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CORROSION & MATERIALS

Vol 43 No 3, August 2018
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CONCRETE & CP FEATURE

Inside this Issue:

Project Profile: *Sacrificial anodes preserve HMAS AE2 (1915) in the Sea of Marmara, Turkey*

Project Profile: *Review of a Once in a Lifetime Façade Rehabilitation Project*

Tech Note: *Laser Cleaning*

Case Study: *The Significance of the Alkali Aggregate Reactivity Provisions in the VicRoads Structural Concrete Specification Section 610*

Case Study: *NZTA Experiences with the Protection and Repair of Concrete Road Bridges*

Research Paper: *Up-to-date Review of Aspects of Steel Reinforcement Corrosion in Concrete*

THE AUSTRALASIAN CORROSION ASSOCIATION INC.

MAJOR SPONSOR:

JOTUN

CORROSION & PREVENTION 2018

AUSTRALASIAN CORROSION ASSOCIATION INC.

SEMPER TUENS

11–14 NOVEMBER 2018 | ADELAIDE CONVENTION CENTRE, SOUTH AUSTRALIA

Registrations open! Go to conference.corrosion.com.au

TECHNICAL PROGRAM

For a full list of papers (based on abstracts received which have been provisionally accepted for C&P2018 by the Conference Technical Committee) please visit the Conference website.

Submitted papers will be subject to a peer review process before they can be officially accepted for C&P2018.

SPONSORSHIP AND EXHIBITION

There are limited sponsorship and exhibition opportunities left.

For further information, please contact Annalee Gielb, Event Manager at the Australasian Corrosion Association +61 3 9890 4833 or email annalee.gielb@corrosion.com.au who will assist you with your enquiry.

THE DESTINATION

Adelaide

Adelaide is an inspiring and dynamic and cultured city. Stylish and artistic it is large enough to be cosmopolitan yet compact and convenient. Renowned across Australia as the Festival City, Adelaide's appreciation of the arts goes hand in hand with excellent food and fine wines.

Situated between the beautiful Adelaide Hills and the long white beaches of the Gulf of St. Vincent, Adelaide with a population of approximately 1.2 million is a picturesque city which is tranquil, convenient and has the energy of a modern city.

Adelaide is also home to world-class meeting infrastructure and accommodation options. Just as important, it offers easy accessibility between the airport, conference facilities and the city centre, and it is a safe and stable destination for international visitors and locals alike.

The final program for C&P2018 will be available on the Conference website in September 2018.

conference.corrosion.com.au

PLENARY LECTURES

Professor Brian Kinsella
Deputy Director Applied Corrosion Research and Testing, Curtin Corrosion Engineering Industry Centre (CCEIC), Faculty of Science & Engineering | School of Chemical & Petroleum Engineering, Curtin University, Australia

Dr Laura Machuca
Lecturer, CCEIC,
Curtin University

Miles Buckhurst
Global Concept
Director
HPI Jotun, Norway

Associate Professor Geoffrey Will
Science & Engineering Faculty
Queensland University of
Technology

+ more to come

PARTNER PROGRAM

All Partner Program registrations include entry to all conference social functions (except the ACA Foundation Networking Evening). Full details, costs and registration for the Partner Program are available via the conference website. Note – Bookings will be subject to availability (limit 30).

Attendees must be 16 years old or over.
No concession prices available.

Sunday 11 November 2018

Welcome Reception & Exhibition Opening
Adelaide Convention Centre
6.30pm – 9.30pm
Cocktail function

Monday 12 November 2018

Barossa Valley Food and Wine Experience
Enjoy the Barossa Valley with a cooking demonstration at Maggie Beer's Farm Shop followed by a wine and cheese flight at Barossa Valley Cheese Company

Tuesday 13 November 2018

Jurlique Farm & Hahndorf
Experience an exclusive tour of the Jurlique Farm and gardens. Explore the historic town of Hahndorf for lunch and shopping.

ACA AWARDS DINNER

Adelaide Convention Centre
7.00pm – midnight
Three course sit down dinner

Wednesday 14 November 2018

Central Market Tour
Experience all the Adelaide Central Market has to offer, learn about the history and stories behind the stalls and taste local artisan cheeses.

FAREWELL FUNCTION

4.30pm – 6.30pm
Adelaide Convention Centre
Cocktail function

conference.corrosion.com.au

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Corrosion & Materials

Corrosion & Materials is the official publication of The Australasian Corrosion Association Inc (ACA). Published quarterly, *Corrosion & Materials* has a distribution of 2,000 to ACA members and other interested parties. Each issue features a range of news, information, articles, profiles and peer reviewed technical papers. *Corrosion & Materials* publishes original, previously unpublished papers under the categories 'Research' and 'Professional Practice'. All papers are peer reviewed by at least two anonymous referees prior to publication and qualify for inclusion in the list which an author and his or her institution can submit for the ARC 'Excellence in Research Australia' list of recognised research publications. Please refer to the Author Guidelines at www.corrosion.com.au before you submit a paper to Tracey Winn at twinn@corrosion.com.au

ACA also welcomes short articles (technical notes, practical pieces, project profiles, etc.) between 500 – 1,500 words with high resolution photos for editorial review. Please refer to the Article Guidelines at www.corrosion.com.au before you submit a short article to Tracey Winn at twinn@corrosion.com.au

The Australasian Corrosion Association Inc
The ACA is a not-for-profit, membership Association which disseminates information on corrosion and its prevention or control by providing training, seminars, conferences, publications and other activities.

Front Cover Photo: *MLC Façade Maintenance Project - Transfer of Mast Climber Work Platform via Suspended Monorail System.*

Photo: D. Lambert.

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Young Corrosion Group: Hannah Watchman	61 428 812 035

*all the above information is accurate at the time of this issue going to press.

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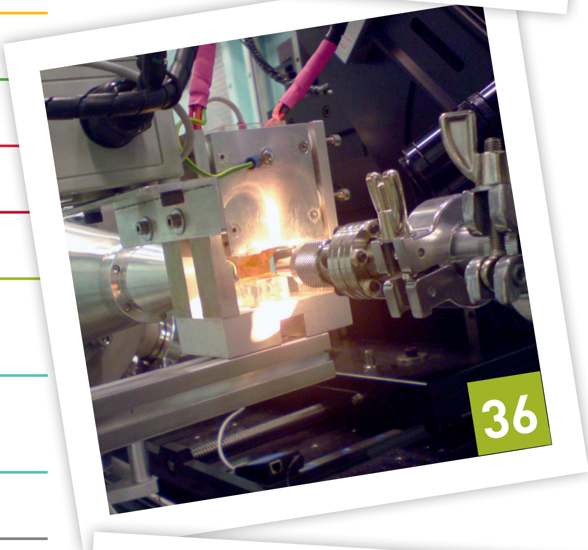
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CHAIRMAN'S MESSAGE

Dean Wall
Chairman

Warmest greetings to all members of the ACA family. This edition of C&M marks well over the half way mark of the ACA year and there is a lot to report. Our industry is busy keeping up with an increasing trend in infrastructure spend across the country as well as the mining industry showing a comeback with good signs of plant and equipment reinvestment.

The Board will have met twice since the last edition of the journal, in Adelaide and Melbourne. We've had a full complement of directors attending, ensuring robust discussion and input into the direction of the organisation. Our chief executive Richard Reilly has been in his leadership position for over four months and has settled in well.

We have had a couple of staff changes and additions to the ACA office recently which Richard has expanded upon in his message. There is continuity in the work being done, especially organisation of the Conference.

The ACA's three year strategic plan is reported on at each Board meeting – we are now over half way through the plan's life and we are quietly ticking off and undertaking the activities required to achieve the plan's strategic goals.

We are working to add value to the membership and improve the organisation's value proposition, by offering and delivering high quality, relevant training courses and running interesting membership events in conjunction with the Branches.

The Board is very conscious of the need to nurture our membership base and make it a champion of the ACA. One of the best ways to encourage non-members to become members is through the advocacy of the existing membership base.

We seek and welcome feedback from our members. The Association exists to provide benefits to the members and this is the sole focus of our staff at the ACA office.

Our training offerings are continuing to expand and we have seen an upturn in the demand for our courses, which show a strong growth over the same time last year. I was pleased to note that an additional CIP Level 1 training course was required in Melbourne; necessitated by an increased level of demand in this area.

The ACA is expanding its training delivery to international markets, and we've recently run two in-house courses in Thailand. The Philippines is on our radar, as are potential training opportunities in Vietnam. We see the international realm as a great opportunity for the ACA to strengthen its revenue base and become the go to organisation for all corrosion mitigation training throughout the south east Asia region.

With a very strong training program having been implemented in the first half of the year, I'm pleased to report that we are in a sound budgetary position year to date, and I expect continuing growth in the final six months. The Conference planning is coming along very solidly.

The ACA is still working with our Branches to consolidate retained earnings at the national level. I won't prosecute the argument again here, but the benefits accruing to the ACA and Branches of such an administrative move are substantial. The Board is expecting this matter to be finalised in the coming months.

The ACA Annual General Meeting was held in Adelaide in May. The organisation's 2017 audited financial report was presented to the membership and passed at the meeting.

Board member Di Brookman's nomination to remain on the Board was agreed at the last Board meeting and Di will now chair the Audit Risk and Finance Committee (ARFC).

The Governance Committee is in the process of recruiting a new Board member to replace Chris Badger. We were sad to see Chris leave and I thank him again publically for his two year contribution to the Board and chairing the ARFC.

The ACA Foundation Board Chairman – Warren Green, recently presented to the ACA Board the Foundation's strategic plan and new joint funding proposal for the future. The ACA Board is considering the options available to it in considering the Foundation's request, however we will be ensuring our ongoing support of this important member of the corrosion community.

This is an exciting time for our organisation. We are financially solid, our governance is strong, our events are well attended and we're trying to improve them. The November Conference will again be our signature event for the year. The state and New Zealand Branches report great engagement by their respective local memberships and are running regular, well attended, technically interesting events.

I look forward to your continued support of the ACA.

Dean Wall
Chairman

Dean Wall

ACA 2018 Events for the balance of the year

Part of the role of the ACA is to organise events that bring together industry experts to present new technologies, updates to standards, and share knowledge and experiences via case studies on a variety of projects. Here are the events planned for 2018.

August

Corrosion Management in the Water and Wastewater Industry
Tuesday 21 August | Melbourne

September

Detection and Prevention of Corrosion in the Oil and Gas Industries
Thursday 6 September | Perth

October

Corrosion in the Pipelines and Process Industries
Thursday 18 October | New Plymouth

November

NACE Joint Event – Managing Corrosion in a Marine Environment
Tuesday 20 November | Cairns

UPCOMING EVENTS

Corrosion Management in the Water and Waste Water Industry

Werribee Treatment Plant
8:30am - 4:30pm
Tuesday 21 August

Detection and Prevention of Corrosion in the Oil and Gas Industries

Novotel Perth Langley
8:30am - 5:00pm
Thursday 6 September

Corrosion in the Process and Pipeline Industries

Trade Show Component
Quality Hotel New Plymouth
8:30am - 5:00pm
Thursday 18 October

CEO'S MESSAGE

Richard Reilly
ACA Chief Executive Officer

Hello to all members, volunteers and friends of the ACA! Good to be speaking to you through our signature magazine, Corrosion and Materials. I've been with the ACA now for just over four months and have been able to meet with many of you in person, on the phone or via email.

I have travelled to a number of Branches already and was in the role in time to help organise and participate in a very well-attended Annual General Meeting that was hosted by our South Australian colleagues in May. The Annual Report was presented to the membership, who duly agreed to accept the document as a true and accurate reflection of the finances and achievements of the ACA Inc for the year ended 31 December 2017.

I want to pay tribute and thanks to Wes Fawaz, who did a tremendous job running the daily operations of the ACA for a number of years as its Executive Officer, having started with the organisation in a marketing role. I know Wes was instrumental in getting the ACA back on a sustainable path; his policy development work is a great legacy for the organisation and I wish him well for the future.

As the Chairman has stated in his message, we are building a new team to better service our membership base and to provide a service that delivers high quality, timely support. Our training and conference/events arms have been strengthened, giving us the tools to grow the organisation, provide additional training options for our membership and seek new demand for the courses we offer.

We have recently welcomed new staff and introduced new positions to the ACA, with Annalee Gielb stepping up and taking the position of Conference and Events Manager, which was vacated by the departure from the ACA by Lucy Krelle. Annalee will be assisted by recent appointee, Nicholas Ferrari, who will now be responsible for assisting our Branches in delivering their events. We also welcomed Rob Slater, our IT Contractor, to a more permanent part time position in the ACA team. Our training capacity has been further strengthened by the addition of Jak Mills, who will work part time with Skye delivering training services to our members.

Our members are the lifeblood of any industry association. We need your help to identify new potential members; we'll act on your recommendations and will contact people and companies and speak to them about the value proposition of the ACA. But you, our existing members, are our entrée to developing new relationships which might lead to new members.

The Branches play a crucial role in new member identification and I'm really pleased and pleasantly surprised at the activities the Branches undertake and how they're so very well attended. More power to you all. We're here to assist and want to continually improve our communication to the Branches and our Technical Groups.

The ACA's strategic plan is the foundation document that we as an organisation will be assessed on, by the membership and ultimately, the Board. There is more to be done and I'm working with the Board and colleagues to get some runs on the board in relation to achieving the Board's clearly delineated expectations.

Richard Reilly
ACA Chief Executive Officer

Richard Reilly

ACA Training Calendar 2018

All registrations are subject to ACA's published terms, conditions and policies

ACA/ACRA Corrosion & Protection of Concrete Structures

Member $1170 | Non-member $1465

Brisbane	September 6-7

ACA Coating Selection & Specification

Member $1640 | Non-member $1995

Sydney	September 3-5

Corrosion Technology Certificate

Member $2450 | Non-member $2870

Melbourne	October 15-19

Corrosion Technology Home Study

Member $2450 | Non-member $2870

At Home	Start anytime

Hot Dip Galvanizing Inspector Program

Member $1640 | Non-member $1995

Sydney	November 29-30

NACE Cathodic Protection CP 1 – Tester

Member $3500 | Non-member $3855

Brisbane	September 10-14

NACE Cathodic Protection CP 2 – Technician

Member $3500 | Non-member $3855

Brisbane	September 17-21

NACE Cathodic Protection CP 3 – Technologist

Member $3500 | Non-member $3855

Brisbane	September 24-29 **FULL**

NACE Coating Inspection Program Level 1

Aust. Member $3950 | Non-member $4490
Thai. Member $3105 | Non-member $3348

Brisbane	September 3-8
Sydney	September 17-22
Adelaide	October 29-November 3
Pattaya	November 19-24
Perth	December 3-8

NACE Coating Inspection Program Level 2

Aust. Member $3950 | Non-member $4490
Thai. Member $3105 | Non-member $3348

Brisbane	August 27-September 1
Adelaide	November 5-10
Pattaya	November 26-December 1

Prerequisites now apply to this course.

SSPC Concrete Coating Inspection Program

Level 1 $3150 | Level 1 and 2 $3675

Melbourne	August 27-September 1

All Australian course fees listed are GST inclusive. All NZ and Thailand course fees are exempt from GST.

To calculate the fee pre-GST, divide the fee by 1.1

IN-HOUSE TRAINING

Did you know that you can have ACA's suite of courses come to you?

The ACA can present any of its courses exclusively for an organisation; we can also tailor any course to your organisation's specific needs. Please contact the ACA's training departmen on +61 03 9890 483 or aca@corrosion.com.au

Vale Brian Wilson Cherry

Brian Cherry passed away peacefully on 27 April 2018.

He was the beloved husband of Miriam, father of James and Liz, and proud grandfather of Nicholas, Gretel and William.

In addition, Brian was many things. A gentleman, a sailor, a scholar, and one of the most significant figures in the history of Australian engineering and engineering education. Brian was a man that had the highest level of respect from all who knew him, and all that have interacted with him professionally and socially. He has inspired countless students, co-authors, practitioners, engineers, and researchers young and old.

Born in 1935 (in Leicester, UK), his intrepid spirit brought Brian to Australia, following his PhD studies at the University of Cambridge. Fascinated by research, and eager to make unique scientific contributions of his own, Brian joined Monash University five decades ago, and was one of a small number of staff to be founding faculty members of the Department of Materials Engineering. In his career, Brian held various positions, rising from a junior academic to become Professor; including many senior secondments and roles in his long career. He was the inaugural Associate Dean of Research and was also instrumental in the establishment of (post-)graduate degrees at Monash. At some point, Brian paused to become a member of the ACA in 1969, and as they say, the rest is history.

In addition to many passions in life and responsibilities that accompanied his academic life, Brian was committed to what he called 'rust busting' – a phrase he used often, and perhaps the most (and only) semblance of slang he ever used. Every student that studies corrosion in Australia, does so based on what we have learnt from Brian. As was resonated at Brian's funeral - with recollection of his involvement in the protection of significant national assets - there is no person in Australia that has not benefitted from the work of Brian. This is because Brian was very practical in his fight against corrosion. He realised that corrosion was an enemy worth fighting, and he took the fight on by educating students, researchers and industry (and the general public at any chance). A committed member of the ACA, Brian would volunteer his time to contribute and participate without hesitation. Brian's legacy includes a stream of undergraduate students trained in corrosion, in addition to countless postgraduate students. These students have permeated industry, nationally and internationally, filling positions at large companies (utilities, mining, oil & gas), consultancies (big and small), one-person companies, and everything in between. His students have also gone on to become academics around the world, spreading the 'rust busting' message far and wide.

Brian is an institution and epitomises what many aspire to. He was rigorous, confident, and funny (when he needed to be). I take this opportunity to share a couple of stories that reflect the sort of man that Brian was, many such stories being shared upon the news of Brian's passing.

"I always remember as an undergraduate Brian turning up to a lecture an hour early, as did one of my mates. Brian lectured to him and him alone for the next hour, asking him all the questions Brian tended to. Then when the rest of us turned up at the right time, Brian just started all over again". Such a story typifies that in what was always a busy career, students, transfer of knowledge, and training, came first.

In a professional context related to Brian's tenure as Associate Dean of Research; "Waiting to see him was like sitting outside the headmaster's office. He was: precise, analytical, always on point. He made quick decisions and had the wisdom to treat situations on their merits, understanding that we had to move with the times, even be ahead of the times". Undoubtedly, considered decisions and a pursuit of excellence were the hallmarks of Brian.

Brian was an inspiration to many, not just for his professional achievements, but also for his courageous battle against illness. For the past two decades, Brian's poise and determination in times of poor health served as his hallmark. He was always smiling, eager to participate, and maintained the continuity of character that only Brian could.

There is no doubt that Brian would want all of us to celebrate his life well-lived, perhaps with a glass or two of red wine, but also to keep smiling and to fighting the enemy – rust! For those in Brian's beloved Melbourne, you will always be able to remember him whenever you look at the spire of the Arts Centre, for we are assured it will not corrode!

By Nick Birbilis

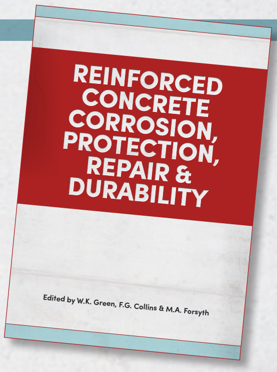
Here is the Forward penned by Nick Birbilus last year for The Brian Cherry International Concrete Symposium organised by the ACA, 26-27 July 2017.

I feel extremely honoured to have the privilege to contribute a foreword for this occasion. Brian is a man that has the highest level of respect from all who know him, and all that have interacted with him professionally and socially. He has inspired countless students, co-authors, practitioners, engineers, and researchers young and old.

We are fortunate that the forces of nature brought Brian to Australia (originally born in Leicester, UK). Brian holds a PhD from the University of Cambridge, UK. Importantly (for all of us) he joined Monash University five decades ago, and was one of a small number of staff to be founding faculty members of the Department of Materials Engineering at Monash University. Since then, Brian held various positions, ending with Professor, and now Honorary Professor Emeritus. At Monash, Brian was appointed to many senior roles including Associate Dean of Research and being instrumental in the establishment of (post)graduate degrees at Monash. At some point, Brian paused to become a member of the ACA in 1969, and as they say, the rest is history.

I am tempted to use this opportunity to detail Brian's many achievements, however no single foreword can do the man justice. Brian is an institution and epitomises what many aspire to. He is rigorous, confident, funny (when he needs to be), and he is never far away from the important things in life such as his beautiful wife, or discussions regarding his children, or an excellent wine recommendation. He has an insightful originality that is very rare, and a sense of clarity that is even more rare. These are Brian's traits, and the reason why we are discussing such traits, is because he decided to use those traits to benefit the Australasian Corrosion Association, and anyone interested in corrosion (more generally) in this country.

I was personally fortunate to be one of Brian's final PhD students, and was able to work with Brian first hand. I am however not the final student of Brian's in spirit, as every student that studies corrosion at Monash, or that pursues a higher degree by research at Monash, does so based on what we have learnt from Brian. There is no person in Australia that has not benefitted from the work of Brian. I want to clarify that statement. I mean, there is no person in Australia that has not benefitted from the work of Brian. This is because Brian was very practical in his fight against corrosion. He realised that corrosion was an enemy worth fighting, and he took the fight on by educating students, researchers and industry (and the general public at any chance). The program that Brian bears the legacy for at Monash has led to a steady stream of undergraduate (materials engineering) students trained in corrosion, in addition postgraduate students. These students have permeated industry, nationally, in some years at a rate of ~20 per year (certainly in recent years). Yes, I am still talking about corrosion. Such graduates (aka 'rust busters' as Brian liked to call them) have filled positions at large companies (utilities, mining, oil & gas), consultancies (big and small), one-person companies, and everything in between. Indeed, next time you drive through a tunnel in Melbourne, over a critical bridge, or admire the height of a local skyscraper, there is not more than one degree of separation to Brian Cherry.



Brian has had a distinguished career in the service of corrosion, and a few snapshots include: Vice-Chairman, the Corrosion Prevention Centre 1988 – 2005, Australian Councillor on the International Corrosion Council 1986 – 2007 (that is not a typo, it was >20 years), ACA P.F. Thompson memorial lecture 1987, Corrosion Medallist 1995, ACA Life Member 2008. He is also one of my personal heroes, and I wish him the very best on this momentous event of a symposium in one of his (many) pet topics.

Friends, colleagues, students, collaborators and indeed, members of the ACA, have been privileged to be beneficiaries of the passion, inspiration, hard work, loyalty, dedication, generosity and education from Brian Cherry. His place in Australian history is cemented (pun intended!).

Thank you, Brian and Miriam.

Professor Nick Birbilis,
Head, Materials Science and Engineering, Monash University. 2017.

May he rest in peace for one thing is so sure, that he made a most remarkable contribution to Australian society and to the world of corrosion and you, as his descendants, will live the memory each day.

Ian MacLeod

My deepest sympathy regarding Prof. Brian Cherry. He was a great leader in both the corrosion and materials science communities and an inspiration to future generations far and wide (farther than one might know). I am very glad to have had the opportunity to hear him speak at conferences and meet him in person.

