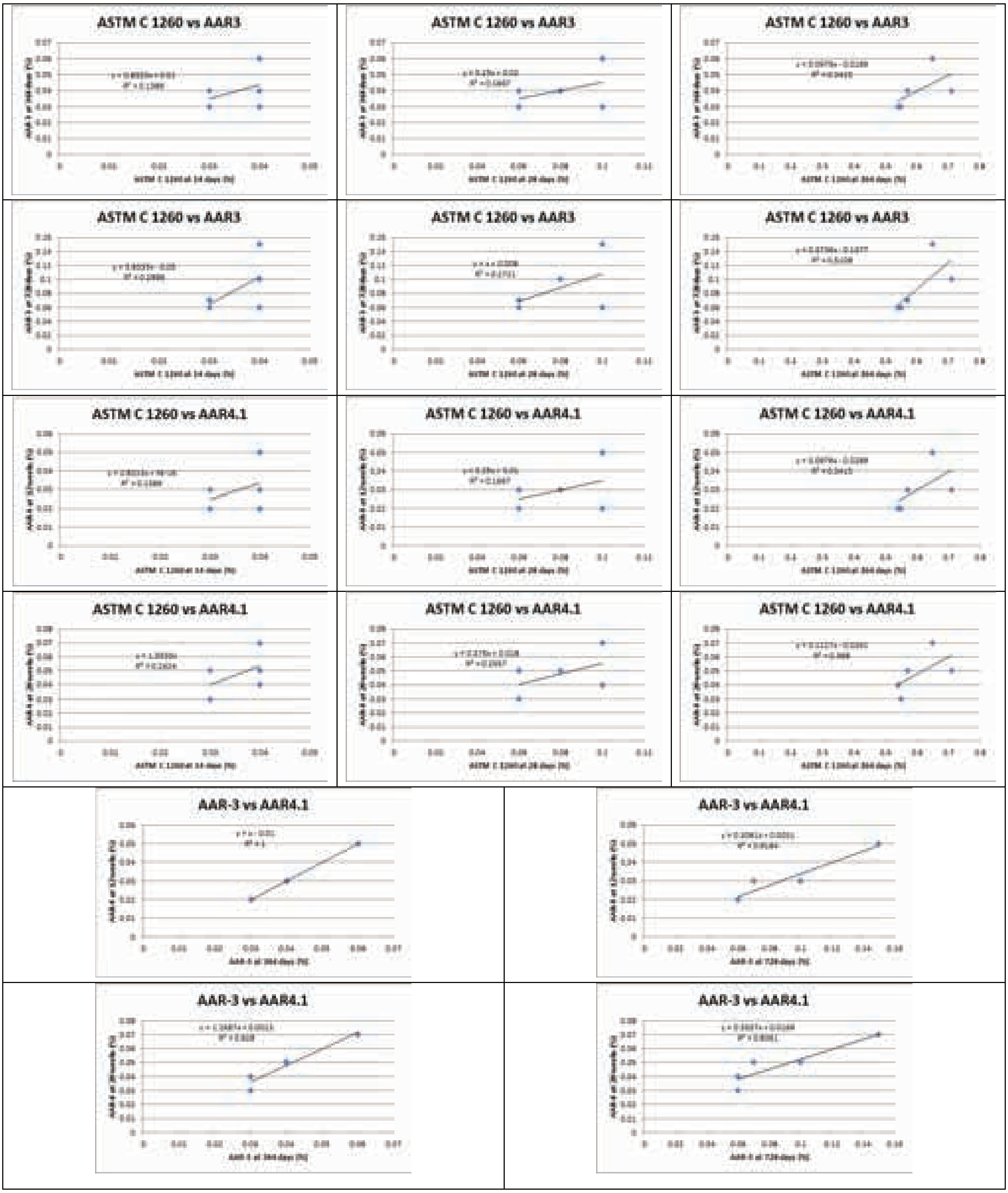



*Figure 3: The results of the different test methods were plotted in x-y charts in order to find possible correlations between each pair of tests. For ASTM C 1620 three test periods were considered: 14 days, 28 days and 364 days; for AAR-3 two test periods were considered: 364 days and 728 days; for AAR-4.1 the test periods were 12 and 20 weeks.*

of rock with different characteristics (mineralogical and/or textural).

Further clarifications have to be done regarding the reasons why ASTM C1260, regardless of being extremely severe, just reflects the potential reactivity of slow reactive rocks when extended to become a long term test.