With deepest sympathy to the Cherry family,

John R. Scully

Vale - Michael (Mike) Dennett

It is with great sadness that the Galvanizers Association of Australia (GAA) report the passing of Michael Dennett on 7 May 2018.

Mike graduated in metallurgical engineering from RMIT in the early 1960's, was a Life Member of the GAA. He commenced with Australian Zinc Development Association (AZDA) in 1964 and over the intervening 31 years was involved with providing technical information and advice on zinc coatings, predominantly hot dip galvanizing to the construction industry throughout Australia, New Zealand, SE Asia, and the USA.

Mike was Chairman of Standards Association of Australia committee on galvanized coatings and was instrumental in the production of the very first Australian Standard (AS 1650) on this subject in 1974. During his working life he was a member of the Australasian Corrosion Association and had many dealings with Ed Potter in their joint promotion of corrosion protection.

Mike was at the very first GAA Board meeting in 1965. He was the GAA Secretary from 1968 until 1994. Together with Colin Bain, Mike judged the Sorel Award from 2007 until 2016.

Photo Caption: Mike Dennett on the far left of the very first GAA Board Meeting, 23 March 1965. Original members of the GAA included famous Australian businesses such as Ajax GKN, Australian Wire Industries, Hills Hoists, Hydro-Electric Commission of Tasmania, John Lysaght, Malleys, Rheem and Stewarts & Lloyds.

Vale - Nasa Chaabani

Nasa Chaabani passed away suddenly over the Queen's Birthday long weekend.

A true gentleman and regular attendee and exhibitor at the ACA's Trades Shows and Corrosion & Prevention conferences, Nasa represented Canusa CPS as its Australian Manager and was passionate about the pipeline industry and the people in it.

His good humour and presence will be missed especially by his colleagues at Canusa CPS.

The ACA community pass on our sincere condolences to Nasa's family and friends.

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International recognition for corrosion research contribution

Mention corrosion and you might think of rusty corrugated iron roofs or rusting car bodies in a scrapyard. Failure of gas pipelines caused by localised corrosion can be catastrophic and it is an issue Deakin's Mike Yongjun Tan (http://www.deakin.edu.au/about-deakin/people/mike-yongjun-tan), Professor of Applied Electrochemistry and Corrosion in the School of Engineering and Institute of Frontier Materials, has spent much of his career researching. rusting car bodies in a scrapyard. But corrosion is also an issue in less obvious places such as the tens of thousands of kilometres of pipelines beneath our cities, towns, oceans and countryside carrying the resources we depend on such as oil and gas.

'Believe it or not,' Mike says, 'under each square kilometre of our major cities is more than 30 kilometres of buried pipes, creating tangled networks of oil and gas lines, water mains and electrical and telecommunications cables.'

Mike has over 25 years of research, teaching and industry engagement experience in the field of applied electrochemistry and corrosion technologies. In April, he received international recognition from global professional organisation for the corrosion control industry NACE International (https://www.nace.org/home.aspx), when he was awarded the honour of NACE Fellow (https://www.nace.org/Membership/Awards/Fellow-Honor/), at the CORROSION 2018 conference (http://www.materialsperformance.com/news/2018/04/corrosion-2018-continues-momentum-initiated-73-years-ago) in Phoenix, Arizona.

The honour of NACE Fellow is given 'in recognition of distinguished contributions in the field of corrosion and its prevention'. Specifically, Mike's fellowship recognises his work developing a technology which can detect localised corrosion which can occur on pipelines.

In technical terms: for the development of an electrochemically integrated multielectrode array, namely the wire beam electrode method and its applications for localised corrosion and inhibitor studies.

Mike has a US patent on this work and has also authored a book on the topic: Heterogeneous Electrode Processes and Localized Corrosion.

Mike says being made a NACE Fellow was rewarding because of the recognition from his peers, the recognition on the world stage for the Deakin Corrosion Research Centre (http://www.deakin.edu.au/ifm/research-strengths/corrosion-and-protection) and also because it makes his family happy. His work contributing to people's safety is also something he values.

'For my career if we are able to make this really practical for use worldwide, I am satisfied… to make something useful and make people safe, that is really rewarding,' Mike says.

And there is also an economic benefit to successfully managing localised corrosion in pipelines.

'A pipeline can be quite expensive; if you have 500 kilometres of pipeline to construct it can cost you a billion dollars,' Mike explains. 'So if we are able to monitor the safety and health of the pipeline, and can extend the pipeline life by 10 years, 20 years, 30 years, that's a huge economic benefit.'

As well as accepting his fellowship honour, Mike gave three talks at the conference before travelling to Ohio to visit two world leading corrosion research centres: one led by Professor Gerald Frankel at Ohio State University and the other led by Professor Srdjan Nesic at Ohio University.

It has been a busy time for Mike – he also has a key role in Deakin's involvement in the recently announced Future Fuels CRC (http://www.deakin.edu.au/about-deakin/media-releases/articles/future-fuels-crc-to-underpin-nations-transition-to-cleanerenergy).

By Vanessa Barber, Communication Officer, Faculty of Science, Engineering and Built Environment

Jeffrey L. Didas, present NACE International President, Professor Mike Tan, Samir Degan, past NACE International President

Cake have moved

Cake Commercial Services moved into their newly renovated Auckland head office in April and they couldn't be happier.

With four times more space than before, you can now find them at 7 Burns Street, Grey Lynn (just behind McDonalds) or give them a call on 0800 376 650.

7-11 October

fib 2018

Melbourne, Australia

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CONCRETE INSTITUTE of AUSTRALIA | *fib* CEB-FIP

Congress Dates
7-11 October 2018

Registration Now Open

The 5th International Federation of Structural Concrete *(fib)* Congress is coming to Australia in 2018.

The Congress, focusing on the theme **"Better - Smarter - Stronger",** is dedicated to bringing together leaders and practitioners in the concrete industry from all over the world.

The multidisciplinary theme of the Congress provides an excellent forum to share knowledge, and to learn about advances in the concrete world. With over 580 abstracts submitted from over 50 countries and across 25 themes, there is something for everybody!

Features include:

- 4 day technical program with over 350 presentations
- 5 excellent key note speakers from around the globe
- Exhibitors of concrete products & services from all over the world
- *fib* Awards for Outstanding Concrete Structures Gala Dinner
- Opportunities to connect with world leading concrete practitioners

A Conference of this type is a once in a life time opportunity for the Australian concrete industry to show the world what we can do in our own backyard. Head to our website to secure your registration and find out more.

Professor Stephen Foster
Congress Chair

www.fibcongress2018.com

NSW AGM

On Thursday 22nd March 2018, the NSW Branch held their annual AGM Dinner and Mini Trade Show.

As part of the 2018 AGM, our Branch President Alan Bird and Branch Treasurer Grahame Vile presented reports outlining the past years activities and this years proposed schedule, which includes a number of Branch and ACA Head Office run events. The President's & Treasurer's reports were accepted unanimously. No office bearer elections were required this year with all committee members available to continue in 2018. One new committee member nomination was received from Michael Barone. Michael's nomination was also accepted unanimously and we welcome Michael to our committee.

The 2018 AGM minutes are available from ACA Head Office.

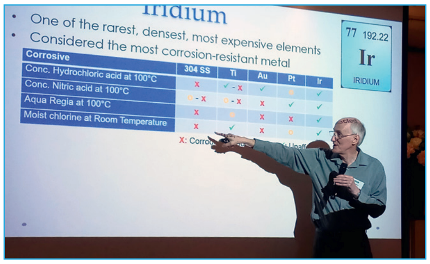
We also had the pleasure of Dr. Rob Francis attending the event as a guest speaker. Rob is well known in the corrosion mitigation industry and is a stalwart of the ACA.

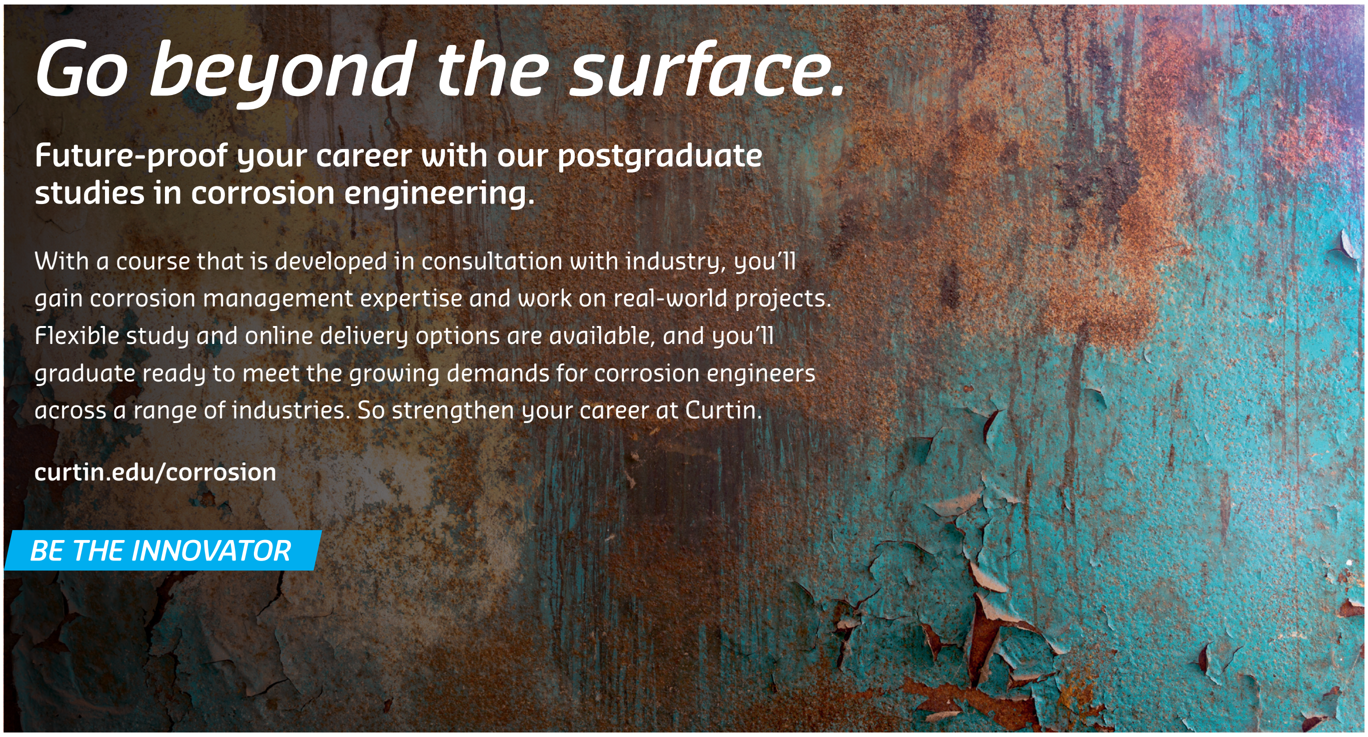
Rob's topic "The Seven Great Non Corroding Wonders of the World" was a real highlight of the evening and provided a fabulous insight into why a number of aged structures around the world should have corroded but hadn't. We thank Rob for both his time and effort in preparing and presenting such a high quality presentation.

Four of the ACA's corporate members Parchem, Russell Fraser Sales, Omniflex and Tox free exhibited at the event and we thank our corporate members for their continued support of the ACA, including branch events.

The event was well attended by over 40 members and guests and from all reports a good time was had by all.

Alan Bird





Queensland ACA Branch hosts Monica Chauviere

Wednesday May 23, Norman Hotel

The Queensland ACA Branch was priviledged to host Monica Chauviere from Monicorr, all the way from USA. Monica has considerable experience in Corrosion Under Insulation (CUI), having spent 25 + years at the Baytown refinery in Houston Texas managing corrosion on their 7000 miles of pipe. Monica's talk introduced the attendees to the background on why insulation is used, such as plant process efficiencies. However there are unintended consequences, such as corrosion on the surface, corrosion inside the pipe and heat losses, all costing money.

For instance insulation with 4% weight of water can cause up to 70% loss of insulation performance. The presentation took the group through the history of insulation and the various characteristics of the materials, such as mineral wool, calcium silicate, fibreglass, which can act as absorbant "cotton balls." As installations progressed a "cadillac option" arose, enclosing the insulation in metal jacketing, such as stainless steel. However, this had the negative effect of trapping in moisture, further exacerbating corrosion mechanisms within the system. It is also important to understand the chemistry of boiling water and silicates that can cause weak acids and erosion inducing particles.

Monica presented a few case studies and contrasted two, many years apart, where the same mistakes were made, the latter being inexcusable considering how CUI technology and understanding has advanced dramatically in recent years. Monica's presentation gave many in the audience an appreciation that the combination of insulation and coatings are a symbiotic engineered system and not a commodity!

Many questions were raised afterwards, keeping Monica busy for some time after her talk."

Wayne Thompson

VIC Branch – Coopers Inn for Failures Analysis Night

On Wednesday 9 May at the Coopers Inn the Victorian Branch was treated to a night of networking, dinner and failure analysis. Bruce Hinton took us through a fascinating failure analysis of corrosion problems associated with Military Aircraft. We were treated to some quick-fire presentations from Sarah Furman, Darren Cram, Graham Sussex, Scott Wade, Greg Moore and Dean Ferguson. The audience was put to the test to guess what happened to failed assets with only their wits and a few photos, including a pipe that had been struck by lightning.

Jess Lyndon

Lean Thinking – Do you really have a choice?

The world is changing rapidly – keeping your way of doing business stable and not changing leaves you behind the field – you have to focus on constant change through Continuous Improvement (Lean Thinking) to keep up.

Plans you made last year are already out of date, technology you are using today will be obsolete in 2 years, competition is snapping at your heels far quicker than 5 years ago... what can you do to keep ahead?

18 year old children these days think that pens are where you keep chickens. They submit their homework on line to the cloud through sharepoint and use surface pros to do their exams. These young people will be embedded in the work force in 3 years. They will be running businesses in 5 years.

The worrying thing is that your business will be employing and competing against businesses that employ them – and you will probably be still here!

What you do today to deliver your goods and services to your clients will not be good enough next year never mind in 5 years.

You need to build a culture that embraces change, that constantly seeks out ways to improve the current way of doing things. A team that thinks that improving the way you do things is why they are at work in the first place is what you need. Constantly looking to the customer to see what can be done to improve the service you provide, tying that customer to you for the long term due to complete satisfaction and surprise at the levels of flexibility, agility and performance you constantly provide.

Lean Thinking, originating in the Toyota Production System and now being applied by CLS in multiple sectors such as healthcare, manufacturing, food, defence provision, logistics, retail and even banking, delivers a culture of continuous improvement to your business.
Can you afford to not be determined to improve?

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ACA's Annual General Meeting

The South Australian Branch hosted the ACA's AGM on Thursday 24 May

The ACA met its constitutional obligation to hold an annual general meeting (AGM) within five months of the completion of its financial year when it held its AGM in Adelaide on 24 May 2018. The SA Branch generously hosted the meeting.

The meeting achieved a quorum and was chaired by ACA Board Chairman, Dean Wall.

We were honoured to have present and Dean welcomed ACA life member Greg Moore and speaker Warren Green, along with ACA Council President Huw Dent, SA Branch President Sam O'Neill, all ACA members and ACA staff.

Dean reported to the meeting the activities and achievements of the ACA for the year to 31 December 2017. He presented and took questions on the 2017 ACA Annual Report, which contained the organisation's audited financial statements. These statements were acknowledged and noted and the Annual Report was duly passed by the meeting. The 2018 auditors were appointed, general business was conducted and the Chair thanked his Board colleagues and all the ACA volunteers for all their assistance and support during the year.

The meeting concluded with the Chair especially acknowledging and thanking ACA Board member, Chris Badger, who was stepping down from the Board after a two year contribution, including chairing the Audit Risk and Finance Committee.

The AGM was followed by a substantial Branch technical event with an international speaker Monica Chauviere and our very own Warren Green.

Monica Chauviere from Monicorr Inc, Texas, USA presented 'The History of Protective Coatings and Insulation

What We Didn't Know, How That Hurt Us, & Why the Future is Brighter'

Monica presented a brief history of protective coatings, insulation materials and practices that caused the phenomenon of Corrosion Under Insulation (CUI). She discussed a timeline showing how events overlapped each other and impacted the propensity for CUI and she looked at the characteristics of thermal insulation which carry the largest responsibility for CUI. Recent developments in insulation materials technology to mitigate the causal factors were discussed along with some common misconceptions regarding CUI, such as debunking common myths and the range of gadgets hitting the market – that are likely not the answer.

(Monica also presented at a number of other ACA Branch Events in Newcastle, Auckland and New Plymouth in May)

Warren Green fron Vinsi Partners presented 'Overview of Aspects of Steel Reinforcement Corrosion in Concrete'

Given the recent passing of Professor Brian Cherry, Warren took the opportunity to undertake an overview of some aspects of steel reinforcement corrosion in concrete. Reinforced concrete its deterioration, repair and protection was a specialisation of Brian's.

Professor Cherry was always a firm believer in first understanding the fundamentals of any aspect of corrosion science, then the mechanisms, before embarking on the engineering of solutions to the management of materials corrosion. Warren went through some of the fundamental and mechanistic aspects of 'steel reinforcement corrosion in concrete'.

Richard Reilly

Tasmania 2018 Trade Show

Hotel Grand Chancellor Hobart
Wednesday 30 May

Jotun - Robert and Dean.

AkzoNobel - John and Grant.

Toxfree - Karlo.

Hychem - Colin.

Duratec Australia - Dymock and Paul..

Industrial Galvanizers - Aaron and Ivan.

Carson - John.

Phillro - Paul and Gary.

McElligotts - Rory and Ivan.

Wattyl - Vic and colleague.

PPG - Dragon and colleague.

ACA Auckland Division May Meeting Report

Surrey Hotel Auckland,
Wednesday 30 May

The meeting was addressed by international Speaker Monica Chauviere, Monicorr Inc, Coatings, Insulation & Fireproofing Consultants, based in Arkansas, USA. Monica was assisted by Maurizio Calzolari, Global Marketing Director for C&C Supply Inc. The Auckland presentation was part of an ACA road show by Monica and Maurizio throughout Australasia. Following a networking session in the hotel lounge, Monica gave her talk to the gathering of ACA members, SCANZ members and guests. Her presentation was entitled "The history of protective coatings & insulation – what we didn't know, how that hurt us, why the future looks brighter.

Monica commenced with an outline of the history of insulation practices and protective coatings used on industrial steel vessels and piping which caused a serious corrosion issue called Corrosion Under Insulation (CUI). The CUI problem is very serious in global Oil and Gas (O&G) industries. Insulation for thermal conservation on O&G plant is a most important need and it is very expensive to fix when CUI occurs.

Monica stated that CUI is such a serious risk to plant integrity that it has spawned its own R&D industry and advances in special protective coatings for plant. For four decades a solution to CUI problems has been to use a water-repellent insulation called expanded perlite, which is molded into rigid shapes for industrial plant insulation. After outlining a number of industrial case studies involving CUI Monica showed a timeline for the past 60 years. The timeline illustrated how insulation developments overlapped each other and they impacted on the propensity for CUI to occur in O&G plant and equipment.

However, a major advancement about a decade ago was the introduction of a water-repellent, blanket-style insulation product that was flexible, strong and re-usable. The product is known as an 'aerogel blanket'; a flexible aerogel-impregnated hydrophobic blanket (HFB) for installation on steel pipework and vessels. Monica described the advantages and benefits of this major plant insulation advancement which was a paradigm shift in the O&G industry.

Monica then outlined some common misconceptions and myths about CUI and she debunked the use of 'CUI gadgets' that had hit the market and which were not likely the answer to mitigating CUI.

After a Q&A session Chaired by Les Boulton, during which Monica displayed her sound knowledge of many CUI issues, Ash Arya, Auckland Committee Member, moved a well-earned vote of thanks to Monica and Maurizio for the excellent presentation. Networking amongst the speaker and attendees continued for quite some time after the formal meeting had closed.

Les Boulton

Monica Chauviere and Maurizio Calzolari at the ACA meeting

Liz Boulton, Hanieh Ghominejad & Monica Chauviere.

Monica (left) talking with attendees before the meeting.

Monica Chauviere giving her presentation at the ACA meeting.

Two guests at the ACA meeting including a very cool cat.

PRACTICAL CONSIDERATIONS & SOLUTIONS FOR THE MANAGEMENT OF REINFORCED CONCRETE STRUCTURES

SPONSOR: AkzoNobel

PROUDLY PRESENTED BY: AUSTRALASIAN CORROSION ASSOCIATION INC.

FRIDAY 25 MAY | 8.30 – 5.00PM | STAMFORD PLAZA BRISBANE

The day long event was excellently chaired by Dave Charters of DCL Consulting, who introduced each speaker and conducted a lively final discussion session. The speakers included the following:

Gavin Chadbourne of Port of Brisbane provided an outline of the Port of Brisbane's extensive facilities and their ongoing new construction program. New wharf works were aimed at increasing durability by lifting the level of the structures and incorporating corrosion inhibitors in the original concrete mix and through improvements in the concrete mix designs. Impressed current CP is extensively used throughout the port, mostly using remote monitoring and control systems.

Torill Pape of AECOM provided several investigation case studies. The Sorell causeway in Tasmania illustrated conflicting results between chloride, half cell potential, carbonation and extent of damage to the prestressed beams. The Hornibrook bridge found very low levels of corrosion at an advanced age despite the high chloride level of over 1% at the steel depth. Torill summarized that there is no silver bullet in terms of concrete corrosion diagnosis and the need to look at the big picture risk to the structure.

Mike Rutherford of Conspectus highlighted the common problems and bad processes that plague many concrete repair projects including many poor workmanship issues.

Ian Godson of Infracorr outlined all the common forms of electrochemical treatment of concrete including Impressed Current CP, Galvanic CP, Hybrid, Chloride Extraction and Realkalization, explaining the advantages and disadvantages of each system for various types of projects.

Ian Godson

Dave Charters of DCL Consulting.

Dave Charters of DCL Consulting & Torill Pape of AECOM.

Rueben Reeves of Sika.

Ian Donoghue of Freyssinet.

CORROSION UNDER INSULATION PREVENTION AND MITIGATION

SPONSORED BY: AkzoNobel PROUDLY PRESENTED BY: AUSTRALASIAN CORROSION ASSOCIATION INC.

3 Workshops: **Perth** – 19 & 20 June | **Sydney** – 25 & 26 June | **New Plymouth** – 28 & 29 June

The ACA was really pleased to host Peter Bock, international CUI specialist and consultant from Houston, to present a series of three workshops for the ACA in June, in Perth, Sydney and New Plymouth.

The two day program was well patronised, with over 50 attendees across the three events.

Our WA colleagues in particular, were very supportive of the event and came in large numbers. While not as large as the event in WA, both Sydney and New Plymouth saw a very solid list of ACA members participating in the program.

Member feedback from those who participated in the events was very positive, with a number of attendees specifically referencing the relevance and applicability of the technical nature of Peter's presentation.

The ACA is very keen to continue to offer our events' program to the membership next year.

We want our events to be well attended, relevant and worth participating in. We value all member feedback and want to deliver the best events we can.

If you have any suggestions on event speakers or topics, please contact the ACA and we'll liaise with the relevant technical group about how to accommodate these ideas and suggestions.

Thanks to AkzoNobel and SN Integrity for their kind sponsorship of these workshops and to all the delegates who attended.

The ACA would like to thank Peter for the success of these events and for making the trip to the Antipodes.

We wish him well and look forward to future masterclasses.

Richard Reilly

Captivated Crowds.

Peter Bock.

DESIGNING FOR DURABILITY IN THE BUILT ENVIRONMENT

THURSDAY 5 JULY | 8.30 - 5PM | QUALITY HOTEL PARNELL

ACA Chairman Dean Wall opened the seminar to 70 engineers, consultants and exhibitors in Auckland when he outlined staff and organisational changes at ACA Centre and introduced new CEO Richard Reilly. Richard's stated focus is on attracting more members and helping Ross Boucher (who also attended) to further develop ACA's training arm.

MC for the day Stewart Hobbs of ProConsult used the leaky buildings issue as an example of ongoing problems of poor design, crack control, thermal disparities and slow remediation as issues the wider industry still needs to come to terms with in regards to durability. It's suspected that too many architects and engineers don't necessarily understand the issues they are required to sign off on via Producer Statements to show compliance with the NZ Building Code's B2 (Durability) clause.

Raed El Sarraf of WSP Opus had developed this seminar and his was the first presentation. He'd prepared a White Paper outlining the NZ Building Code's B2 Clause and summarised issues and possible solutions around it.

In its efforts to ensure safe, healthy and durable structures, the NZBC sets minimum performance standards for all components. Local authorities further require Producer Statements from "approved experts" (predominantly engineers and architects) to guarantee every material's performance in the situation presented.

Clause B1 of the NZBC deals with the design of structures themselves, and in this area experts agree compliance is working well. However Clause B2 has limitations that can lead to misunderstandings on how to achieve and demonstrate durability compliance. This creates problems for architects and engineers attempting to confidently sign off and peer review Producer Statements.

Functional requirements and performance expectations are stated clearly, but no reference to the relevant metal/s or protective coatings relating to durability are explained, and nor are Acceptable Solutions defined. Consequently, Verification Method processes are open to interpretation by local authorities, who are then confused by engineers' reluctance to approve durability compliance without caveats.

"There is no guidance on how an organisation and/or practitioner can become qualified to undertake steelwork and other metals' durability design," Mr El Sarraf said. He proposed that appropriate accreditations and qualifications be developed in conjunction with Engineering NZ, perhaps leading to Chartered Professional Durability Practitioner certification.

It would be expected that such a qualification would require at least five years' field experience following tertiary achievement before a participant could demonstrate competency, much like current CPEng requirements in other engineering fields.

Subsequent speakers expanded on this issue, including an architect, representatives of industry organisations, coatings suppliers and applicators, and a BRANZ materials scientist.

Case studies highlighted examples of durability problems due to poor design, specification, installation and application.

The audience included a number of consulting engineers and all were interested in discussions held during both the seminar and networking opportunities presented during tea breaks and lunch.

Corrie Cook

Representing sponsors Carboline, Grant Moran and Abbie Clark chat with Willie Mandeno (at left).

Attendees at the seminar were consistently interested in the presentations.

Left-right MC for the day Stewart Hobbs of Proconsult, Ross Boucher and Richard Reilly of ACA.

NEW PRODUCT SHOWCASE

The ACA does not officially endorse any of the products advertised in *Corrosion & Materials.*

Australia Manufacturing Cast-in-Place Pipe Epoxy

The growing populations and economies of the Asia-Pacific region place more and more constraints on the maintenance and operation of urban infrastructure.

In particular it is becoming increasingly difficult to efficiently manage the many thousands of kilometres of pipelines that are buried beneath cities and towns. The continual expansion of urban environments makes accessing these pipes difficult when repairs are necessary. Maintaining the structural integrity of pipelines—both the coatings and linings—is essential for safety of the asset and the surrounding environment.

Large ruptures of pipes requires the damaged sections to be dug up and replaced. However, according to Peter Morgan, Managing Director of Rhino Linings Australia (RLA) there are now methods available to repair breeches that can be carried out without the expense of disrupting roads, railways and other public or private property.

Cast-in-Place Pipe (CIPP) involves relining a damaged pipe with an epoxy resin. A mesh sleeve—like a large tube sock—is soaked in the resin and then pulled through a length of pipe. The sleeve is inflated with air or steam to conform to the contours of the pipe and allowed to cure, forming a new, smooth inner surface.

Morgan stated that the CIPP method was increasingly being used by councils and utility companies throughout the region to repair water and sewer pipes. “CIPP is ideal for both the structural and lateral water pipes in our cities,” he added.

The resin and hardener system provided by Rhino Linings for use in pipe rehabilitation is designed to have a life span of a minimum of 50 years. This life span is dependent on using the system in accordance with Rhino Linings Product Data Sheet and following the methods of the relevant Standards.

The Gold Coast-based company has been manufacturing CIPP resins for several years, but many companies involved in the relining industry still buy the material overseas and have to contend with the many supply delays and disruptions.

All products RLA manufactures in Australia are regularly tested to ensure continued compliance with appropriate Australian Standards and international guidelines. “A large part of the CIPP market is in water and wastewater so we made sure that the material we supply to our customers meets the highest standards,” Morgan stated.

For further information, please visit the web site:
www.rhinolinings.com.au
or contact: Michelle Gunn
Telephone: +61 (07) 5585 7000
E-Mail: info@rhinolinings.com.au

3D stereo measurement during critical component inspection

Jet aircraft, racing cars and other high-performance machines are expensive to operate and maintain. As a consequence, asset owners expect the engineers and technicians tasked with maintaining their machines to minimise the time spent repairing and maintaining them.

To check the condition of aircraft engine turbines or the inner workings of a sports car usually means dismantling the components. According to Sean Fogarty, Senior Sales Specialist at Olympus, the ability to see inside an engine or other confined space without having to take it apart can save both time and money. “Regularly inspecting the inside of an aircraft engine means that it only has to be opened up when a flaw or defect is observed.”

Remote visual inspection (RVI) is one of many NDT technologies manufactured and supported by Olympus. A videoscope is an inspection instrument that consists of a small camera mounted on a length of cable. The camera can be controlled remotely by an operator while it is inserted in the cavity to be inspected. Modern videoscopes incorporate light sources into the tip of the probe as well as motors to move the LED and lens assembly.

Fogarty said his company had been at the forefront of advances in RVI design and production for decades. Olympus videoscopes can be used to carry out inspections without causing damage to the delicate parts of equipment.

“The iPLEX NX is the latest videoscope to be released by Olympus in Australia and incorporates high quality optics with bright illumination aids. The optics have been combined with an intricate but robust mechanical network allowing fine articulation to improve usability,” he said.

RVI of materials, components and structures allows engineers and technicians to inspect internal surfaces and other features of an engine, motor or machinery. Aircraft maintenance engineers regularly use them to inspect the inside of engines to ensure optimal performance.

“A constraint of videoscopes has been the challenge of getting the best optical and lighting components small enough to fit in the 'business end' of the videoscope's probe,” said Fogarty

The iPLEX NX is equipped with sophisticated 3D stereo measurement capability over a much larger area. This functionality saves time and increases efficiency, especially when inspecting larger defects in aerospace components.

For further information, please visit: www.olympus.com.au

Plantweb Insight application for wireless pressure gauges

Emerson announces a new Plantweb Insight application for wireless pressure gauges that displays data in an easy-to-understand dashboard for maintenance leads and instrumentation and electrical (I&E) personnel. An entire suite of Plantweb Insight applications collectively helps users quickly make sense of plant data and drive overall enterprise profitability.

This Industrial Internet of Things (IIoT) application delivers field data from a fleet of wireless pressure gauges as frequently as once per minute. By keeping operators updated on changing conditions remotely, the app allows personnel to make fewer manual rounds and minimize their exposure to hazardous areas.

The gauge itself, the industry’s first WirelessHART® pressure gauge, utilizes industry-proven Rosemount pressure sensor technology to deliver reliable pressure readings. It provides up to 150x overpressure protection compared to traditional gauges using bourdon tube technology, and two layers of process isolation for a safer field environment. The gauge, which has a 10-year life, also reduces maintenance costs by eliminating common weak points found in mechanical gauges.

The new application is the latest addition to Emerson’s Plantweb™ digital ecosystem, a scalable portfolio of technologies, software, and services that take advantage of IIoT innovations to extend the benefits of automation beyond process control to the entire enterprise, improving operations, strengthening decision-making, and institutionalizing best-practices.

Easily integrated with a variety of WirelessHART gauges and remote field sensors, Plantweb Insight applications combine continuous, real-time data provided by Emerson’s Pervasive Sensing™ strategies with predictive analytics to give maintenance and operations personnel actionable, up-to-date process information in any location, improving reliability, safety, production, and energy management.

Learn more at www.Emerson.com/Plantweb-Insight

Emerson Smart Meter Verification Software

Emerson has launched the latest version of its Smart Meter Verification software for Coriolis and magnetic flow meters, providing flow meter verification on demand and empowering process engineers, technicians and operators to look beyond the meter and make real-time decisions based on the most advanced meter and process diagnostics in the industry today.

New tools in the Smart Meter Verification software allow users to fine tune and adjust their engineering processes to ensure absolute measurement confidence and top performance in the chemicals, food and beverage, life sciences, oil and gas, and other process industries. In addition to onboard diagnostics, Smart Meter Verification also accelerates implementation of companies' Industrial Internet of Things (IIoT) strategies with its powerful remote diagnostics, digital intelligence and multiple data points providing users with a complete process overview and greater operational certainty.

Rather than costly and time-consuming calibrations and laboratory testing, leading to production interruptions, shut-downs and safety concerns, the advanced Smart Meter Verification provides in situ calibration verification on-demand without any impact on process or meter outputs. The new system also provides operators with crucial information on other flow issues across the plant.

“Whereas traditional diagnostics often provide just an entry point to further, time-consuming analysis, the Smart Meter Verification system generates real-time, decision-making intelligence and flow measurement confidence here and now,” said Taylor Scott, software product specialist, Emerson Automation Solutions. “For plant operators and engineers, this move from reactive to predictive diagnostics means improved knowledge, operational certainty and productivity, and the acceleration of IIoT strategies."

Key features of the advanced Smart Meter Verification include:

- Innovative algorithms that detect coating, corrosion and erosion in the meter with remedial action able to be instigated immediately. Emerson is also the first company to integrate a 99 percent-confidence statistical meter damage detection algorithm that enables early detection without false alarms.
- New process diagnostic capabilities that include a “flow range” diagnostic, which alerts the engineer when flow rates are not within the specified range of the meter; instrument diagnostics that can identify if entrained gas is in the process; and immediate alerts to process upsets that may affect measurement performance, such as severe aeration.
- Tube coating diagnostics that offer crucial data points and drive valuable information to the end user, alerting them when the meter is coated by something unexpected from the process line, particularly important in food and beverages and life sciences applications.
- Clear and transparent verification audit trails, and advanced visual analysis and reporting software that meets third party regulatory agency compliance requirements in lieu of meter calibration, inspection or removal. By providing a time-stamped verification report, an increasing number of third-parties, such as the U.S. Food and Drug Administration and the U.S. Environmental Protection Agency, recognize verification technologies, such as Smart Meter Verification, as a method to confirm instrument calibration and extend recalibration or proving intervals.
- Reduced meter maintenance requirements with vital variables, such as mass flow, verified to be within factory accuracy specifications. Smart Meter Verification also generates detailed information on all sensors, including serial numbers, condition temperature and calibration information, ensuring a simple path to instrument and process compliance.

Emerson's Smart Meter Verification diagnostics are an easy-to-use, automatic tool for Micro Motion™ Coriolis and Rosemount™ magnetic flow meters that monitor the entire flow meter's performance and integrity and are applicable in a wide variety of process industry sectors, such as oil and gas, food and beverage and chemicals.

Olympus launches new portable, powerful videoscope

Olympus is pleased to announce the launch of the IPLEX G Lite industrial videoscope featuring powerful imaging capabilities and a small, rugged body. Lightweight and able to go almost anywhere, the IPLEX G Lite videoscope provides users working in challenging environments with a remote visual inspection tool that has the image quality and ease of use to get the job done.

The IPLEX G Lite is the successor to the compact and lightweight IPLEX UltraLite model, and can be used to capture images inside aircraft engines, piping, and other equipment without the need for disassembly. With two times the brightness of its predecessor, the IPLEX G is also suitable for a variety of applications within the security industry and clean energy sector, including wind turbines.

According to Jack Zhang, RVI Product General Manager at Olympus Asia Pacific, “Recent years have seen an increasing emphasis on safety management and quality assurance in fields such as aerospace, security and architecture. This has been accompanied by the use of industrial videoscopes for equipment inspections as these instruments can be used to conduct inspections without the need for disassembly.”

The IPLEX G Lite is small and lightweight making it easy to use with one hand, while also featuring enhanced image processing. The tip of the videoscope is fitted with a very small camera and can be freely manipulated, making these instruments ideal for tasks such as periodic maintenance or inspecting a component’s quality.

Ease of use has been improved in the IPLEX G with the adoption of a touch panel monitor and electrically operated scope tip bending, enabling users to complete inspections more quickly. New recording and playback functions have also been added; including constant video recording and the ability to add bookmarks to save time during video reviews and find critical moments quickly.

When inspecting in oily environments, getting oil on the scope’s lens can make it difficult to see. To address this, the IPLEX G Lite is equipped with a new oil clearing tip adaptor that uses capillary action to draw oil away from the lens. The grooves on the oil clearing tip adapter drain unnecessary oil quickly and image keeps clean and visible, preventing your inspection being suspended.

“The IPLEX G Lite also has an option that allows users to switch the light source from LED to infrared (IR) or ultraviolet (UV) illumination. IR is a very important feature, particularly for the security industry, capturing images in the dark while UV is used to detect fine scratches that are hard to see with the naked eye,” explained Zhang.

Along with these performance features, the IPLEX G videoscope is designed to meet IP65 standards and U.S Military Defense testing (MIL-STD) to support its use for accurate and efficient inspection work, even under harsh conditions.

For further information, please visit: https://www.olympus-ims.com/en/rvi-products/iplex-g-lite/#!

NEWS FROM THE ACA FOUNDATION

ACA FOUNDATION STRATEGIC PLAN 2018–2021

Our Charter

Advancing corrosion mitigation through education.

Our Mission

Our mission is to sponsor the education of participants in the corrosion workforce and to stimulate interest and knowledge about corrosion science and engineering within schools and the wider community.

Our Values

- ✔ The Foundation embraces the values of the ACA.
- ✔ We will act with integrity;
- ✔ Demonstrate tolerance and respect;
- ✔ Strive to be informative, relevant and innovative;
- ✔ Act in a spirit of co-operation and collaboration; and
- ✔ Work conscientiously to achieve our goals.

Our Aims

To improve community understanding of the impact, treatment and prevention of corrosion.

To engage teachers and students in corrosion science education.

To attract and support new corrosion industry participants.

To continue as a valuable partner of the ACA in supporting the corrosion industry.

To contribute to ACA growth by providing education and development opportunities for members.

Four Strategic Focus Areas
2018–2021

FINANCES

Diversify funding and develop donor base

SCHOLARSHIP & EDUCATION PROGRAM

Provide a focussed scholarship and education program with future planned expansion

ADVOCACY & COMMUNICATION

Demonstrate the value of the Foundation to the corrosion industry, community and ACA membership

GOVERNANCE

Review Governance documents to ensure relevance & a sound functioning framework

Focus Area
FINANCES

Diversify funding and develop donor base

Strategic Goal No. 1

ACAF has a strong financial base to enable delivery of its key programs and to ensure organisational longevity

Objectives

- ✔ To increase income from donations & sponsorships
- ✔ To revitalise the historical donor base
- ✔ To attract new corporate and individual donors
- ✔ To attract Project Sponsors
- ✔ To reconnect with previous Centurions & recruit a new generation of Centurions
- ✔ To investigate new sources of funding

Focus Area
ADVOCACY & COMMUNICATION

Demonstrate the value of the Foundation to the corrosion industry, community and ACA membership

Strategic Goal No. 2

The role & value of the ACAF is clearly understood by ACA membership and the wider community

Objectives

- ✔ To attract and support future corrosion industry participants through educational programs and community engagement
- ✔ To educate the ACA membership regarding the role of the ACAF
- ✔ To add value to the industries served by ACA members
- ✔ To form partnerships with educational institutions & organisations to promote the study of corrosion science & engineering
- ✔ To add value to the work of the ACA

Focus Area
SCHOLARSHIP & EDUCATION PROGRAM

Provide a focussed scholarship and education program with future planned expansion

Strategic Goal No. 3

ACAF supports & attracts current & future corrosion industry participants through its Scholarship & Education Program

Objectives

- ✔ To provide training & professional development opportunities to those in the early stages of their careers in the corrosion industry
- ✔ To provide access to these opportunities for those who may not be able to participate without ACAF assistance
- ✔ To encourage participation in future training & professional development
- ✔ To encourage secondary school students to pursue STEM studies
- ✔ To improve understanding of corrosion in community and domestic settings

Focus Area
GOVERNANCE

Review Governance documents to ensure relevance & a sound functioning framework

Strategic Goal No. 4

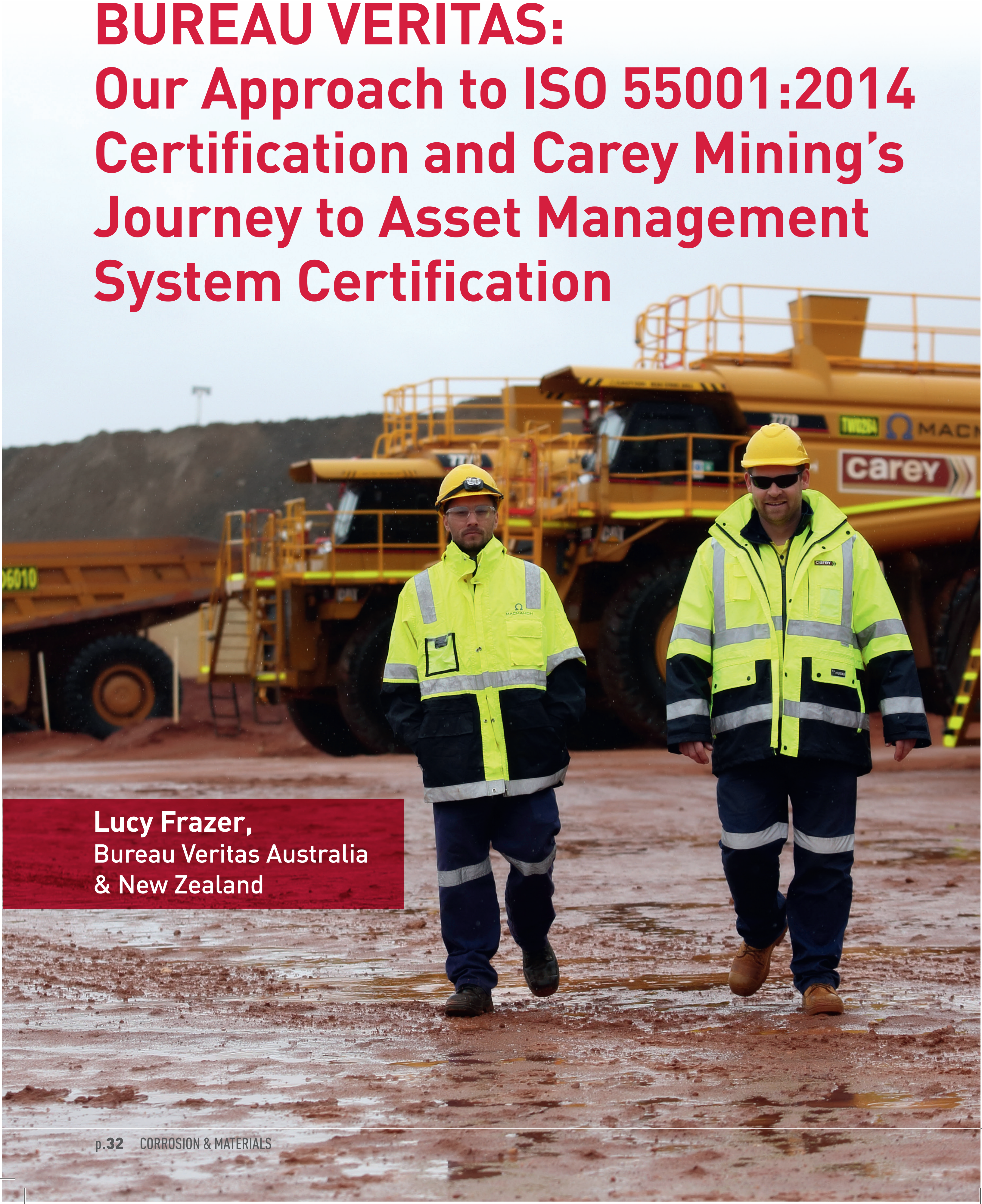
ACAF meets its legal & ethical obligations to ensure a sound functioning framework

Objectives

- ✔ To ensure that a sound reputation for good governance is maintained within the ACA and the wider community
- ✔ To maintain Board competence
- ✔ To facilitate Board renewal

BUREAU VERITAS:
Our Approach to ISO 55001:2014 Certification and Carey Mining's Journey to Asset Management System Certification

Lucy Frazer,
Bureau Veritas Australia
& New Zealand



Background

Bureau Veritas gained accreditation by the Joint Accreditation System of Australia and New Zealand (JAS-ANZ) to certify organisations against the ISO 55001:2014 Standard and issue JAS-ANZ accredited certificates in May 2017. Since then Bureau Veritas has worked with multiple organisations as part of their compliance journey, including Carey Mining Pty Ltd.

What does it mean for a Certification Body to be accredited by JAS-ANZ for ISO 55001 certification?

Being accredited by JAS-ANZ means Bureau Veritas, as a Certification Body, has been independently assessed that our capabilities, policies, procedures and systems are all in place when certifying organisations against the requirements of ISO 55001:2014. This process of accreditation assures Bureau Veritas' "impartiality, competence and consistency"[1].

The JAS-ANZ approach to ISO 55001 certification requires the Certification Body to ensure that the audit team can demonstrate a high level of asset management system knowledge, understanding and working experience. This is in line with the Competency Specifications (2014) set by the Global Forum on Maintenance and Asset Management (GFMAM) – background prerequisites include qualifications with in-depth knowledge across disciplines of asset management plus general business experience of at least 5 years[2]. Furthermore, this level exceeds the requirements of ISO/IEC 17021-5 to provide value add for the organisation seeking certification.

The ISO 55001 certification process

An overview of the certification cycle can be seen in the image below.

In line with JAS-ANZ requirements and our internal procedures for ISO 55001:2014 certification, there are two important elements, which as a combination, facilitate a value-added certification process – our auditor competence and the planning phase.