In consequence of all the above, it can be concluded that the fractions to be used in structures should preferably also be used in the laboratory tests, which restricts the laboratory tests to the concrete prism tests. The effect of crushing in certain types of aggregates for laboratory testing has to be studied. By observing the samples under optical microscope, it can be concluded that subgraining occurs in the boundaries of the coarser grains of quartz. At what point the operations of crushing destroy this intercrystalline smaller grains is to be clarified.

## 5.0 CONCLUSIONS

The main conclusions of the present work refer to the usefulness of the available test methods in identifying the potential reactivity of slow reactive aggregates of granitic composition.

The study confirms that the AMBT should not be used to classify this type of aggregates. The expansion was found to start in the long term, nullifying the main advantage of this test as a quick method of assessment of potential reactivity of aggregates. For slow reactive rocks, the expansion should be evaluated for more than 90 days of test duration. In this context, the concrete prims test is preferable as it allows that the grain size curve of the aggregate is closer to the one to be used in the construction.

Also, different mixtures can be tested, including the use of SCMs, therefore taking advantage of the tests to be carried out as performance tests, after a first classification of the aggregate by detailed petrographic analysis. AAR-4.1 correlates very well with AAR-3 which has the great advantage of providing results in a shorter time. Anyway, a careful study has to be carried out based on the expansion curve of any test in order to understand if the expansion is stabilized or if there is potential for further expansion.

## ACKNOWLEDGEMENTS

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## REFERENCES

AFNOR FD P 18-464 (2014). Béton: Dispositions pour prévenir les phénomènes d'alcali-réaction (Concrete: Guidelines for the prevention of the alkali-aggregate reaction). Association Française de Normalisation, Paris, France (in French).

Alaejos, P., Lanza, Bermúdez, M.A., Velasco, A. (2014). Effectiveness of the accelerated mortar bar test to detect rapid reactive aggregates (including their pessimum content) and slowly reactive aggregates. *Cement and Concrete Research* (58): 13-19.

ASTM C 1260 (2007). Standard test method for potential alkali reactivity of aggregates (mortar bar method). The American Society for Testing and Materials, Philadelphia, USA: 4 pp.

Barisone, G., Restivo, G. (2000). Alkali–silica reactivity of some Italian opal and flints tested using a modified mortar bar test. In: Bérubé, M.A., Fournier, B., Durand, B. (Eds.). *Proceedings of the 11th International Conference on Alkali–Aggregate reaction in Concrete:* 239–245.

Bérubé, M.A., Fournier, B., Mongeau, P., Dupont, N., Quellet, C., Frenette, J. (1992). Effectiveness of the accelerated mortar-bar method, ASTM C-9 proposal P 214 or NBRI for assessing potential AAR in Québec (Canada). In: Poole, A.B. (Ed.). *Proceedings of the 9th International Conference on Alkali-Aggregate Reaction,* London, UK: 1842-1856.

Blight, G.E., Alexander, M.G. (2011). Alkali-aggregate reaction and structural damage to concrete. Engineering assessment, repair and management. Taylor and Francis Group, London, UK: 229 pp.

CCANZ (2003). Alkali-silica reaction. Minimizing the risk of damage to concrete. Guidance notes and recommended practice (2nd edition). Technical Report (TR3), Cement and Concrete Association of New Zealand: 84 pp.

CUR Recommendation 89 (2008). Measures to prevent concrete damage by the alkali-silica reaction. (In Dutch.) 2nd revised edition. Centre for Civil Engineering Research and Codes, Gouda, the Netherlands.

EN 197-1 (2011). Cement Part 1: Composition, specifications and conformity criteria for common cements. CEN, Brussels, Belgium.

Feng, X., Clark, B. (2012). Correlations between laboratory tests methods for potential alkali silica reactivity of aggregates. In: Drimalas, T., Ideker, J.H., Fournier, B. (Eds.). *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction,* Austin, USA: 9 pp.

Fertig, R., Tanner, J. (2012). Evaluation of ASR potential in Wyoming aggregates using multiple accelerated tests. In: Drimalas, T., Ideker, J.H., Fournier, B. (Eds.). *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction,* Austin, USA: 10 pp.

Folliard, K.J., Thomas, M.D.A., Fournier, B., Kurtis, K.E., Ideker, J.H. (2007). The use of lithium to prevent or mitigate alkali-silica reaction in concrete pavements and structures. Publication No. FHWA-HRT-06-133, Office of Infrastructure Research and Development, Federal Highway Administration, USA: 47 pp.