Right at the onset of Bureau Veritas' engagement with a prospective ISO 55001 certification client, we must work to understand the asset portfolio. Bureau Veritas utilises a number of channels to capture important information relating to the asset type, industry, size and complexity. Initially, we ask for the Application Form to be completed and returned along with the organisation's Strategy Asset Management Plan (SAMP). This provides key insights into the nature of the assets and the complexity of the system which will then be considered in order to determine audit specifics i.e. the audit team selection, the audit duration and sampling approach.

Auditor Competence

Asset Management System auditors go through a stringent qualification process and are highly competent with extensive industry experience. As per GFMAM requirements audit teams will have at least one member who has the Certified Asset Management Assessor (CAMA) qualification with asset experience in the same industry sector as the organisation being assessed. The audit team shall have the necessary competence to cover the asset management audit scope and may include experts to provide input where necessary.

Planning Phase

Once the audit team has been selected, the audit will be scheduled in consultation with the client's representative to ensure that it considers the client's scope of activities, associated asset portfolio, and operational environment. This planning phase of the audit will help to identify and ascertain focus on critical business issues of the organisation. It is important for the client to make the audit team aware of any significant changes to the SAMP.

Quality Approach

To ensure high quality and consistency technical experts for Asset Management Systems are engaged throughout the certification process in the following activities: Contract Reviews, Technical Reviews of Reports, Review of Corrective Action Plans and Root Cause Analysis. Technical Experts can only conduct the Technical Review for client's which they have not been part of the Audit Team. To comply with JAS-ANZ requirements and internal procedures, Technical Experts are required to demonstrate experience and knowledge inherent to specific asset and industry sectors, and have a CAMA qualification.

The ISO 55001 certification cycle

CASE STUDY

Leading the Way with Certification – Carey Mining Pty Ltd

Carey Mining Pty Ltd (Carey Mining) provides mining, civil and training services to clients in the resources sector. They have a strong proven track record working directly with major mining companies in Western Australia. As a 100% Indigenous owned organisation, Carey Mining's vision is to create new horizons and push the boundaries for Indigenous business while working with partners, clients, and broader community stakeholders to generate long-term sustainable outcomes.

Carey Mining identified Asset Management as one of the key aspects for adding value to the business. This value is realised by improving asset availability and utilisation while decreasing the cost of maintaining assets. This is achieved through improving equipment reliability and proactive maintenance practices over the long term with the safety of employees being paramount.

The Certification Journey

Carey Mining engaged Bureau Veritas to certify their Asset Management System against the ISO 55001:2014 standard as part of their continuous improvement process.

The main drivers behind gaining certification were to match and exceed client requirements and to gain a competitive advantage when tendering on mining and civil contracts.

Carey Mining's ISO 55001 certification covers the provision of asset management for mobile, fixed and auxiliary plant and equipment utilised in earthworks, crushing, screening and processing at sites operated by Carey Mining.

Preparation For The Audits

Prior to the audit activities, Carey Mining engaged with all staff for them to understand the process. As an organisation, they use audits as an opportunity to understand whether their practices, methods of implementation and ways of working could be improved through the sharing of constructive feedback and reasonable recommendations for continuous improvement.

Benefits Of A Certified Asset Management System

Aligning their Asset Management System to the international standard helps to give Carey Mining confidence in their focus on sustainable operations and the techniques used to improve dimensions of overall equipment effectiveness, reliability, capability and quality – throughout the lifecycle of the equipment.

For an effective asset management system, Carey Mining have recognised that buy-in and support is required from each department that interacts with the maintenance team, especially operating teams which are financing assets and signing off associated CAPEX.

Since achieving ISO 55001:2014 certification, there has been an increased emphasis on effectively managing assets company wide. The increased awareness of how assets are managed, through training and certification, has had a positive impact in the business.

Following the audits, an asset management module has now been added to the Carey Mining corporate induction. This module introduces new employees and contractors to Carey Mining's asset management approach right from the onset of employment with the group.

Furthermore, this asset management approach has increased clarity for several other departments including maintenance, finance, procurement, HSE and human resources on what is expected with asset management.

Challenges Faced

The challenges faced linked to competing client expectations and business priorities. Carey Mining already have other ISO certifications; each with their own internal and external audit calendar.

Experience with Bureau Veritas

"Bureau Veritas were very helpful and accommodating throughout our certification process. The auditor was professional and put us at ease during the audit. He also had a lot of experience in the area."

"The certification process has helped to make the business better. The auditor has been a great ambassador for Bureau Veritas. He was highly skilled within the industry sector and also added value by helping Carey Mining to understand what the ISO 55001 standard looks for and also by identifying gaps in a positive manner. With the industry best practice advice and guidance provided by the auditor, Carey Mining left the closing meeting with the confidence to move forward and continue to improve".

BUREAU VERITAS 1828

For background details on BUREAU VERITAS you will find it all at www.bureauveritas.com.au etc.

For more information please get in touch with our Certification Manager, Jeremy Leu (Jeremy.leu@au.bureauveritas.com)

References

[1] IAF (2011) 'Why use an accredited certification body' www.iaf.nu page 2

[2] GFMAM (2014) Competency Specification for an ISO 55001 Asset Management System Auditor/Assessor First Edition, Version 2 www.gfmam.org

ACA Standards Update

Welcome to the corrosion related standards report for August 2018.
The standards reporting for 2018 is scheduled against specific interests and as indicated below:

Issue 2018	Standards search for Specific Interests
February	Oil & Gas
May	Water & Wastewater
August	**Concrete & CP**
November	Asset Management / Coatings

This Standards report focuses on Concrete and Cathodic Protection (CP) in relation to corrosion.

As previously this is in two stages, namely:

1. A global standards and publication focus at 28 June 2018, searching through SAIGLOBAL Publications at https://infostore.saiglobal.com/store, for all current publications and standards relating to corrosion and its prevention for the topic of 'Concrete' and 'CP'.

These results are shown in Tables 1in the full report for Members via Resources/**www.corrosion.com.au**.

2. A SAI Global search, as previously, at https://infostore.saiglobal.com/store/default.aspx?SearchType=power for new standards, amendments or drafts for AS, AS/NZS, EN, ANSI, ASTM, BSI, DIN, ETSI, JSA, NSAI and standards and amendments for ISO & IEC published from 16 April 2018 - 28 June 2018, using the key words and key word groups:

- 'durability'.
- 'corrosion' or 'corrosivity' or 'corrosive'; but not 'anodizing' or 'anodize(d)'.
- 'paint' or 'coating'; but not 'anodizing' or 'anodize(d)'.
- 'galvanize' or 'galvanized' or galvanizing'.
- 'electrochemical' or 'electrolysis' or 'electroplated'.
- 'cathode' or 'cathodic'.
- 'anode' or 'anodic'.
- 'corrosion' and 'concrete' or 'concrete' and 'coatings'.

These results are shown in Table 2 in the full report for Members via Resources/**www.corrosion.com.au**.

Summary

1. Through SAIGLOBAL Publications at https://infostore.saiglobal.com/store for a search of current publications, from all publishers over the title (see Stage 1 Report Table);

A. there were 157 citations on 'Concrete' and 'Corrosion'; there were 9 from AS, AS/NZS & SNZ; 110 BSI; 57 DIN; 29 NACE; 22 ACI.

See Table 1a in the full report for Members via Resources/**www.corrosion.com.au** for these titles.

B. on 'Cathodic' and 'Protection' there were 396 citations; 7 from AS; 26 NACE; 21 DIN; 9 ISO; 2 API; 2 ASTM; 1 AASHTO; and 1 Underwriters Laboratory.

See Table 1b in the full report for Members via Resources/**www.corrosion.com.au** for these titles.

2. Across SAIGLOBAL online Standards Publications there was a total of 45 listings of new standards, Drafts and Amendments found that were issued from 16 April 2018 - 28 June 2018; 0 from AS, AS/NZS & SNZ;

These results are shown in Table 2 in the full report for Members via Resources/**www.corrosion.com.au**.

See the Tables in the full report for Members via Resources/**www.corrosion.com.au** for details.

Regards

Arthur Austin
(Arthur.Austin@alsglobal.com)

***For the full Standards Report, please visit www.corrosion.com.au**

Callaghan Innovation

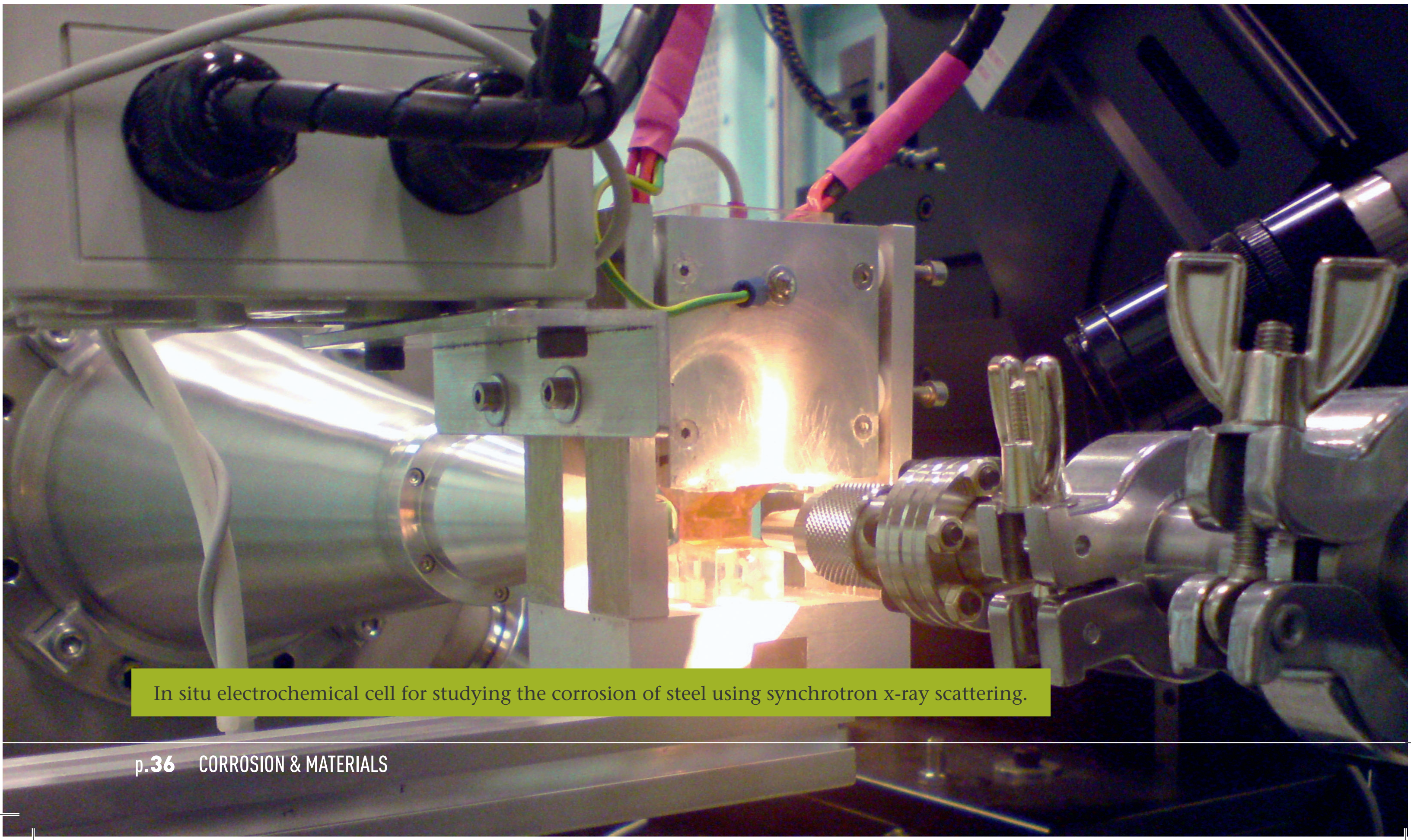
Since its inception in 2013 Callaghan Innovation has been the New Zealand Government's Innovation Agency working on behalf of the NZ government to activate innovation and help businesses grow faster. The Research and Technical Services (RTS) division of Callaghan Innovation provides direct R&D services, technology foresighting, advice and education. RTS has deep historical roots, beginning with the formation of the Department of Scientific and Industrial Research (DSIR) in 1926, continuing as Industrial Research Limited (IRL) in the 1990s before its current incarnation. RTS currently has four research groups (materials, manufacturing, biotechnologies and data science), two commercial divisions as well as housing the nation's Measurements Standards Laboratory.

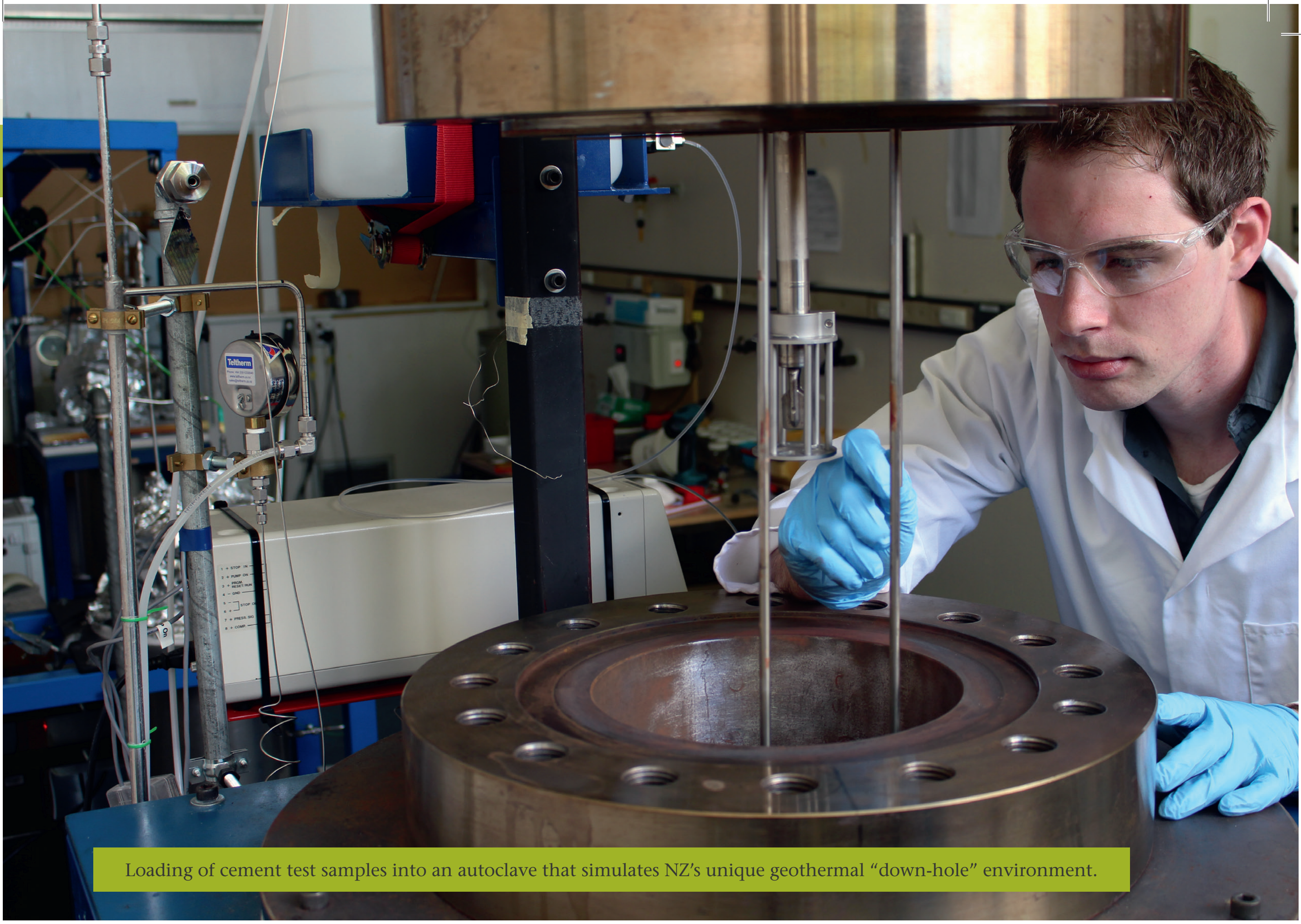
Advanced Materials is one of the four groups within RTS and works with New Zealand firms to improve their choices around the materials that comprise their products - whether to improve an existing product/process or to develop a new product. The group's expertise spans materials design, selection, modelling, characterisation, processing, optimisation, property testing, and product specification. With such a diverse range of expertise and R&D activities a concise summary is not possible, however each of the five teams within the group has activities and expertise directly related to materials degradation and service in extreme environments.

The Metals & Ceramics team uses powder-based approaches to produce a wide range of materials including stainless steels, titanium alloys, shape memory alloys, advanced structural ceramics, refractories, and electroceramics. Extensive furnace, thermal characterisation and feedstock preparation facilities are available to the team. The team also has experience in measuring the performance of such materials in corrosive, high temperature and tribological applications.

Recently, a key area of research and commercial interest has been in the net shaping of powder metallurgical parts by novel processes such as powder bed fusion (for example selective laser melting (SLM) and electron beam melting), metal injection moulding, and emerging additive manufacturing processes. Such processing routes can however influence the properties of the parts so that they differ from what might be expected of traditionally manufactured parts. While extensive data exists on mechanical properties, the durability of these materials is much less well understood. Electrochemical corrosion testing of SLM stainless steels and titanium alloys produced in NZ has shown that the corrosion behaviour of each material differed to that of the traditional equivalent alloy but that the difference depended on the alloy. Furthermore, the surface of the SLM parts exhibited dramatically different corrosion behaviour to that of the bulk. Sliding wear tests have demonstrated that the wear behaviour of SLM materials also differs from that of traditional alloys. Such information is crucial to help businesses make best use of the design freedoms offered by such materials and to avoid costly mistakes.

The Cement and Mineral Processing team works with a number of partner industries in the mineral resources, construction, and energy fields. A key example of capability built up by the team is in the area of high performance geothermal cements. The success of a geothermal well relies on a sound seal between the steel liner (which


In situ electrochemical cell for studying the corrosion of steel using synchrotron x-ray scattering.



Loading of cement test samples into an autoclave that simulates NZ's unique geothermal "down-hole" environment.

conveys geothermal steam to the surface for power generation) and the surrounding rock formation. In NZ geothermal applications this requires the cement and cement-steel interface to survive over many years under the combined action of high pressure, high temperature (around 300°C), super-heated water, dissolved sulphurous gases and carbon dioxide. Due to the unique make-up of the NZ geothermal resource, cements formulated for other geothermal applications may not be successful. The team established a specialised autoclave to simulate down-hole geothermal conditions and allow the degradation of cements and metal-cement couples to be assessed. This capability coupled with a deep understanding of cement chemistry was used to develop more durable advanced cement formulations.

The Coatings & Polymers team works with advanced materials synthetic chemistry, including organic dyes, polymers, nanoparticles, and encapsulation of active materials. Application of this expertise to coatings allow the team to create surfaces that are fire retardant, corrosion resistant, self-healing, self-cleaning, anti-microbial, or super-hydrophobic. A recent project investigated the surface modification of cellular titanium materials generated by additive manufacturing. A process was developed that provided short-term antibacterial action with a long-term enhancement in osseocompatibility.

The Optical Materials & Devices team investigates the development of materials for optical sensing, optical characterisation of materials and the use of optical devices for monitoring harsh environments. This latter capability offers some unique advantages compared to conventional sensing and monitoring technologies. The sensors themselves are resistant to many forms of chemical attack and are not affected by electric fields. This allows such sensors to be embedded within structures to continuously monitor aspects such as temperature, chemical composition and mechanical strain throughout the lifetime of the component.

Linking all of these teams together is the Simulation Analysis and Testing team who are responsible for many of the characterisation techniques carried out – both in service of the other teams but also as a direct service to NZ and international businesses. Facilities include failure analysis, microscopy, materialographic preparation, thermal analysis, x-ray diffraction, chemical composition of inorganic materials and metals, and mechanical property measurement. These facilities are coupled with a decades-long experience in assessing the structure and performance of a wide range of materials in an even wider range of applications and environments. A recent example has been research carried out in collaboration with Qatar University, Victoria University of Wellington and Quest Integrity using the Australian Synchrotron to carry out in situ x-ray scattering studies of the corrosion behaviour of pipeline steels in carbon-dioxide saturated NaCl solutions. These experiments were initially conducted in static electrochemical corrosion experiments and then extended to flowing corrosion conditions using a specially designed erosion-corrosion cell.

The Advanced Materials group also offers materials advice based on our broad experience of materials technologies and applications, and provides contacts and links to other materials research groups nationally and internationally.

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Sacrificial anodes preserve HMAS *AE2* (1915) in the Sea of Marmara, Turkey

Introduction

The Australian submarines *AE 1&2* were built in 1912 by Vickers Armstrong at Barrow-in-Furness, England, launched in 1913 and arrived in Australia on 24th May in 1914 (Figure 1). The *AE2* was under the command of Lieutenant Commander Henry Stoker. The *AE1* was lost with all hands off New Britain in Papua New Guinea in 1914 after which the *AE2* returned to Sydney. The wreck of *AE1* was found in December 2017 and it lies in more than 300 metres with clear evidence of a massive implosion as the pressure on the vessel increased beyond crushing depth. Having come from England to Australia, the *AE2* went back to the Aegean Sea with the second ANZAC convoy in 1915 and penetrated the heavily mined Dardanelles strait to enter the Sea of Marmara on the 25 April (Figure 2). The signal from *AE2* on entering the Sea of Marmara (Marmora) provided the impetus to proceed with the ill-fated landing at Gallipoli. After five days of creating havoc for Turkish naval movements, it was holed by the torpedo boat *Sultanhisar*. Stoker ordered his crew to abandon ship and then scuttled the vessel in 73 metres of water at 47º32' N, 27º 17'E. It lies half in a slit mound at the bottom of the Sea of Marmara. The wrecksite was discovered by the Turkish maritime archaeologist and museum director Selçuk Kolay in 1995.

The conservation project has involved in situ assessments in 2003 and 2007 to determine the extent of decay of the submarine. These observations led to the plan to use 10 tonnes of zinc anodes, attached in three locations over the length of the boat, to drive out the chlorides and stop corrosion in its tracks. This program was effected in 2014. Technical challenges of working at depth are significant: tri-mix gases (O_2, N_2 & He) are routinely used with a 30-minute dive requiring two hours decompression on the way to the surface. Previous experience with in situ conservation of historic iron artefacts using anodes had demonstrated that the method is effective for the treatment of anchors, cannon and the *Xantho* engine. The shallow waters facilitated routine measurements to establish the kinetics of the process (MacLeod 1986, 1996, 2014, 2013). An additional complication with the *AE2* is the presence of one unexploded torpedo; both the explosive charge and the mercury fulminate detonator become increasingly sensitive to shock over time. Any significant impact on the boat will detonate the torpedo unless corrosion has enabled water to penetrate the device. Sealed watertight doors prevented the ROV from entering this section of the submarine.

Physical Oceanography in the Sea of Marmara

The water column above the wreck is dominated by fresh water dilution from the Black Sea, as the salinity was 26‰ compared with open ocean values of 36 ± 2 ‰. At the wreck site a counter-current of hyper saline water from the Aegean Sea brings the salinity to 41.3±0.8 ‰. Through the normal concentration processes associated with inward diffusion of chlorides, to balance the charge of increasing concentration of Fe^{2+} ions, the interfacial concentration of chloride typically increases by a factor of 2.5 over and above the surrounding environment (MacLeod 1996).
The mean water temperature on the site was 17 ± 1.5 °C and the dissolved oxygen was recorded at 2.8±0.2 ppm which represents 32-36% saturation (Riley and Skirrow, 1975). There was essentially zero oxygen (0.07 ppm) in the silt. All corrosion measurements were relative to a 3M KCl Ag/AgCl electrode that was calibrated against a quinhydrone solution at pH 4.0 at +0.228 volts vs. NHE.

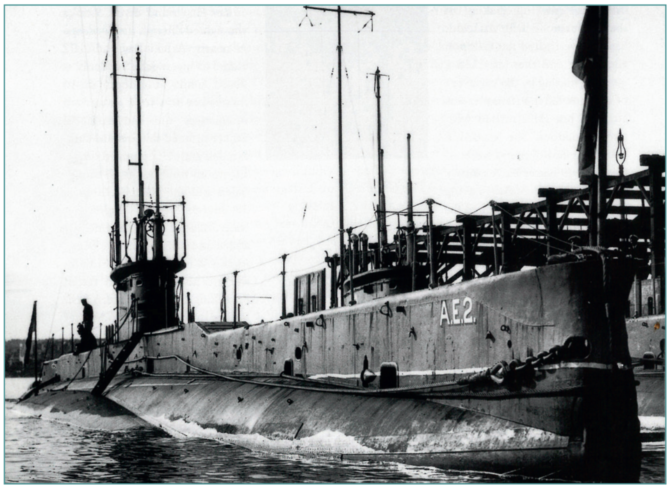

Figure 1: AE2 docked in Sydney May 1914 after its delivery journey from England.

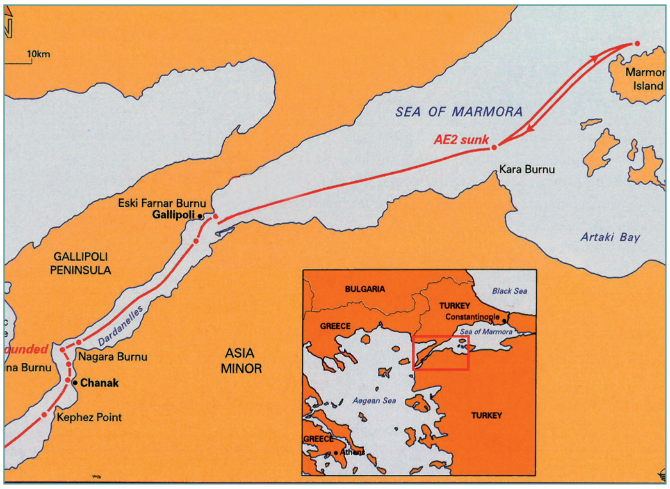

Figure 2: Map of the Dardanelles and route of AE2, adapted from the AE2 Commemorative Foundation reports.

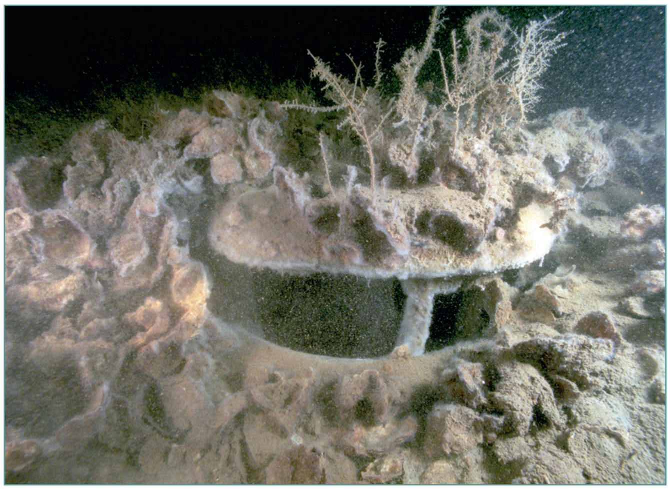

Figure 3: Hatch cover in partially open position showing 10 cm gap for taking the drop camera.

Figure 4: ROV mounted image of interior of control room after the main hatch had been opened.

Corrosion of the submarine in the Sea of Marmara

The submarine is half buried in a silt mound and images of the wreck can be seen at www.submarineinstitute.com. A combination of corrosion and trawler-net damage has holed the thin plate sections at the bow and on the casing (structure that covers a range of fittings to streamline the water flow) behind the conning tower, leaving frames exposed. To ensure effective scuttling, Stoker had left the main hatch 10 cm open and so a drop camera was able to be manipulated into the confined space (Figure 3). All the non-ferrous metal fixtures on the interior of the conning tower were covered in a thin layer of concretion from the galvanic protection afforded by the surrounding iron objects (MacLeod 1982). The hatch cover, ladder, control valves and steering gear were all made of brass or bronze. Operational difficulties allowed only one corrosion potential to be recorded. The value was -0.619 volts which is the same as the turret and armour plating sections of the USS *Monitor* (1862), which had a mean value of -0.600 ± 0.016 volts at the same depth (Arnold et.al. 1991). The pH was 7.27 which is the very similar to the mean pH of 7.11 ± 0.54 for the WWI J5 submarine which lies in 32.5 m in Bass Strait, Victoria.

AE2 concretion and site history

A sample of the solid concretion was recovered when a storm caused a 2-tonne mooring clump-weight to hit the wreck. The matrix was a typical anaerobic concretion with a very dense milieu of sharp shell debris and black iron corrosion products. The iron corrosion products were Fe_3O_4 and various iron sulphides, which included FeS (North 1976). Other species containing iron, sulphur, chloride and oxygen were present (Ozenbas 2008). The priming coat of red lead oxide, Pb_3O_4 was found at the original metal surface during an SEM examination of the concretion section. The first layer of concretion was ≈1.6 mm thick, a secondary layer 8.8 mm while the outer layer was 3.9 mm thick. Sections of concretion showed pitting corrosion beneath the original surface to a depth of 3 mm. The colonisation of the conning tower and the upper sections of the combing are very different to lower parts of the wreck. This indicates that the sediment levels have not always been the same. The primary corrosion layer in the concretion appears to correspond to the first 13±2 years of immersion i.e. from 1915 to 1928. Changing conditions due to massive storms disturbing the site resulted in the second and third layers.

Assessment of the corrosion rate on *AE2* and its impact on the environment

Metal thickness was determined in situ using a Cygnus® ultrasonic gauge; the mean hull plate thickness was 4.6±0.9 mm which is a loss of only 1.55 mm of metal over the 92.4 years. This equates to a corrosion rate of 0.017 ± 0.003 mm/year or just under 20% of the normal shallow water long-term corrosion rate of marine iron. Comparative data from the interior of the turret USS *Monitor*, which is at the same depth, gave the same result (MacLeod et al 2008). Empirical data from several historic iron shipwrecks has established that the log of the corrosion rate (mm/year) is directly related to the mean water depth *(d)* of the wrecksite, (MacLeod 2006).viz.,

$$^{\text{Open-ocean}} \log d_g = -0.630 - 0.0156\, d,$$

In this relationship d_g is the depth of graphitisation of cast iron (mm/year). For the site depth of 71 metres the calculated corrosion rate of 0.0183 mm/year for *AE2*, which is the same as the observed in situ rate.

An assessment of how long-term corrosion of the *AE2* submarine has affected the local microenvironment was made by taking sediment cores in the immediate vicinity of and at 20 metres distance from the hull (MacLeod 2010). There was no statistically significant difference between the mean redox potential of the two sediment cores. However, the rate at which the redox potential in the cores changed was much more rapid for the core adjacent to the submarine which fell at -36 mV/cm compared with 20 metres away when the voltage fell by 6 mV/cm. The more rapid fall in the redox potential for the *AE2* core indicates that the microenvironment near the submarine rapidly becomes anaerobic as a direct result of the corrosion process consuming oxygen trapped in the silt. The off-site core was 35 mV more oxidising than that by the submarine.

The redox and the pH data from the *AE2* core indicated that reduction of dissolved oxygen is the dominant electrochemical process viz,

$$\tfrac{1}{2} O_2 + 2H^+ + 2 e^- \rightarrow H_2O$$

The regression analysis of the E_h and pH data conformed to the equation $E_h = 0.759 - 0.084\text{pH}$ vs. NHE which had an R^2 of 0.9090. The intercept value of 0.759 ± 0.069 volts is essentially the same as the standard reduction potential of 0.680 volts for the above oxygen reduction reaction, but the slope for the pH at 84 ± 9 mV is higher than the theoretical 59 millivolts. The reason for the deviation from the theoretical slope is possibly an effect of the activity of the hydrogen ions in the hypersaline environment as no corrections were made to the hydrogen ion activity in the cores. The off-site core data does not follow any systematic trend for the pH and E_{corr} values. The ${}^{AE2}pH_{core}$ values shows a steady alkaline microenvironment for the initial 25 cm at pH 7.80 ± 0.02 before rapidly falling over the last 7 cm a rate of -0.05 pH per cm distance down the core. The change in ${}^{AE2}pH_{core}$ may reflect a limiting impact of the vessel on the sediment since the pH values for both cores coincide at 7.3 ± 0.1 at a sediment depth of ≈ 30 cm. The ${}^{off\text{-}site}pH_{core}$ rapidly fell from its initial value of 7.7 to 7.1±0.1 in the first 25 cm of sediment. The dissolved oxygen content was essentially zero in both cores at 0.02 ± 0.02 ppm.

Modelling corrosion processes on *AE2*

Since international protocols prevented recovering of any metal from the *AE2* structure the initial corrosion behaviour was modelled using a section of mild steel from a recovered from an 1890's paddle steamer boiler. A section of *AE2* concretion was placed over the metal plate with a 1.5 mm gap to simulate the corrosion microenvironment. The plate had been pre-drilled to accommodate insertion of chloride and pH electrodes into the interstitial solutions and insulated copper wires had been silver soldered to it before the electrode and concretion assembly was cast in an epoxy resin annulus to allow monitoring of the E_{corr} data. The geometric surface area of the test cell was 40 cm². After filling with seawater (35.7‰) from Bathers Bay, Fremantle, Suba-seals were inserted into the measuring holes and the unit was placed in a 4-litre plastic container for 11 months at a temperature of 22 ± 2ºC. There was a systematic increase in the acidity and the chlorinity of the interstitial solutions. The pH fell from 7.9 to 4.3 while the chloride concentration increased from 16.3 to 34.6 g/litre. The equilibrium chloride and pH values were reached after 10 months, which supports shipwreck conservators belief that the in situ E_{corr} and pH data reflect the dynamic equilibrium between hydrolysis of the corrosion products and the steady state of decay. The simple *AE2* concretion-corrosion cell showed that after less than a year, the chloride ions increased by a factor of 2.1 times which is comparable with the 2.9 times increase in chlorinity found with a tompion-sealed cast-iron cannon bore from the *Zuytdorp* (1712) after exposure to 270 years of heavy surf (MacLeod 1996). The final E_{corr} of the simulated concretion hull corrosion experiment was the same as observed on site. It can be concluded from these experiments that, after nearly 100 years of corrosion, the *AE2* steel is sitting in an acidic and chloride-rich microenvironment, which promotes corrosion.

Application of sacrificial anodes

By the end of the inspection visits in 2007 and 2009 it had become apparent that although the *AE2* was in no immediate danger of collapsing from corrosion, the impact of fishing nets and un-authorised access presented a real danger to the long-term preservation of this significant wreck, which is held in high regard by both the Turkish and the Australian governments. It was decided to mount another expedition to the site and have commercial divers' complete internal surveys of the wreck, using miniature ROV's to manoeuvre inside the submarine. To achieve this a replica conning tower seal was constructed so that at the end of the works, it could be placed into position with gap between it and the hull providing the same configuration as it had in 1915. As expected, the bronze fittings on the original lid were covered with a thick calcareous layer, resulting from cathodic protection from the submarine, so hydraulic jacks were used to open the hatch and so make way for ROV access. The original hatch cover is still attached to the submarine, but it is in the open position. Some of the extraordinary images of the interior of the boat have filled in gaps in the understanding of the differences between the as-constructed and the plans of the vessels (Figure 4 & 5).

Three clumps of 17 anodes (150 x 7.5 x 7.5 cm) were located on support frames that could be craned into location then attached to the submarine at locations aft (near the rear hydroplane), forward on the windlass and amidships on the conning tower (Figure 6). Each pod was bottom filled with concrete to provide defence against falling into the silt. The in-filled steel supporting structure weighed 0.5 tonne with an aggregate weight of around 1.5 tonnes for each pod. Prior to attaching the anode clamps to the submarine, the surfaces were hydro-blasted to remove small areas of concretion from the metal surface to get ohmic connections. Divers used standard oil and gas industry brackets, with three threaded bolts, to secure the attachments. This work represents the largest in situ

Figure 5: Lead crystal decanter on wooden table in the officers' quarters.

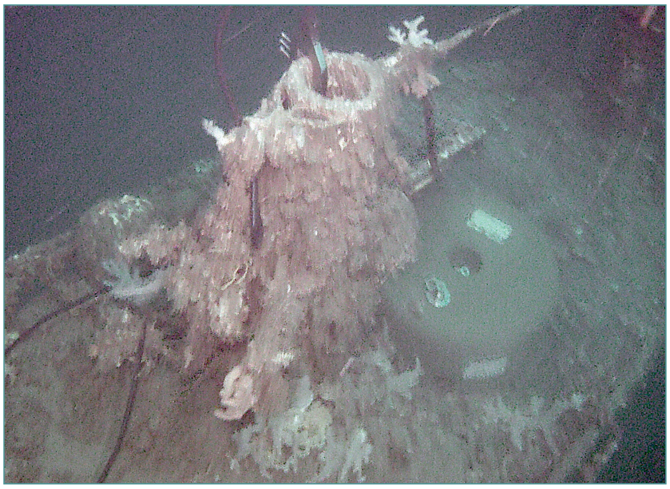

Figure 6: Attachment of anode cables on periscope stand amidships.

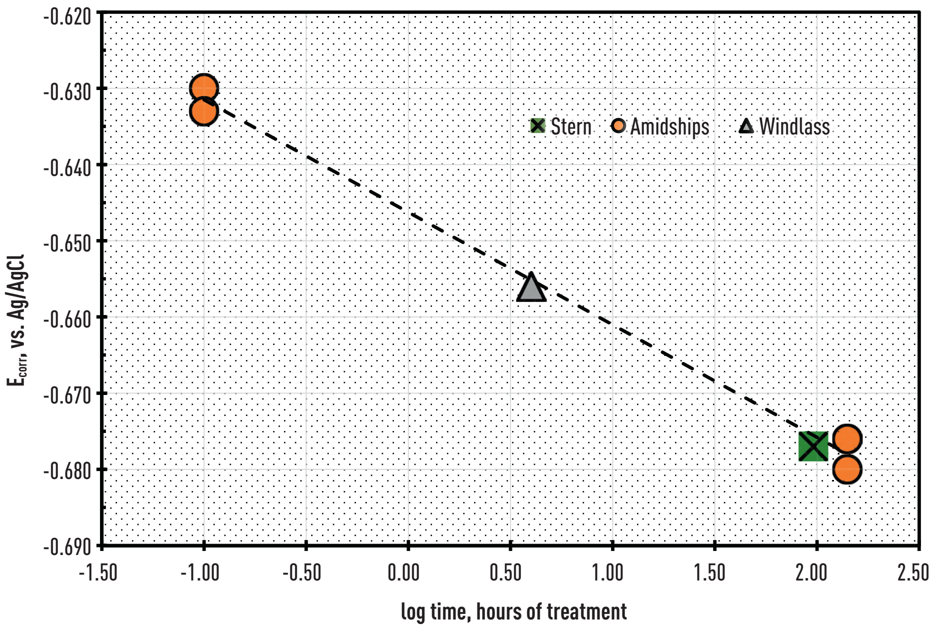

Figure 7: Excel plot of response of Ecorr over 4 days to attachment of the three anode pods.

conservation project ever attempted on an historic iron shipwreck. One of the challenges of operating at depth is that the number of measurements that can be taken is limited and so only one complete set of E_{corr} data was obtained on the three parts of the submarine was taken after four days (Figure 7). Given that the submarine has a surface area of approximately 660 m^2 it is not surprising that it took some time to achieve a cathodic polarisation of 50 mV in four days. The voltages fell from the pre-disturbance value of -0.63 to -0.68 in accordance with the regression equation,

$$E_{corr} = -0.647\ (0.001) - 0.0150\ (0.0005) \log t$$

where the time since the anodes were attached (t) is in hours. The R^2 for the regression equation was 0.9947 and the numbers in parenthesis are the standard deviations of the variables.
A series of bad weather events and financial constraints has limited post-anode installation documentation to one ROV inspection seven months after installation. This confirmed that all three anode pods were working.
It is hoped that a detailed inspection of the submarine will take place early in 2019 some five-years after the treatment began. Design calculations have predicted that the anodes will need to be replaced in 2029 by which stage the drain on the anodes will be much less as the bulk of the chlorides and acidity will have been removed from the interfacial region surrounding the submerged vessel.

Conclusion

The data gathered from in situ corrosion measurements on the hull of the submarine *AE2* and from the core profiles close to and 20 metres from the vessel has shown that the dense marine concretion and the great depth of the wreck site is providing a relatively benign storage environment for the vessel. The dissolved oxygen profiles and Pourbaix diagrams from the in situ data indicated that corrosion of the submarine is consuming oxygen from the surrounding silty sediments. The submarine has a real but limited impact on the silt and sediments. The application of three clumps of zinc anodes to the submarine has begun the in situ stabilisation of the *Silent ANZAC AE2* so that it can live another 100 years and tell its story to generations as yet unborn.

Acknowledgements

Special thanks are given to the AE2 Commemorative Foundation who provided logistical and financial support for the Turkish operations, Roger Neill and Peter Graham from the Defence Science and Technology Organisation gave vital assistance in the field. Special thanks to Wayne Burns of Anode Engineering who supplied data loggers that were unable to be deployed due to overseas government procedures.

Ian D MacLeod is the corrosion and conservation advisor to the AE2 and AE1 submarine preservation and management teams.

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Review of a Once in a Lifetime Façade Rehabilitation Project

1. Introduction

Sydney's MLC Centre, an iconic building on the city's skyline was the tallest reinforced concrete structure in Australia when it was built in 1978. The building’s original precast façade has weathered over time and required a full range of treatments to its façade to restore it to an aesthetically pleasing condition and to safeguard its service for a further 40 years. To conduct repairs to the skyscraper, a unique site access method was designed and implemented for the project which consisted of four fully enclosed climbing work platforms, that were raised gradually up the façade on columns of telescopic masts anchored to the building.

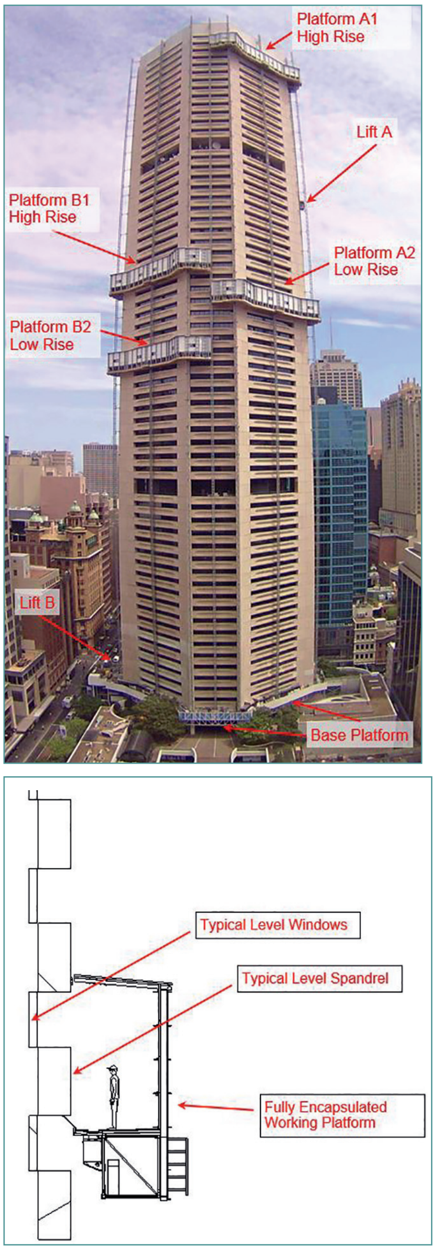
Construction works were undertaken on a 2 shifts per day, 7-day week working cycle with all noisy works performed overnight and all work methods, equipment and hours of work implemented to minimise disturbance to building occupants - an important factor at this prestigious central business district address.

The MLC façade maintenance works were completed by Freyssinet Australia in a little over 6 years, commencing in 2012 and achieving practical completion in early 2018.

2. Access System

The MLC Centre is a 220m tall high-rise building with an octagonal footprint, located in Sydney’s CBD. An access system was developed based on the Mast Climber system, whereby 4 independent fully enclosed climbing work platforms were used on telescopic masts, supported by a cantilevered truss platform (known as the base platform) 8m above podium level (Figure 1). In addition to this base platform supporting the whole access system, it allowed for movement of men and materials to the work platforms, as well as providing a base of operations for the site team. This facilitated the normal functioning of the building without hindrance to occupants or the public.

The work platforms (Figure 2) are serviced with water, power, waste water removal and two service lifts that utilise the masts independently of the work platforms, delivering flexibility for movement of labour force, equipment and materials without interruption to work. Two platforms operate per set of masts, ensuring continuous work-face availability to maximise productivity, with complete encapsulation of work-faces ensuring total safety, noise reduction, and containment of construction debris.



Figures 1 & 2 – The Access System (4 independent Mast Climbing Platforms) & sectional view of work area with one of the platforms.

There were two main phases of the project: North side works and South side works. For transition of the access system from north to south, a ‘Monorail Transfer System’ (Figure 3) was designed and implemented whereby all 4 platforms would be transferred 180° around the perimeter of the building while suspended from a circular self-supporting structure anchored from the first plant room level located on Level 26. This system was implemented to drastically reduce the need for road closures and cranes, thus further minimising the impact of the overall works on the building occupants and public alike.

Figure 3 – Monorail Transfer of platforms between phase 1 and 2 of the project.

3. Condition Assessment

Previous condition audits were used to determine the extent of remediation required. A proposal was put forth detailing suggested repair methods that were determined with onsite trials once the contract was awarded.

An in-depth Non-Destructive Investigation (NDI) survey of the entire building façade was conducted once the access system was installed, to help confirm previous condition audits and outline the entirety of the works involved. The process used during the NDI’s was:

1. Visual Inspection (identifying cracks, fractures, spalls, erosion);
2. Low cover inspection (investigate previous condition audit reported low cover areas);
3. Delamination testing;
4. Potential & Corrosion Mapping; and
5. Base Spandrel Survey (investigate reinforcement cover at base of spandrels).