Fournier, B., Nkinamubanzi, P-C., Lu, D., Thomas, M.D.A., Folliard, K.J., Ideker, J.H. (2006). Evaluating potential alkali-reactivity of concrete aggregates – how reliable are the current and new test methods? *Proceedings of SIABE 06/INCOS 06 – "II Simpósio Ibero-Americano sobre Concreto Estrutural":* 1 -21.

Grattan-Bellew, P.E. (1997). A critical review of ultra-accelerated tests for alkali-silica reactivity. *Cement and Concrete Composites* (19): 403-414.

Hooton, R.D., Rogers, C.A. (1992). Development of the NBRI rapid mortar bar test leading to its use in North America. In: Poole, A.B. (Ed). *Proceedings of the 9th International Conference on Alkali-Aggregate Reaction,* London, UK: 461-467.

Ideker, J.H., East, B.L., Folliard, K.J., Thomas, M.D.A., Fournier, B. (2010). The current state of the accelerated concrete prism test. *Cement and Concrete Research* (40): 550-555.

Kerrick, D.M., Hooton, R.D. (1992). ASR of concrete aggregate quarried from a fault zone: results and petrographic interpretation of accelerated mortar bar tests, *Cement and Concrete Research* (22): 949–960.

Lindgård, J., Andiç-Çakır, O., Fernandes, I., Thomas, M.D.A., Rønning, T.F. (2012). Alkali-silica reactions (ASR): literature review on parameters influencing laboratory performance testing. *Cement and Concrete Research* (42): 223–243.

Lindgård, J., Nixon, P.J., Borchers, I., Schouenborg, B., Wigum, B.J., Haugen, M., Akesson, U. (2010). The EU "PARTNER" Project – European standard tests to prevent alkali reactions in aggregates: final results and recommendations. *Cement and Concrete Research* (40): 611-635.

LNEC E 461 (2007). Concrete. Methodologies to prevent internal expansive reactions (Betões. Metodologias para prevenir reacções expansivas internas). Laboratório Nacional de Engenharia Civil, Lisboa (in Portuguese): 6 pp.

Locati, F, Marfil, SA, Baldo, E (2010). Effect of ductile deformation of quartz-bearing rocks on the alkali-silica reaction. *Engineering Geology* (116): 117-128.

Lu, D., Fournier, B., Grattan-Bellew, P.E. (2006a). Effect of aggregate particles size on determining alkali-silica reactivity by accelerated tests. *Journal of ASTM International* (3): 11 pp.

Lu, D., Fournier, B., Grattan-Bellew, P.E. (2006b). Evaluation of accelerated test methods for determining alkali-silica reactivity of concrete aggregates. *Cement and Concrete Composites* (258): 546-554.

Monteiro, PJM, Shomglin, K, Wenk, HR, Hasparyk, NP (2001). Effect of aggregate deformation on alkali-silica reaction. *ACI Materials Journal,* Technical Paper, March-April: 179-183.

Multon, S., Cyr, M., Sellier, A., Diederich, P., Petit, L. (2010). Effects of aggregate size and alkali content on ASR expansion, *Cement and Concrete Research* 40: 508–516.

Multon, S., Cyr, M., Sellier, A., Leklou, N., Petit, L. (2008). Coupled effects of aggregate size and alkali content on ASR expansion, *Cement and Concrete Research* (38): 350–359.

Oberholster, R.E., Davies, G. (1986). An accelerated method for testing the potential alkali reactivity of siliceous aggregates. *Cement and Concrete Research* (16): 181-189.

Ramos, V. (2013). Characterization of the potential reactivity to alkalis of Portuguese aggregates for concrete. *PhD Thesis on Geology,* University of Porto: 417 pp.

RILEM AAR-0 (2014). Outline guide to the use of RILEM Methods in assessments of aggregates for AAR potential. In: 2013 Special Issue RILEM TC219-ACS. *Materials & Structures* (46): (in press).

RILEM AAR-2 (2014). Detection of potential alkali-reactivity – the accelerated mortar-bar test method for aggregates. In: Special Issue RILEM TC219-ACS. *Materials & Structures* (46): (in press).

RILEM AAR-3 (2014). Detection of potential alkali-reactivity – 38 °C method for aggregate combinations using concrete prisms. In: Special Issue RILEM TC219-ACS. *Materials & Structures* (46): (in press).

RILEM AAR-4.1 (2014). Detection of potential alkali-reactivity – 60 °C method for aggregate combinations using concrete prisms. In: Special Issue RILEM TC219-ACS. *Materials & Structures* (46): (in press).

Santos Silva, A., Braga Reis, M.O. (2000). Avaliação da reactividade aos álcalis dos agregados para betão. Encontro Nacional de Betão Estrutural, Faculdade de Engenharia da Universidade do Porto, Portugal (in Portuguese): 23-32.