All information collected during the NDI stage was downloaded to a database which would be used to assess the conditions identified and based on an agreed (and independently verified) design criteria, establish the appropriate repair extent and method.

4. Construction Methods & Practices

4.1 Safety

Working at heights on a 'live' high-rise building in the middle of a bustling city draws many safety challenges. Adding two working shifts of up to 50 site personnel on each, along with works conducted at night raises the level of preparation required to safely execute the works to new heights.

The project developed many safety systems, and consisted of:

1. Developing a 'Safety Culture' on site, where safety was the number one priority;
2. Develop multiple system redundancies when working at height;
3. Focus on 'Lead Indicator' reporting as developed by the management team to prevent incidents from occurring;
4. Ongoing consultation with the site crews through safety committee meetings, toolbox talks, pre-starts (conducted at high-level and at local level);
5. Implementing 'HAZOB' (Hazardous Observations) reporting, work activity 'Take 5's';
6. Ongoing site training relating to ongoing tasks;
7. Setting aside safety 'Soft/Safe Starts' after every extended period away from the project (Christmas breaks, etc.); and
8. Active and consultative participation by the Client.

The project finished with over 1,000,000 man-hours worked.

4.2 Façade Maintenance Works

The D&C contract stipulated a 10-year warranty period covering all maintenance works coupled with a 40-year design life on all repaired and unrepaired conditions of the building façade with the entire façade to be inspected twice during the warranty period, during the 5th and 10th years. In depth review of previous condition audits identified the main repairs required, and the addition of the NDI process allowed for specific repair solutions to be adopted.

4.2.1 Spandrel Repairs

Repairs to the spandrel panels consisted of:

1. Foreva Hybrid Cathodic Protection

   One of the repair solutions adopted on the building was the Foreva Hybrid Cathodic Protection (HCP) system. This system worked twofold: 1) re-alkalising the concrete panel, and 2) installation of sacrificial anodes for ongoing protection of the embedded steel reinforcement (Figure 4).

   This system is common in marine environment structures but was chosen as an effective solution in this instance, due to the life span of the building and the limited access for future maintenance requirements.

2. Concrete Repair

   Concrete repairs to the spandrel panels were focussed on the 'erosion zones' (being the bottom edge of the scallop), as well as the base of spandrel. The areas identified as requiring repair were cut away (including the reinforcement), new 6mm diameter stainless steel reinforcement was drilled and chemically embedded to the substrate, and welded in place according to design. Two forms of repair mortar were developed – 'Foreva MLC Hand Apply' and 'Foreva MLC Form & Pour'. As the name suggests, the application of those products (Figure 5) was dependant on the volume used and thickness of application. A pre-determined mix of white quartz was added to the mortar and once applied and sufficiently dried, the surface laitance was washed in order to expose the embedded quartz and match surrounding panel exposure.

4.2.2 Column Panels

Repairs to the column panels were focused on the perimeter edges. Cracking located along the edges, or spalls at corners were identified and subject to approved design criteria, broken out and repaired. New reinforcement was added at these locations in the form of 6mm diameter stainless steel, drilled and chemically embedded to the surrounding precast panel and anchored to the concrete substrate. As with the spandrel repairs, specifically developed repair mortar mixed with white quartz aggregate (to match original panel finish) was poured in custom fitted formwork and allowed to dry. The form was stripped at a specified time to allow for the 'washing' of the surface laitance, thus exposing the quartz aggregate to achieve a uniform appearance.

Figures 4 & 5 – HCP in process & concrete repair application of new mortar.

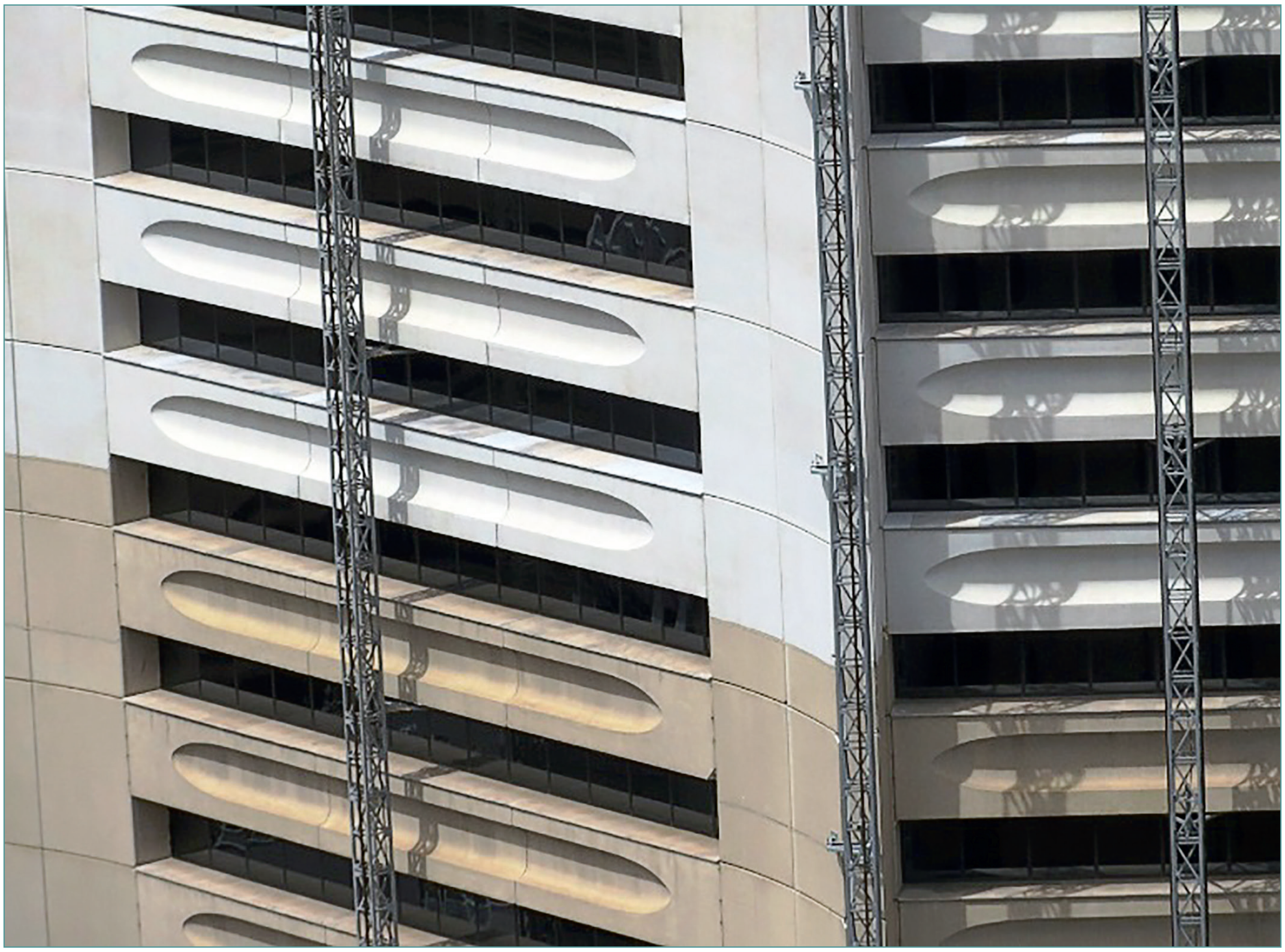


Figure 6 – Cleaning (JOS blasting) works in progress.

4.2.3 Marble Tiles

Above each spandrel panel and below each window sill are white marble tiles, a feature designed for the aesthetic observance of occupants. All marble tiles (totalling more than 4,100 individual tiles) were inspected during the NDI stage, and as required by the design criteria, repairs or replacements were carried out. In addition, a new aluminum baffle was installed to the underside of all leading edges to protect from possible future damage caused by unwanted strikes from the Building Maintenance Unit (BMU).

4.2.4 Cleaning

Rejuvenating the building was achieved by cleaning the entire façade with a JOS wet sand blasting system. This fine media was chosen over water pressure cleaning due to the uniformity of the finish and the gentler nature of the blasting pressure to achieve better performance. All media was delivered in 20kg bags to allow for easy transport to the work front, and each blasting kit consisted of a compressor, air tank, air dryer and blasting pot. The system was a wet blasting system which helped minimise the dust generated and allowed for easier clean up once complete. The results of the cleaning are quite evident when compared to the uncleaned levels (Figure 6).

4.2.5 Surface coating/sealing

Upon the completion of all repairs and cleaning, the application of silane – a hydrophobic treatment product which slows down the rate of moisture ingress to the concrete panels - was carried out to every exposed precast panel. This was a spray on application at a consumption of 200g/m², which was measured and monitored as part of the QA system.

4.3 Quality

With overall D&C responsibility, Freyssinet adopted a robust database system to report all identified conditions of the building façade. Quality recording during the construction phase, combined with an as built record of all repairs conducted were entered in the database to produce a final record of the current repairs and conditions on the precast façade panels.

Further quality checks were developed and implemented during the project, including the implementation of a 'Mini QA audit', whereby all repair practises were able to be witnessed and audited in a controlled way. This allowed for ongoing monitoring, improvement and adherence to the defined procedures.

5. Conclusion

The MLC Façade Maintenance Project demonstrates that remediation and repair solutions can be applied to high-rise buildings, regardless of location or construction type. The architectural highlights of one of Sydney's most iconic structures was no deterrent to finding and implementing realistic repair and constructability solutions that have revitalised one of architect Harry Seidler's lasting legacies.

Michael Acic
Freyssinet Australia, Sydney, Australia

Bureau Veritas

Q: What does Bureau Veritas do?

A: Bureau Veritas is a global leader offering Testing, Inspection and Certification (TIC) services. Founded in 1828 in France, we are a Business to Business to Society company, contributing to transforming the world we live in. Bureau Veritas' mission is to reduce risk, improve clients' performance and help them to innovate to meet society's challenges with confidence. Today Bureau Veritas boasts an unrivalled global reputation, and network, operating within over 140 countries with more than 1,400 offices and laboratories.

Bureau Veritas Certification is the independent division of the Bureau Veritas Group. Our brand is recognised and respected throughout the world as a valued symbol of reliability, impartiality and trust. Bureau Veritas Australia & New- Zealand operates in each state with its head-office located in Melbourne.

Q: What markets does Bureau Veritas' services cover?

A: Our services create value for clients in six key ways; providing a license to operate, facilitating trade, helping them enter global markets, reducing risk, optimising costs and protecting brands. We work across all industries, covering the full lifecycle of products and assets. Our experience across complementary sectors brings added value to our clients, supporting their innovation. These include:

- Marine
- Oil & Gas
- Power & Utilities
- Buildings & Infrastructure
- Process Industry
- Metals & Minerals
- Chemicals
- Consumer Goods & Retail
- Agriculture & Food
- Transport, Aerospace & Rail
- Automotive
- Manufacturing of Industrial Goods
- Public Authorities
- Health
- Banking & Insurance

Q: What is certification and why is it important?

A: Certification is the act of assurance by an independent accredited body of conformity to specific requirements. It covers products and their components, services, people and systems.

The certification process is suitable for both small and large organisations. It typically includes on-site audits and standardised testing and inspections. Once a certificate has been delivered, it is maintained through regular audits.

Certification can improve reputation, open up new markets or simply enable the company to operate. It also enables companies to manage risk and drive performance, by tracking a number of key variables over a period of time. This third-party process can also reassure stakeholders about compliance to legal and other requirements.

Q: Does Bureau Veritas offer any specialty services outside your core business?

A: Bureau Veritas offers a wide range of professional and cost effective training solutions in the areas of quality, health, safety and environment. We have trained individuals and organisations across the world from small firms to government agencies. Our courses are available to be delivered publicly, in-house or online. Our programmes can be customised to suit any company, in any location worldwide and we closely monitor all of our programs to continuously offer quality, adapted and pertinent training solutions to keep you ahead of the game.

Q: What are the challenges and opportunities of the industry you see in the coming years

A: There is now a standardised approach for the future of management system certification schemes. This approach is the High Level Structure (HLS) which is a common general structure comprising of a set of 10 clauses and is predefined in Appendix SL of the ISO/IEC Directives, Part 1. The characteristics and requirements specific to each standard (i.e. food management and environment management) are inserted into this structure in the appropriate chapters.

The introduction of this approach by ISO (International Organisation for Standardisation) means that new standards will share a consistent structure and this presents the opportunity to facilitate integration and alignment. Deeper linkages in business processes (i.e. business language) will result in increased value and efficiency. This standardisation also aims to foster compatibility and support other management system standards.

Q. Why is Bureau Veritas a Member Company of the ACA?

A: Bureau Veritas is a member of the Australasian Corrosion Association in order to gain deeper insights into the industry but also share expertise and knowledge with fellow members.

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Laser Cleaning

Introduction

In recent years, ultrashort laser pulses (order of picosecond, 1 ps = 10^{-12} s, and shorter) have emerged as a new precision tool for removal of contamination from any surface (Rode, et al 2018). The purpose of this article is to better shape the understanding of laser cleaning, its applications and how the corrosion industry can utilise this technology. This article outlines the operating principle of laser cleaning, examines the physical principles of laser cleaning related to particle removal, investigates the characteristics of a "Laser Cleaned Surface" and how this relates to coating adhesion. This article is by no means exhaustive on the application or progressive nature of this technology. Additionally, the article relies on existing practical case studies whereby the application of high-intensity pulsed laser has become normal practice for the cleaning of metal surfaces from rust and decayed paint. Laser cleaning is a well established technique in Defence service industries, industrial production lines and with the restoration of cultural heritage structures - such as the cleaning of stone building façades, historical artefacts.

Operating principle

The laser generates a directed and monochromatic beam of light which is tightly focused to create high power density. At the focal point, the energy of the intense laser beam will be absorbed by the contamination or paint layer, thermally incinerating or sublimating the target material, such as paint or contamination (see Figure 1). These processes will, in combination with the resulting micro-thermal shockwave, remove the target material as long as the target material is able to absorb the laser energy. The better the target material absorbs the energy, the faster it can be removed.

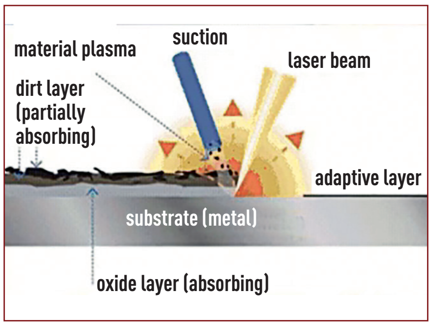


Figure 1. Process outline.

The main advantages of ultra-short pulses is attributed to the strong non-linear interaction with materials with reduced pulse duration resulting in a significant increase in intensity of the laser radiation to above 10^{12} W/cm^2.

The interaction with matter becomes non-thermal, which offers the possibility of surface layer removal with sub-micron precision. The minimal thermal load on the substrate diminishes any collateral effect induced by heat conduction such as burning, cracking, chemical modification and residual thermal stress in the surface layers.

Physical principles

The main concept of laser cleaning is based on the fast-thermal expansion of target materials causing mechanical stress and inertial force in the target material by the end of the pulse.
If these forces exceed the adhesion force, cleaning occurs (separated particle or whole contamination film removal from the substrate). The physical nature of adhesion forces can be different: there are Van der Waals forces, capillary forces, and electrostatic forces. For films of micron and submicron thickness, the prevailing adhesion forces are Van der Waals and capillary forces (in the case of liquid film presence). The main mechanism of particle removal in the case of Laser Cleaning is the fast-thermal expansion of particles or the substrate.

The particle tearing off occurs if the inertial force exceeds the adhesion force:

$$F_a < \frac{q_m m}{\tau_1}\left(\frac{\alpha_s A_s}{\rho_s c_s} + k\frac{\alpha_p A_p}{\rho_p c_p}\right)$$

F_a is adhesion force of the particle to the substrate, q_m is the peak laser intensity during the pulse, τ_1 is the trailing edge duration of the pulse, A is the absorption coefficient, ρ is density, c is heat capacity. Index <<s>> is related to the main material, index <<p>> to the contamination particle. Coefficient k varies from 0 to 1 and defines the the dependance between thermal expansion of the whole particle and its mass centre displacement (Shakhno 2008).

The main mechanism of dry laser cleaning of contamination films is thermomechanical. Thermal stresses occuring by laser heating of the layer cause its tearing away. The rate of the process can be defined as as velocity of the teared fragments movement:

$$V = \sqrt{\frac{E}{\rho}}\,\frac{\alpha\varepsilon}{\rho c h}$$

ε is laser pulse fluence, h is coating thickness, E is elasticity module of the coating.

In short, the dynamics between thermal expansion of contaminates and substrate combined with adhesion forces and pulsed laser results in ablation of target materials.

Characteristics of laser cleaned surface

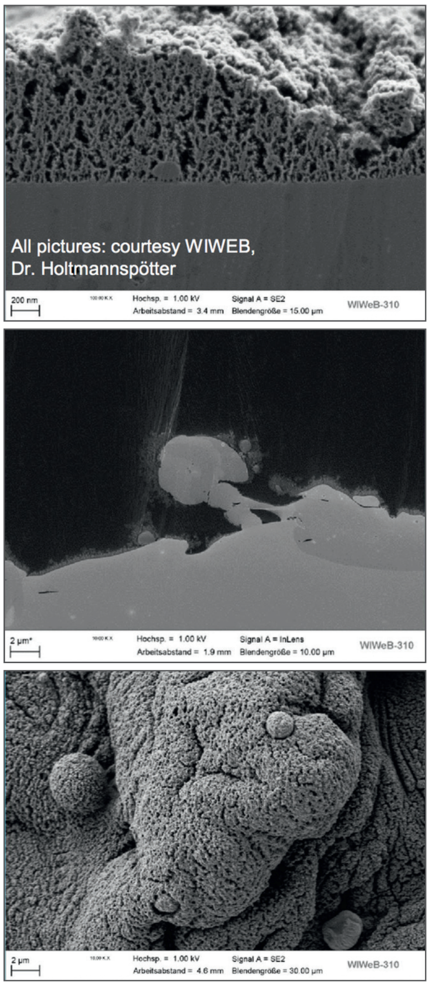
Examinations of the surface micro-structure of a steel substrate after being exposed to very short pulsed laser displayed several unique characteristics. Using an electron microscope Holtmannspoetter (2016), described the upper most layer as amorphous. This micro structuring of laser treated surface created a thin layer with strong nano-scaled bonding evident. (see Figure 2).

When considering adhesive qualities of coatings, understanding the micro restructuring of the surface and the resultant increase in surface area is central to achieving improved chemical and mechanical adhesion. Coatings capable of filling nano-pores, (see Figure 2 – cross section) such as low viscosity epoxies deliver outstanding results (J. Holtmannspoetter 2016).

Practical case studies

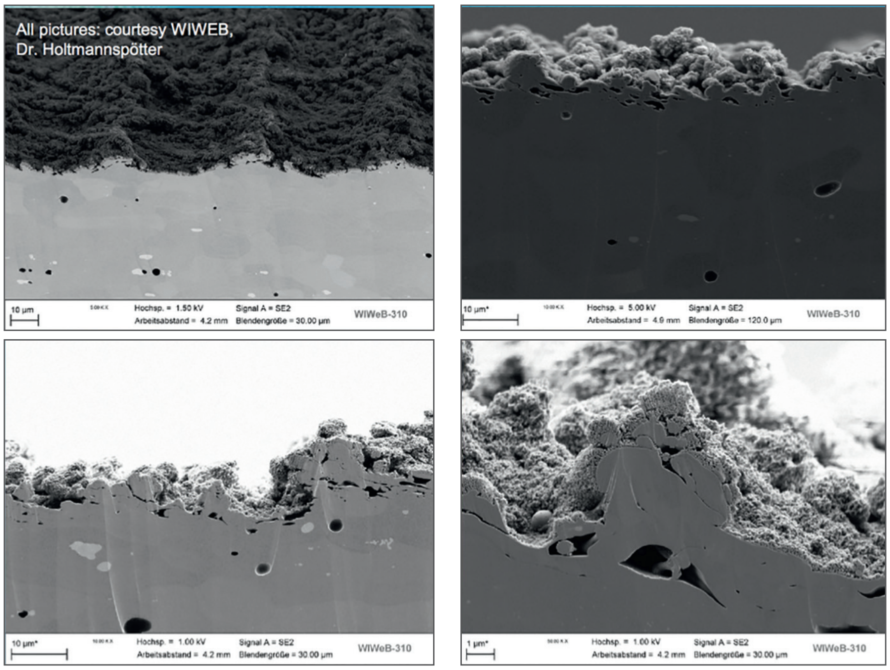
A versatile technology such as laser cleaning offers many possible applications. For example, it is being used to restore historic relics dating back thousands of years as well as the most advanced aircraft equipment. Most of the systems used today are fibre-coupled Nd:YAG laser systems in the power range of 100W to 1600W, either handheld or fully integrated into an automated process.

In most applications, an organic contamination layer or coating is


DETAILS OF LASER TREATED MICRO STRUCTURE

All pictures: courtesy WIWEB, Dr. Holtmannspötter

Figure 2. Details of a micro structured surface.


CROSS – sections

All pictures: courtesy WIWEB, Dr. Holtmannspötter

being removed from a substrate, or with applications that require a gentle removal without damage to the underlying substrate, as required in the aviation industry. Laser systems have been certified and are being used by civilian aircraft manufacturers to precisely remove coatings, such as the area around grounding contacts. One of the most progressive applications of laser cleaning technology exists where coatings are needed to be removed for NDT weld inspections in areas where abrasive blasting is considered problematic.

Another application with great potential is the cleaning of moulds. Lasers are being used to clean very large steel moulds for composite structures in the aircraft industry, moulds in the rubber and plastics industry, and even moulds used for the preparation of food. Laser surface preparation is a very clean process generating no additional waste. It does not spread waste around like CO_2 blasting. Further, laser cleaning does not degrade the precise geometry of expensive tooling in the same manner as abrasive cleaning methods. This enables the technology to be automated or integrated into existing production lines with considerable ease. For example, laser cleaning systems are being used to clean moulds in large baking ovens. Cleaning is carried out while the oven is producing a product, resulting in zero downtime.

The possibility of the rust and paint removal from the power transmission towers was investigated with the pulsed Nd:YAG laser for the first time. The red rust and paint were successfully removed without damaging underlying Zn(zinc) galvanized steel substrates.

External application for cleaning heritage buildings has obvious advantages with public safety. (see Figure 4.)

Conclusion

There is little doubt laser cleaning has progressed significantly from the success of inline manufacturing. The rapid advancements in fibre optic engineering has created a more compact powerful generation of mobile laser cleaning systems for a range of industry ready to adopt environmentally responsible, safer and more commercially viable solutions.

Figure 3. Laser cleaning steel.

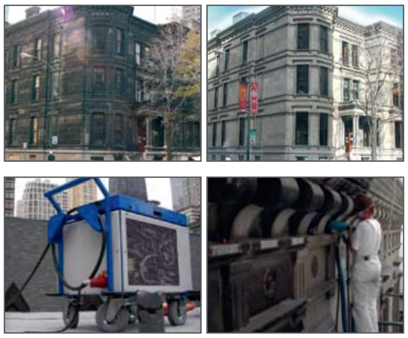


Figure 4. Cleaning heritage buildings.

BEN GUNNESS
Australia / Pacific Business
Development Manager
Laser Cleaning Technologies

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The Significance of the Alkali Aggregate Reactivity Provisions in the VicRoads Structural Concrete Specification Section 610

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1. Introduction

Deterioration of concrete has both internal and external origins. Deterioration of an internal origin is closely linked to the nature and chemical composition of the various constituents of concrete (cementitious materials, aggregates, water, admixtures etc), and to the internal chemical reactions in which they participate, particularly alkali aggregate reaction (AAR). The extent and rate of deterioration can also be controlled by the natural environment in which the concrete structure is situated (e.g. availability of water), the technological make up and mechanical properties of the concrete and the construction practices adopted (1).

AAR can cause expansion and subsequent cracking of concrete, thus further compromising its durability by exposing the concrete to the easier ingress of aggressive agents such as moisture, carbon dioxide, oxygen, other gases, and salt solutions which lead to premature corrosion of the steel reinforcement (1, 2, 3, 4). AAR also has important implications in the management of bridge assets and other concrete structures (2, 3).

The most common type of deleterious AAR in Australia is alkali silica reaction (ASR). ASR is a chemical reaction between the alkali hydroxides (sodium and potassium) in the pore solution and reactive silica minerals within the aggregates. It produces an expansive sodium or potassium rich (alkali) silica gel which has the ability to absorb further amounts of moisture and thus expand. When this expansive gel completely fills the pore system within the concrete it exerts excessive expansive stresses which can exceed the tensile capacity of the concrete. The result may be severe cracking of the concrete (1, 4).

For deleterious ASR to occur in a structure, the concrete must contain aggregate with a high proportion of reactive silica; the concrete pore solution must have a sufficiently high alkali hydroxide content; and there must be sufficient moisture, typically >85% internal relative humidity. The absence of any one of these inhibits the reaction.

AAR may take many years to manifest itself in a structure that contains the necessary ingredients for the reaction, with older bridges taking 20 to 30 years to exhibit visible signs of AAR damage. However, in recent years, significant AAR damage has been observed on structures, within 10 years of construction. This is mainly due to the use of higher cement contents and lower water to cement ratios without taking appropriate precautions to prevent AAR when reactive aggregates are used. For example, VicRoads structural concrete specification Section 610 (5) now specifies that adequate amounts of fly ash, slag, or silica fume, or combinations of these supplementary cementitious materials (SCMs), be incorporated into concretes containing reactive aggregates.

This paper outlines the causes and consequences of AAR, and describes how VicRoads manages the risk of AAR in its concrete structures. It explains the preventive measures specified in Section 610, and includes a case study illustrating the type of investigation needed to identify AAR and its effects in an existing structure.

2. Sources of Alkali and Moisture and Types of Potential Reactive Rocks

The alkali hydroxides are mainly derived from the Portland cement as they are present in its raw materials. Other possible sources include chemical admixtures, SCMs, water and alkali released from some aggregates. Ground water, sea spray and sea water can also supply alkali.

Mixing water in excess of that required to hydrate the cement can be retained as moisture within the pore system. More moisture can become available from rain and runoff, condensation, seasonal increases in humidity, leaking joints and inadequate drainage scuppers. Structures in moist environments, with surfaces immersed in water or exposed to regular cycles of wetting and drying, are particularly vulnerable.

Rocks must contain unstable amorphous or fine-grained silica minerals to be potentially reactive to alkalis. In Australia, potentially reactive aggregates include some originating from basalt, rhyolite, dacite and andesite, hornfels, granite and quartzite. Potentially reactive sedimentary aggregates include those originating from river gravel and sandstone (1, 4).

3. Visible Signs of Damage

The characteristic sign of AAR damage is a network of cracks known as map cracking. Cracking can also be directional, influenced by the direction of the largest applied stresses, such as in heavily reinforced concrete and prestressed concrete components, where cracking tends to be more prominent in the direction parallel to the steel reinforcement. Other visible signs of damage include damp patches, usually at crack junctions, and discolouration due to the calcium rich alkali-silica gel which migrates to the surface of the concrete.

A greater awareness of AAR and its potential damage to concrete in recent years has made it easier to identify the problem. Previously, AAR induced cracking of 20 to 40 year old bridges may have been attributed to other factors such as drying and plastic shrinkage, surface crazing or structural movements or loadings. Shrinkage cracks and surface crazing normally develop early in the life of the structure (i.e. within hours, or days/weeks after casting the concrete and certainly within the first year), whereas AAR induced cracking may appear after about 5 to 8 years, with further deterioration taking place in subsequent years.

4. Durability Considerations

The main deleterious consequences of AAR are related to potential reductions in compressive strength (up to 30%), tensile strength (up to 50%), flexural strength, elastic modulus (up to 60% to 80%), bond strength of the steel reinforcement and increased creep strain for concrete (1). Although not much evidence exists of significant reductions in structural capacity, reductions in the above physical properties do have the potential to adversely affect structural capacity with subsequent rehabilitation and strengthening requirements. The issue of greatest concern is the long term durability of concrete structures due to the network of cracks which substantially increase the permeability to aggressive agents. This can further accelerate deterioration mechanisms such as carbonation, chloride attack and corrosion of the steel reinforcement. Very porous and low strength concrete may be less susceptible to AAR induced damage as the gel products will tend to fill the porous microstructure first before they start cracking the concrete.

5. Management of Structures Affected by Cracking caused by AAR

Given the potential durability consequences it is important that AAR affected structures are inspected on a regular basis by personnel with appropriate experience. Monitoring of cracks should be undertaken using suitable measuring devices. Concrete cores are extracted from structures and examined by viewing thin sections with a petrographic microscope. Alternatively, a more detailed examination of polished sections of concrete can be done by scanning electron microscopy (SEM). An assessment is made of the existing and predicted future AAR expansion to determine the timing and type of remedial options. Measurement of residual expansion of AAR affected concrete may show that for some elements of a structure the reaction has been exhausted and they would not develop any further AAR related cracking (1, 4).

Depending on the source of external moisture remedial measures to prevent moisture ingress may include:

- the injection of cracks with flexible epoxy or elastomeric chemical grouts;
- the application of flexible epoxy, elastomeric acrylic or cementitious coatings; and
- silane impregnations where appropriate.

In severe cases, concrete encasement or concrete repairs and strengthening in combination with the above may be required whereas in the more severe cases, even propping and strutting may be required.

At present there is some precedent for extensive AAR repairs including the rehabilitation of Mitchell River and Tallangatta bridges undertaken by VicRoads some 15 years ago. More repairs will probably be carried out as AAR affected bridges and other concrete structures age and given the greater awareness of the problem by asset owners, especially State Road Authorities.

Given that cracking and subsequent deterioration occurs in the presence of water, cracks greater than 0.2 mm in width should be chased out and filled (injected) with a suitable flexible epoxy resin to prevent further ingress of water. In atmospheric or splash zones, the structure should subsequently be coated with a pore-lining penetrant such as pure silane to dry it out (or in combination with acrylic top coats), a flexible urethane or epoxy coating or a suitable cementitious coating.

Where cracks are less than 0.2 mm, an application with a pure silane, crack bridging or crack filling epoxy, urethane or flexible acrylic coating may be sufficient. In tidal or submerged zones flexible epoxy or urethane coatings, or polymer modified cementitious coatings may be the most appropriate. Re-application of these coatings will be required at regular intervals (in the order of 10 to 20 years) depending on the type of coating and exposure conditions until the problem is effectively controlled.

Based on the extent of cracking and other AAR related durability deficiencies, the required treatments may represent a significant ongoing cost to asset managers, given the expectation to significantly increase the service life of concrete bridges and other structures (1, 2, 3, 4).

6. VicRoads Specification Section 610 AAR Provisions

AAR expansion can be very difficult to stop once it commences, therefore minimising the risk at the time of construction is considered to be the most effective control. This can be best managed as part of specification requirements in the first place.

The AAR provisions of the 2013 version of VicRoads Section 610 (5) are aimed to further enhance and augment the momentum and knowledge already generated on the subject in the previous two decades including the initial AAR measures.

VicRoads Section 610 requires that a petrographic examination of aggregates be undertaken in accordance with ASTM C295. This is to characterise the aggregate source and to determine the presence of potentially reactive silica minerals.

The specification also requires that the potential alkali silica reactivity of the coarse and fine aggregates be determined using either the accelerated mortar bar test (AMBT) (VicRoads RC376.03, (6)) or the Concrete Prism Test (CPT) (VicRoads RC376.04, (7)) at least once every three years. Regular testing of aggregates for AAR is a very important requirement as the reactivity level of aggregates does change over time as influenced by the location within the bedrock deposits from which the aggregates are quarried. This is also strongly supported by AAR research work which shows several batches of low reactivity gneiss, dacite, hornfels and granite aggregates becoming more reactive than the batches tested some 5 and 10 years ago. Monitoring over time of AAR test results from the same source during VicRoads concrete mix design assessment work also supports this observation.

Establishing the alkali reactivity of aggregates is fundamental to the long-term management of VicRoads concrete bridges. Up to date knowledge of the actual reactivity of aggregates that are used in a particular bridge will assist with any future condition assessments and avoid limiting the range of options and adverse influence on the cost effectiveness of remedial measures that may have to be undertaken to ensure the 100-year design life requirements.

The average AMBT expansion should not exceed 0.1% at 21 days for coarse aggregates, or 0.15% at 21 days for fine aggregates, when tested with straight Type GP cement. Where potentially reactive aggregates are used, the total alkali content within the concrete mix must not exceed 2.8 kg/m^3 and SCMs must be used to ensure that expansion does not exceed either 0.1% at 21 days for coarse aggregates or 0.15% for fine aggregates.

As an alternative, for a longer term evaluation of aggregates using the less aggressive concrete prism test method (RC 376.04), the average expansion at 12 months is to be less than 0.03%, when tested with straight Type GP cement (7). Aggregates classed as reactive by the concrete prism test method in a concrete mix design, cannot be used in that particular concrete mix design. Alternative aggregates and/or alternative concrete mix designs must be used subject to compliance with the requirements of the specification.

The specification requires that where blended aggregates are used, the aggregates from different sources must be tested individually, and where fine and coarse aggregates are procured from the same source, only one alkali silica reactivity evaluation per source is required to be undertaken.

Table 1 - Minimum proportion of supplementary cementitious material (SCM) combination with Portland cement in the concrete mix to mitigate alkali aggregate reactivity (%) (5).

Supplementary cementitious material (SCM)	Minimum proportion of SCM in single combination with portland cement in the concrete mix to mitigate alkali aggregate reactivity (%)	Minimum proportion of SCM in double combination with portland cement in the concrete mix to mitigate alkali aggregate reactivity (%)		
		Fly Ash	Slag	Amorphous Silica
Fly Ash	20	-	-	-
Slag	50	-	-	-
Amorphous Silica	8	-	-	-
Fly ash + Slag	-	15	15	-
Fly Ash + Amorphous Silica	-	15	-	5
Slag + Amorphous Silica	-	-	40	5

Further to the minimum testing requirements above, where it is proposed to use aggregates that have been classed as reactive, the specification requires the use of concrete mixes which contain as a minimum the proportions of supplementary cementitious material as stated in Table 1 (5).

Where it is proposed to deviate from the minimum blended cement requirements stated in Table 1, the specification explicitly requires that further testing is undertaken to demonstrate compliance with both the maximum mortar bar and concrete prism expansion limits as determined by VicRoads test methods RC 376.03 and RC 376.04.

In addition to the above provisions, reference in Section 610 to the ATIC-SPEC SP43 (8), limits the amount of alkali content of the cementitious materials within the concrete mix to prevent or minimise the risk of AAR. These include:

(a) General purpose cement and Portland cement clinker to AS 3972, plus additional acceptance criteria within ATIC-SPEC SP43, including the total alkali content (Na_2O equiv.) not to exceed 0.6%.

(b) Fine grade fly ash to AS 3582.1 (9) and the following acceptance criteria. ‘Significant oxides’, defined as silicon oxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3), to be greater than 70%, plus the total and available alkali (Na_2O equiv.) to meet either of the following criteria:

- Total alkali content to be less than 3.0%, or
- For total alkali content greater than 3.0%, but less than 4.5%, the available alkali not to exceed 2.0% for any single determination.

(c) Slag to AS 3582.2 (10) plus additional acceptance criteria within ATIC-SPEC SP43, including the available alkali content (Na_2O equiv.) not to exceed 0.5%.

(d) Amorphous silica (silica fume) to AS/NZS 3582.3 (11) plus additional acceptance criteria within ATIC- SPEC SP43, including the available alkali content (Na_2O equiv.) not to exceed 0.5%. For slurried and densified (i.e. condensed or microsilica) amorphous silica, sampling and testing to be done from the raw silica used to make these products.

Minimum sampling and testing as appropriate for both available alkali content and total alkali content within the cement, fly ash, slag and amorphous silica is prescribed within ATIC-SPEC SP43.

The use of SCMs as cement replacements has proven to be very effective in reducing the negative effects of AAR. SCMs reduce the availability of alkalis for expansive reactions and make the concrete more water tight. Depending on the type of aggregate and magnitude of potential reactivity the minimum effective cement replacement levels are as indicated in Table 1.

It must be emphasised that from ongoing monitoring of VicRoads bridges constructed since the introduction of the AAR provisions into VicRoads Section 610 in 1996, no bridges have been found to exhibit any signs of AAR. The effect of fly ash is described in section 7 below.

7. Influence of Fly Ash in reducing the AAR Effect

Fig. 1 demonstrates the effectiveness of one particular fly ash in reducing AAR induced expansions (4). However, what Fig. 1 also shows is that whereas, 25% fly ash would definitely suppress the AAR expansion, 15% fly ash is unlikely to suppress the AAR reaction into the longer term and especially in situ, as AAR expansion appears to be taking off when the test actually ceased at 21 days. Insufficient amounts of SCMs may show up in testing as being adequate to suppress AAR, whilst in reality could lead to expansion and cracking of concrete structures in situ. The minimum proportions of supplementary cementitious material as stated in Table 1, aim to address this deficiency.

A research project undertaken by the ARRB on behalf of Austroads (12) studied the appropriateness of both the test methods and current test limits to be able to evaluate the effectiveness of SCMs to effectively suppress AAR. In addition, it studied the efficiency of the SCMs concerned and the optimum amount to be used in concrete to suppress AAR. These findings will be reported in a future technical paper. Based on these findings further improvements and refinements may also be undertaken in VicRoads Section 610 with respect to its AAR provisions including the requirements of Table 1.

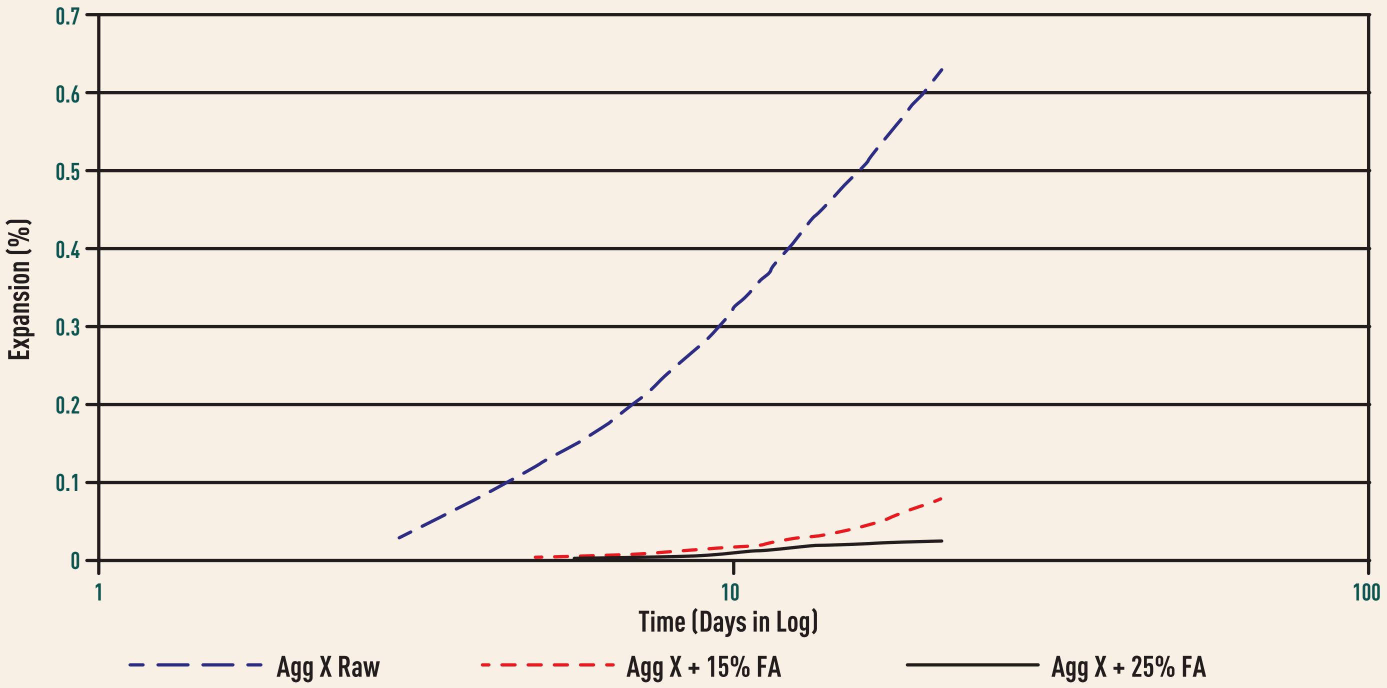


Figure 1. Accelerated Mortar Bar Expansion - Aggregate X with and without Fly Ash (4).

8. Testing for Potential Alkali Reactivity of Aggregates

VicRoads assesses concrete aggregates for potential alkali reactivity using of the following laboratory test procedures.

(a) Petrographic examination: an optical examination and analysis of the aggregate. This is undertaken to identify the types of minerals present and any suspect mineral phases. This is done using test method ASTM C295. Additional examination can be undertaken using scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis.

(b) VicRoads accelerated mortar bar test method RC 376.03 (6): Mortar bars are stored in caustic soda (sodium hydroxide) solution at 80°C and their expansion is monitored for the required period. The test is rapid and provides results in about 3 to 4 weeks. The average expansion should not exceed 0.1% for coarse aggregate and 0.15% for fine aggregate at 21 days.

(c) VicRoads concrete prism test method RC 376.04 (7): This test is considered to be less severe on the test samples and can be used to evaluate the aggregate performance over a 12 month period. The concrete prism test is appropriate when a longer period of time is available. Concrete prisms are produced using the actual concrete aggregates, with a minimum cement and alkali content, and are stored in sealed containers at 100% relative humidity and 38°C. The length of the prisms is measured at prescribed intervals for the 12 month period. Average expansion exceeding 0.03% at one year is considered deleterious.

(d) Determination of residual expansion in concrete from existing structures (2): Demec measuring studs are bonded onto the concrete cores with epoxy. Following the curing of the epoxy resin adhesive cores are soaked overnight in 0.5M sodium hydroxide solution at room temperature to allow them to absorb water without significant dilution of alkali in the pore solution of the concrete. The initial length is then measured, after which the cores are wrapped in moistened cloth and stored over water in sealed containers and transferred to a room kept at 38°C. The length change of the cores is measured periodically after equilibration at 23°C for a period of 12 months.

Two Australian standard test methods for evaluating the potential alkali reactivity of aggregates were published in 2014, namely, AS 1141.60.1 (accelerated mortar bar test) (13) and AS 1141.60.2 (concrete prism test) (14). These tests are similar to the methods used by VicRoads. However, the AS test methods require validation with actual testing and a reliable performance correlation established with the corresponding VicRoads test methods, for local aggregates before acceptance by VicRoads. In the meantime, VicRoads will continue to use its own test methods, which have proved reliable to date.

9. Case Study: 3 Year old Concrete Bridge affected by Alkali Aggregate Reaction (15, 16)

9.1 General

The occurrence of AAR in this bridge, built in 1991, highlights the significance of the AAR provisions in the VicRoads Section 610 first introduced in 1996 and further enhanced between 1996 and 2013. This bridge was constructed with a concrete comprising reactive aggregates and Type GP cement with a total alkali content exceeding the acceptable limit 0.6%, and without the inclusion of any supplementary cementitious materials. Premature cracking attributed to AAR, was identified some 10 years later.

The two-span bridge consists of a pre-stressed concrete (PSC) box girder and a monolithic pier wall and two abutments. Cracking was observed on the southeast abutment some 10 years after construction. A brief examination undertaken in 2003, of cores taken only from the south east abutment, indicated that alkali aggregate reaction (AAR) was present in the concrete. However, no other concrete was sampled at the time and it is unclear whether the pier wall had exhibited cracking in 2003, although cracking was clearly evident in the pier wall in the more recent investigation.

In 2014 an investigation (16) was commissioned into the concrete cracking at both the pier wall and the southeast abutment crosshead. The aim of this investigation was to assess the concrete for AAR and its future expansion potential and to determine the relevant mechanical properties of concrete which may influence the bridge integrity. The methodology described herein is appropriate for the investigation of suspected AAR in any existing structure.

9.2 Scope of investigation (16)

The investigation was limited to visual inspection and the extraction of five concrete cores taken from each of the pier wall and the southern abutment crosshead for the determination of the following properties:

- Visual features of cores
- AAR-related properties:
  - Petrographic examination
  - SEM examination
  - Available alkali content (soluble)
  - Residual expansion
- Compressive strength
- Modulus of elasticity
- Volume of permeable voids (VPV)

9.3 Field Investigation

9.3.1 Concrete Cores

Five cores were drilled from each component; one 95 mm diameter core and four 74 mm diameter cores. Cores were drilled from the southern side of the pier wall adjacent to cracks and cores from the abutment were taken from near the west end of the element, where cracking was seen a few years ago. The abutment crosshead has been coated since that time as part of maintenance intervention and the cracks are no longer visible.

Examination of the cores showed that the coating was elastic and was about 140 µm thick. Additional cores which stopped as they intersected the steel reinforcement showed no corrosion on the exposed bars.

9.3.2 Cracking in Components

Examination of the pier wall showed extensive cracking on all four faces. A few cracks were present on the side wall of the box girder and on the parapet near the abutments, where the components were accessible. Cracks in the abutment crossheads were covered over by the 140 µm grey elastic coating.

9.3.2.1 Cracking on Pier Wall

Long vertical cracks have developed from top to bottom of the pier wall surfaces, which are visible on enlargement of photographs due to the masking effect of the concrete coating previously applied as part of maintenance. The crack width was about 0.3 to 0.4 mm for finer cracks and 0.5 to 0.6 mm for the wider cracks (Fig. 2).

9.3.2.2 Cracking in Box Girder

Horizontal cracking was observed on the side face of the box girder over the west end of the southern abutment, which was highlighted in previous investigation (Aug' 03). The widest part of the box girder crack was measured at 0.25 mm (Fig. 2).