Santos Silva, A., Soares, D., Fernandes, I., Custódio, J., Bettencourt Ribeiro, A. (2014). Prevenção das reações álcalis-agregado (RAA) no concreto – melhoria do monitoramento da reatividade aos álcalis de agregados. In: Véras Ribeiro, D. (Coord.). *Proceedings do 1° Encontro Luso-Brasileiro de Degradação de Estruturas em Concreto Armado (DEGRADA),* Bahia, Brasil (in Portuguese): 293-306.

Shayan, A. (2007). Field evidence for inability of ASTM C 1260 limits to detect slowly reactive Australian aggregates. *Australian Journal of Civil Engineering* (3): 13-26.

Shayan, A., Diggins, R.G., Ivanusec, I., Westgate, P.L. (1988). Accelerated testing of some Australian and overseas aggregates for alkali aggregate reactivity. *Cement and Concrete Research* (18): 843-851.

Shayan, A., Morris, H. (2001). A comparison of RTA T363 and ASTM C 1260 accelerated mortar bar test methods for detecting reactive aggregates. *Cement and Concrete Research* (31): 655-663.

Shayan, A., Xu, A., Morris, H. (2008). Comparative study of the concrete prism test (CPT 60°C, 100% RH) and other accelerated tests. In: Broekmans, M.A.T.M. and Wigum, B.J. (Eds). Proceedings of the 13th International Conference on Alkali-Aggregate Reaction, Trondheim, Norway: 391-400.

Thomas, M.D.A. (2011). The effect of supplementary cementing materials on alkali–silica reaction: a review. *Cement and Concrete Research* (41): 1224–1231.

Velasco-Torres, A., Aejos, P., Soriano, J. (2010). Comparative study of the alkali-silica reaction (ASR) in granitic aggregates. *Estudios Geologicos* (66/1): 105–114.

Wenk, H.R., Monteiro, P.J., Shomglin, K. (2008). Relationship between aggregate microstructure and mortar expansion. A case study of deformed granitic rocks from the Santa Rosa mylonite zone. *Journal of Materials Science* (43): 1278–1285.

Zhang, C., Wang, A., Tang, M., Wu, B., Zhang, N. (1999). Influence of aggregate size and aggregate size grading on ASR expansion. *Cement and Concrete Research* (29): 1393–1396.

Zollinger, D.G., Mukhopadhyay, A.K., Ghanem, H., Shon, C-S., Gress, D., Hooton, D. (2009). Mitigation of ASR in concrete pavement – combined materials testing. Report IPRF-01-G-002-03-2, Innovative Pavement Research Foundation: 117 pp.

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## 329R-14 Report on Performance-Based Requirements for Concrete

*ACI COMMITTEE 329, AMERICAN CONCRETE INSTITUTE, FARMINGTON HILLS, IL, 2014*

This report discusses the differences between performance and prescriptive requirements for concrete, and provides information on developing performance requirements as an alternative to the current prescriptive requirements in codes and specifications. Performance-based requirements allow the contractor and concrete producer to be more innovative in concrete applications, providing an element for sustainability of concrete construction. The essential elements of a performance-based requirement are reviewed, which include the desired performance characteristics, sampling and testing procedures to verify these characteristics, and acceptance criteria.

Because acceptance criteria are crucial elements of effective performance specifications, factors to consider in developing criteria that distribute risks to the owner and members of the construction team are also discussed. Considerations for implementing performance-based requirements on a project are presented and development of performance-based requirements for durability emphasised. Alternative performance based requirements are proposed for the prescriptive durability requirements in ACI 318.

## Updating Environmental Externalities Unit Values

*EVANS, C., NAUDE, C., TEH, J., MAKWASHA, T., AI, U. AUSTROADS, 2014*

This report provides updated unit costs and price indices used to estimate environmental costs in the economic evaluation of Australian road infrastructure and transport projects.

A series of calibrated environmental costs and user guidance is provided across a range of externality types such as air pollution, greenhouse gas emissions, noise, soil and water pollution, biodiversity, nature and landscape, urban effects and upstream and downstream categories. These are further disaggregated according to passenger and freight transport (road and rail) in urban and rural locations. Maximum and minimum ranges are also calculated for these externalities. Detailed user information on the application of the externality values derived is also provided.

The project used revised methodologies and data sources to derive the updated estimates. The research that informed the methodology is detailed in the report.

## Cement plant environmental handbook, 2nd edition

*TRADESHIP, SURREY, UK, 2015*

This latest edition features a selection of 45 authoritative articles from leading experts, associations and cement producers from around the world, looking at best practice in cement manufacturing technology from the perspective of the environment, energy efficiency and sustainability. The main themes covered in the handbook are:

- environmental context and sustainability challenges
- quarry operations and ecosystems
- $CO_2$ emissions and energy efficiency
- strategies and systems for using alternative fuels and raw materials
- alternative fuel case studies
- emission monitoring and abatement
- cement milling and products

Contributors to the handbook include many of the best-known experts in the field.

## AS 3600-2009 Supp 1:2014 : Concrete structures – Commentary (Supplement to AS 3600-2009)

*STANDARDS AUSTRALIA, NORTH SYDNEY, 2014*

This supplement provides background reference material to AS 3600–2009, indicates the origin of particular requirements and departures from previous practice, and explains the application of certain Clauses.

# New Members

*These companies and individuals recently became Members of the Concrete Institute.*

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Neville Babb
Rob James
Stuart Jacquet
Andrew Martin
Douglas Knox
Prachya Jomkamsing
John Donovan
Khin Soe

**INDIVIDUAL YOUNG MEMBERS**
Sushma Upreti
Todd Clarke
Ethan Thomas

# Academic Institutions

**Curtin University of Technology**
**Deakin University**
**Griffith University**
**Monash University**
**Northern Melbourne Institute of TAFE**
**Qld University of Technology**
**RMIT University**
**Swinburne University of Technology**
**University of NSW**
**University of Queensland**
**University of Sydney**
**University of South Australia**
**University of Southern Queensland**
**University of the Sunshine Coast**
**University of Technology, Sydney**

# Bronze Plus Members

**New South Wales (ACT)**
Brenntag Australia
Elvin Group
Hobson Engineering
Krystol Group
Mahaffey Associates
Rocla
Structural Concrete Industries
The Reinforced Earth Company

**Queensland**
Bornhorst & Ward
Brisbane City Council
Concrete Colour Systems
RO Bird & Associates
Sunstate Cement

**South Australia (NT)**
Cairns Industries

**Victoria**
VicRoads

**Western Australia**
Duratec Australia
Main Roads WA

**International**
Golik Concrete

# Bronze Members

**New South Wales (ACT)**
ACOR Consultants
BCRC (NSW)
Bridge Design
Concrite
DW Knox & Partners
Enstruct Group
Geoff Ninnes Fong & Partners
Henry & Hymas
Interspan
ITS Pipetech
Laing O'Rourke
Mott MacDonald Australia
Northrop Engineers
Richmond & Ross
Roads & Maritime Services
Sellick Consultants
TA Taylor (Aust)
Taylor Thomson Whitting
The Construction Store
Ultrafloor
Waeger Constructions
Woolacotts Consulting Engineers

**Queensland**
Active Minerals Australia
AECOM
ALS Industrial
Aurizon Holdings
Austrak
Building Chemical Supplies
Byrne Bros Concrete
Concrib
Construction Skills Training Centre
Cozens Regan Williams Prove
Gold Coast City Council
Intelara
J F Hull Holdings
Lesa Systems
McVeigh Consulting
Northern Consulting Engineers
Port of Brisbane Corporation
Precast Concrete (Qld)
Sedgman
Si Powders
SmartReo
Structerre WBA
Sunwater

**South Australia (NT)**
APJ Concrete
Department of Infrastructure (NT)
Inconmat Australia
Wallbridge & Gilbert

**Tasmania**
Duggans

**Victoria**
Actech International (Vic)
Adams Consulting Engineers
Baigents
Bonacci Group
CSIRO MIT
E.B. Mawsons & Son
Economix
Halcrow Group
Iccons
Intrax Consulting Engineers
Irwinconsult
O'Neill Group
Postenco
Ramset
Westkon Precast Concrete

**Western Australia**
Actech International (WA)
Airey Taylor Consulting
CCM Group Australia
Cockburn Cement
Concretus
Delta Corporation
Elite Concrete Protection & Repair
FormAction Concrete Civils
Mobile Wetbatch Global
Peritas Group
Pritchard Francis
Prompt Engineering
Reinforced Concrete Pipes Australia (WA)
RSA
Structerre Consulting Engineers
Turner Builders
Water Corporation (WA)
Whittens
Wood & Grieve Engineers

**International**
Dr Fixit – Institute of Structural Protection & Rehabilitation
Monier

**Association Members**
Amorphous Silica Association of Australia
Ash Development Association of Australia
Australasian Concrete Repair Association
Australasian (Iron & Steel) Slag Association
Concrete Pipe Association of Australasia