9.3.2.3 Cracking in Parapet

Cracking was noted in the lower part of the parapet, above the abutment crosshead, and in the kerb below the safety barrier. The vertical cracks are of regular space, which may be caused by shrinkage.

9.4.3 Visual Examination of cores

9.4.3.1 Cores from Pier wall

Concrete Core 1 was noted as dense, with no cracking evident. One aggregate particle at the fracture surface showed signs of AAR gel formation. The coarse aggregate contains a dark variety of 7-20 mm size and white/cream variety of a small particle size. Some of the white aggregate pieces show faint signs of gel impregnation at the cement paste interface. Core 2 and Core 4 were noted to be very similar to Core 1.

Core 5 was found to be similar to Core 1 with dark aggregate particle exhibiting definite signs of AAR and a nearby void filled with AAR product. Some white aggregate particles also exhibit signs of gel impregnation at their boundaries with the cement paste. Weak to moderate AAR may be present in the concrete.

The coarse aggregate in Core 3 is also largely of the darker variety and the white aggregate is largely in the fine fraction. A few of the white particles of 7-10 mm show mild signs of gel formation at their interface with cement paste. Several dark aggregate pieces show stronger signs of gel impregnation at their boundaries with the paste. Some AAR seems to be present in the concrete.

9.4.3.2 Cores from abutment crosshead (Surface coating on the outer face of cores)

Both types of dark and white aggregate are present in Core 6. Two pieces of steel reinforcement (16 mm dia.) are cut at depth of 60 mm and the edge of another bar is cut at 80 mm depth. A crack is present at the outer end of the core, which penetrates about 50 mm into concrete. A large pore and some small pores are filled with AAR products. Some aggregate pieces show AAR gel impregnating in the paste around them. Moderate AAR has occurred in the concrete. Internal aggregate cracking is present in some pieces.

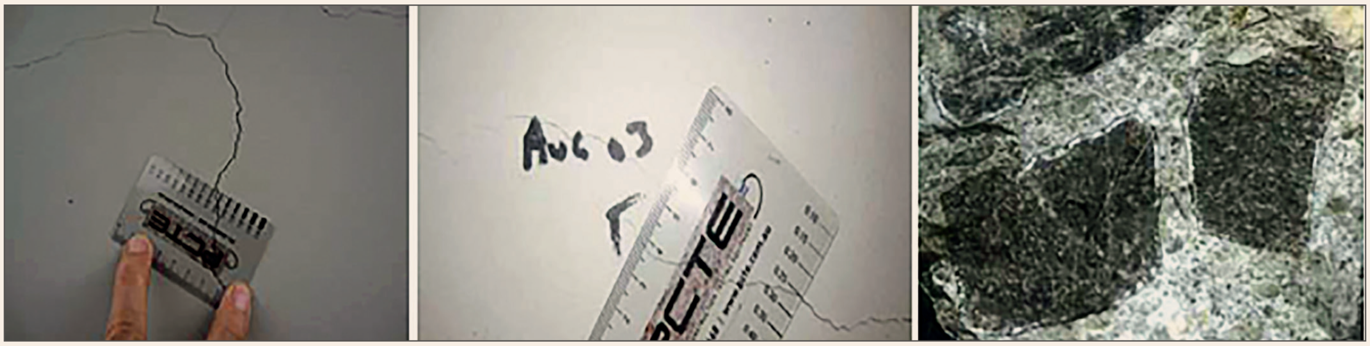


Figure 2. (L) Crack (0.6 mm) pier wall; (C) Crack on box girder wall; (R) typical reaction rim (16)

The interior fracture surface of Core 7 shows several aggregate particles with AAR rims and a 5 mm diameter void was filled with AAR product. Many aggregate particles exposed at the drilled surface of core exhibited a sweating look indicating AAR gel impregnation in the surrounding mortar. Both the dark and cream/brown aggregates have reacted. Moderate AAR is present in the concrete.

The features of Core 8 are similar to Core 7, but there is also a crack at the outer end of the core (beneath the surface coating) which penetrates about 80 mm on one side and 60mm on the opposite side. Finer cracks also extend to 80 mm depth. Some aggregate pieces show internal cracking. Another Core 9 has features similar to Cores 7 and 8 but the AAR signs are milder. There is no cracking at the outer end of the core.

Core 10 has features are very similar to those in Core 9. Cores 9 and 10 are from the middle of the crosshead which appears to have weak AAR.

Overall, the visual examination of cores indicated that moderate AAR is present in the concrete. This is illustrated by the typical, white reaction rims around some aggregate particles (Fig.2).

9.4.4 Petrographic examination of cores

9.4.4.1 Pier wall

The coarse aggregate in Core 3 is a mixture of metamorphic rock types of schist and gneissic rock types and all the particles exhibit strong signs of deformation and orientation, as indicated by elongated quartz grains and bands of micaceous minerals in parallel orientation. Some particles comprise a fine matrix of microcrystalline quartz and highly birefringent amphibole type minerals. Another variety includes a similar mineral assemblage, but with larger quartz crystals and the quartz also exhibits elongation. Some other particles resemble hornfels rock type. Particles of quartzite and quartz gravel with highly deformed quartz crystals are also present in which quartz shows patchy extinction and large undulatory extinction angles and sutured boundaries. All of these rock types are considered to be susceptible to AAR.

The fine aggregate fraction is a mixture of monomineralic quartz and feldspar crystals as well as finer fragments of the coarse aggregate particles. Some of the single quartz crystals also show moderate undulatory extinction angles. A portion of the fine fraction may be susceptible to AAR.

The cementitious matrix shows a considerable number of microcracks at the aggregate periphery, extending into the cement paste. AAR gel is definitely identified in some microcracks around the aggregate and in the microcracks within the paste. This concrete has clearly undergone AAR.

9.4.4.2 Abutment crosshead

The coarse and fine aggregates in Core 6 are similar to those described for Core 3. In addition, one dark brown and one black particle with cryptocrystalline matrix were present, comprising very fine quartz and probably micaceous minerals. These particles could be of rhyolitic nature. Carbon may be present in the black particle. Similarly to the previous core, the coarse aggregate and part of the fine aggregate are considered to be prone to AAR. The cementitious matrix exhibits considerable microcracking and AAR gel is clearly identified in the concrete, even to a greater extent than in Core 3 from the pier wall.

The petrographic examination clearly shows that ARR is present in the pier wall and abutment crossheads concrete.

9.4.5 Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis

The SEM/ EDX examination of both the pier wall and abutment crosshead cores provided strong evidence of the presence of AAR products in the concrete, both in and around aggregate particles, and in the microcracks in the cement paste. Some products were highly enriched with alkali and some contained aluminium, which indicated that in addition to the silica minerals, feldspar minerals may also have been involved in the reaction. Overall Core 7 from the abutment crosshead appeared to contain more extensive reaction products than the cores from the pier wall.

9.4.6 Compressive Strength

The average compressive strength of the four cores tested was 41.2 MPa, and there is no difference in the level of strength for the pier wall and abutment crosshead (Table 2). The strength indicates that the concrete may be of VR400/40 strength grade, although it is just on the borderline of the required 40 MPa for characteristic strength. These values of compressive strength may overestimate the actual strength of the element as cores are drilled in sound portions of concrete away from cracks, whereas the element itself would contain a considerable extent of cracking.

ID	Component	Strength (MPa)	Mean ± 95% confidence range
Core 1	Pier wall	43.1	41.2 ± 4.0 MPa
Core 4	Pier wall	37.7	
Core 7	Abutment Crosshead	42.9	
Core 10	Abutment Crosshead	41.3	

Table 2 - Compressive Strength (16)

9.4.7 Volume of Permeable Voids (VPV)

VPV undertaken in accordance with AS 1012.21 (17) is a measure of porosity and permeability of concrete and influences several durability properties of concrete. VicRoads Section 610 states that cores drilled from a concrete of VR400/40 grade must not exceed a VPV value of 16%.

The VPV results for the cores taken from sound portions of concrete away from cracks of the pier and abutment crosshead were 15.4% and 15.6%, respectively. These values can be considered acceptable with respect to VicRoads requirements.

9.4.8 Modulus of Elasticity

Cores 5 and 9 were subjected to modulus of elasticity testing, in accordance with AS 1012.17 (18)

When tested, core 9 (abutment crosshead) achieved the lowest static chord modulus value (19 GPa). The static chord modulus value for Core 5 was of the order of 27 GPa (reduction of about 20% compared to design requirements for this type of concrete). The lowest modulus of 19 GPa (reduction of about 45%) for the abutment crosshead in young bridge is attributed to the more extensive occurrence of AAR in this concrete.

9.4.9 Water soluble Alkali Content

The water soluble alkali content in the cores from the pier wall and the abutment crosshead was 3.78 kg/m^3 and 3.06 kg m^3 (> than permitted maximum of 2.8 kg/m3), respectively, as shown in Table 3. Assuming that the concrete was of VR400/40 grade, the water soluble alkali as a percentage of cement mass would be 0.94% and 0.76% in the concrete of

	Alkali per weight of concrete (%)				Alkali per volume of concrete (kg/m^3)			
ID and Component	CaO	Na_2O	K_2O	Na_2O eq.	CaO	Na_2O	K_2O	Na_2O eq.
Core 3, Pier	0.249	0.112	0.086	0.169	5.59	2.51	1.92	3.78
Core 8, Abutment Crosshead	0.269	0.090	0.071	0.137	6.02	2.01	1.59	3.06

Table 3 - Water Extractable Alkali Content (16)

the pier wall and abutment crosshead, respectively. These values are higher than the 0.6% permitted, which may indicate that a local GP cement which is no longer available was used in the concrete, which had alkali contents in the range of 0.9 – 1.1 %. If the cement alkali content was actually lower than in the local cement, then the additional alkali may have been contributed from the aggregates and chemical admixtures in the concrete mix.

It is generally accepted that an alkali content of greater than 2.8 kg/m^3 (refer also to Section 610) is required to sustain AAR in concrete. Therefore, it can be expected that AAR will continue in the concrete, if sufficient moisture is available and sufficient reactive silica remains, particularly if the aggregate phase releases alkali into the concrete. Petrographic features of the aggregate identified as part of this investigation suggest that this may be possible.

9.4.10 Residual Expansion

Cores 3 (pier wall) and 6 (abutment crosshead) which had a diameter of 95 mm were fitted with Demec studs and exposed to conditions of 100% RH, 38°C to enhance AAR expansion, which would reflect the residual expansion potential of the concrete. The expansion of the cores is being measured by using a Demec gauge. The residual expansion potential is determined by the value of expansion measured after one year, when the expansion usually flattens out.

The expansion results are presented in Fig 3 and at 365 days of exposure the expansion of both cores is relatively large and far exceeds the allowable limit of 0.03%. Core 6 from the abutment crosshead exhibits significantly higher expansion at the age of one year. The trend for both cores indicates that further reaction and cracking is likely in these elements.

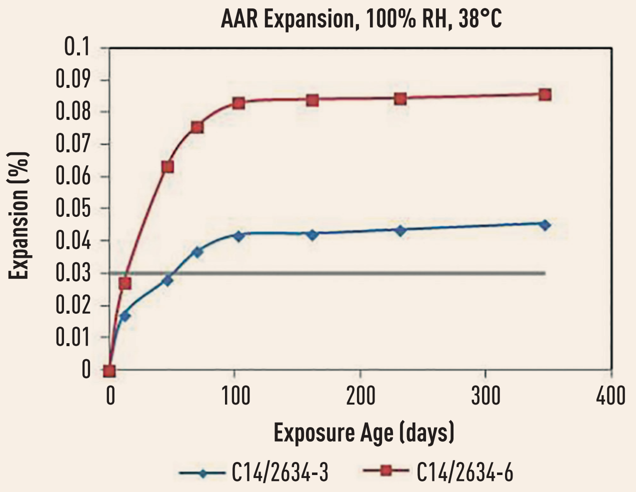


Figure 3. Residual expansion of concrete. Core 3 from pier wall. Core 6 from abutment crosshead(16)

9.4.11 Discussion

The post-tensioned box girder bridge referenced in this paper (constructed in 1991) situated in a moderate environment (exposure classification B1), was constructed with a concrete comprising reactive aggregates, Type GP cement with a total alkali content exceeding 0.6%, and without the inclusion of any supplementary cementitious materials. Within 10 years in service it was identified as suffering from premature cracking. A brief examination undertaken in 2003, of cores taken only from the south east abutment, indicated that alkali-aggregate reaction (AAR) was present in the concrete. A more detailed AAR investigation undertaken in 2014 established that both the pier wall and the abutment crosshead of the bridge are suffering from AAR. Both elements have developed considerable amount of cracking as a result of AAR. Crack widths in the pier wall are in the range of about 0.4 mm to 0.6 mm. The cracks previously reported for the abutment crosshead have been masked by the newly applied, grey surface coating. In addition both elements have exhibited high residual expansion potentials as judged by measurements for up to 365 days of exposure. This trend is expected to continue and indicates that the concrete would develop further expansion and cracking. This is further supported with the water extractable alkali content in the concrete of 3.8 and 3.0 kg/m^3 (> than allowable of 2.8 kg/ m^3) in the pier wall and abutment concrete, respectively, which is adequate for AAR to continue.

The elastic modulus of the concrete in the pier wall at this stage was determined at around 27 GPa (about 20% lower than design requirements for this type of concrete) and that in the abutment crosshead 19 GPa (about 45% lower than design requirements for this type of concrete), which suggest that the latter element was more seriously damaged by AAR. This is in agreement with other microstructural observations.

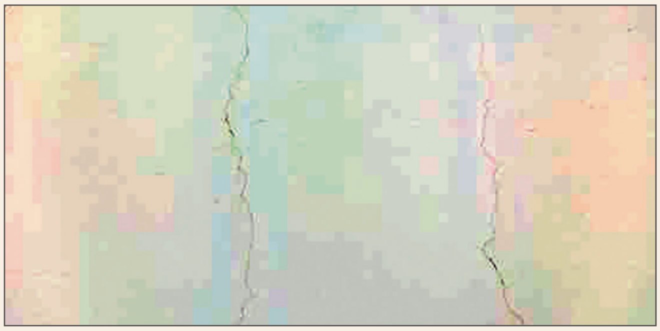
It is important to emphasise that given the high alkali content within the concrete to sustain further reaction and expansion and the confirmed high residual expansion potential into the future, further cracking and reductions in strength and modulus of elasticity and possibly flexural and bond strengths will occur.

Based on these results an effective coating should be maintained to reduce the rate of AAR induced expansion. It was also considered that suitable strengthening and/or durability measures may be required for the bridge in the longer term to reduce the rate of expansion. The box girder of the bridge was not tested. However, given its importance it is considered that the bridge box girder also required testing given the likelihood that it may be made from similar concrete. In addition, it was considered that other bridges in the area that used similar concrete would also need to be assessed for AAR induced deterioration.

Overall view of bridge constructed in 1991.

Bridge viewed from west and core drilling on the south side of the pier wall.

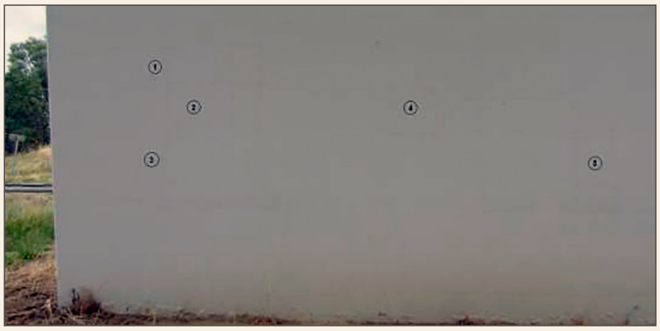
Locations of 2 cores taken from the middle part of the west abutment crosshead.



Enlargement to show vertical cracks.

Cores of 95 mm diameter taken for residual expansion measurement: Core 2634-3 from pier wall; Core 2634-6 from abutment crosshead.

Typical Alkali Aggregate Reaction rim .



Locations of cores taken from the pier wall.

Crack (0.35 mm) on south face of pier wall.

Crack (0.40mm) on north face of pier wall.

10. Conclusions

The unsatisfactory results of the 23 year old freeway overpass bridge, the significant AAR investigation costs over the past 10 years and the expected high repair costs highlight the importance of the AAR provisions, the concrete mix design (aggregate and other ingredient properties change over time) requirements and the overall integrated durability provisions in Section 610 progressively introduced and further enhanced since 1996. The AAR provisions in Section 610 which would have prevented the AAR damage in the 23 year old bridge presented in this paper can be summarised as follows:

- Petrographic examination of aggregates.
- Alkali silica reactivity testing of both the coarse and fine aggregates on a 3 yearly basis.
  - AMBT testing has shown that low reactivity aggregates were found to be significantly more reactive than the same aggregates tested over a 10 year period.
- AAR expansion limits for both fine and coarse aggregate.
- Provision for both accelerated mortar bar test method (RC 376.03) and concrete prism test method (RC 376.04).
- Concrete mixes to contain minimum proportions of supplementary cementitious material to mitigate AAR.
- Limitations on alkali content within the cement and the various cementitious materials.
- Alkali content in the concrete mix not to exceed 2.8 kg/m^3 (Na_2O equiv.).

Finally, it should be noted that in contrast to the condition of the 23 year old freeway overpass bridge (which showed AAR affected cracking some 10 years after construction), ongoing inspection and monitoring of a number of VicRoads bridges constructed since the mid 1990s in various in-service exposure conditions have not exhibited any signs of AAR related damage, demonstrating so far the effectiveness of the AAR preventative measures included in VicRoads Section 610. It is considered that these preventative measures will ensure the long term durability performance of VicRoads bridges and minimise unnecessary and costly maintenance needs.

11. Acknowledgements

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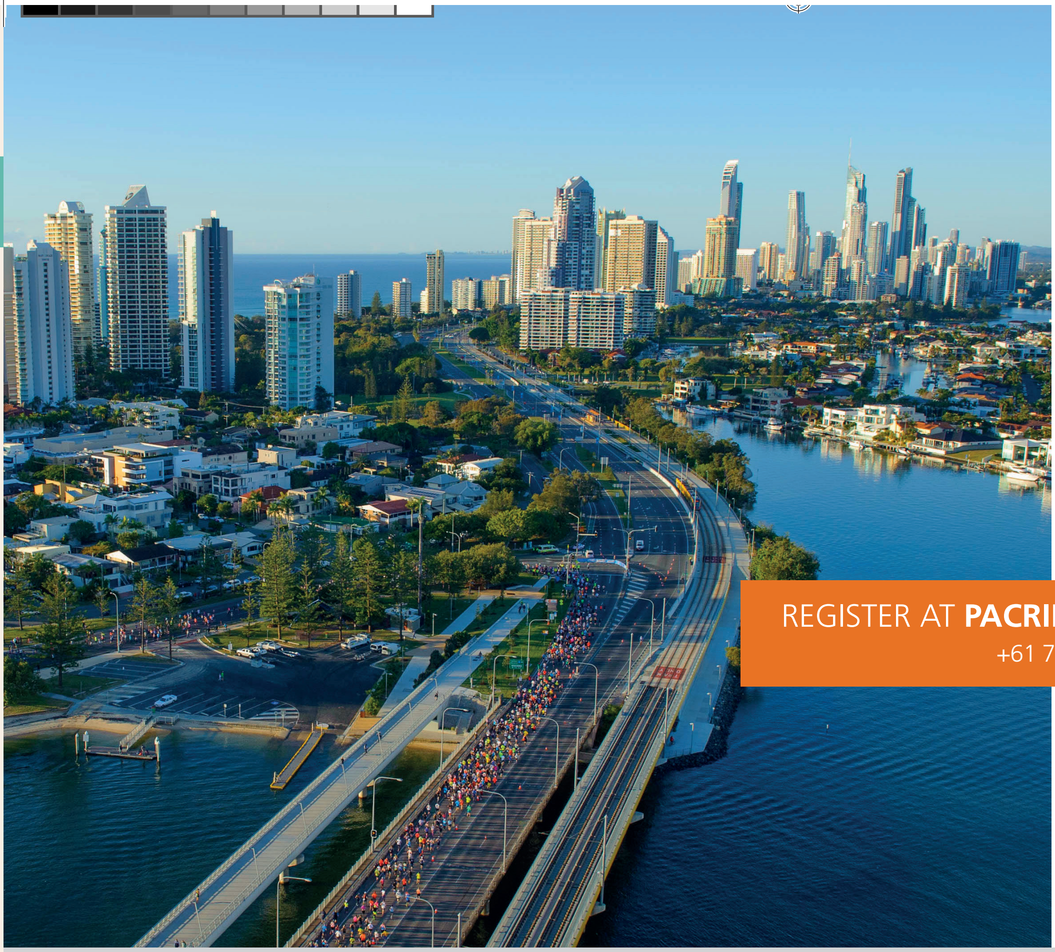
For further information on this topic refer also to *SA/CCAA HB 79-2015, Alkali Aggregate Reaction - Guidelines on Minimising the risk of Damage to Concrete Structures in Australia*.



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NZTA Experiences with the Protection and Repair of Concrete Road Bridges

Barry Wright

New Zealand Transport Agency, Wellington, New Zealand

1. Introduction

The NZ state highway network includes approximately 4,300 bridges and major culverts. The structures numbers and material types are summarised in Tables 1 and 2 below. A summary valuation is shown in Table 3.The average bridge age on the state highway network is approximately 40 years old compared to the standard design life of 100 years. The bridge asset is therefore relatively young. However, approximately 5% of existing structures are over 90 years old and approximately 17% are over 80 years old. In addition to this, approximately 13% of all NZ state highway bridges are located in the coastal frontage or tidal splash/spray environments and are therefore more susceptible to chloride ingress causing steel reinforcement (conventional and prestressing) corrosion.

Table 1. NZ State Highway Bridges Material Types

Superstructure Material Type	Number	Percent by Number	Percent by Area
Reinforced Concrete	1260	45%	30%
Prestressed Concrete	915	32.7%	49.8%
Steel	440	16%	20%
Timber	3	0.1%	0.1%
Masonry	5	0.2%	0.1%
Not recorded	170	6%	-
Total	2793		

Table 2. NZ State Highway Culvert Material Types

Superstructure Material Type	Number	Percent by Number
Reinforced Concrete	964	76%
Prestressed Concrete	3	0.2%
Steel	210	16.8%
Timber	2	0.2%
Aluminium	30	2%
Not recorded	57	4.8%
Total	1266	

Table 3. NZ State Highway Structures Valuation

Description	Replacement Value (NZ$)	Depreciated Value (NZ$)
Bridges	$6.0B	$3.9B
Culverts	$0.5B	$0.3B
Auckland Harbour Bridge	$0.8B	$0.3B
Total	$7.3B	$4.5B

2. Bridge Management Practices

The inspection and maintenance management of state highway structures is outsourced to consultants through ten regional contracts that cover the whole country. Bridge inspections are specified to identify defects and there are processes in place to cover the development of maintenance proposals, funding, design and physical works. This has generally resulted in a reactive approach to corrosion in reinforced and prestressed concrete bridges. When defects, such as concrete spalling, were identified then wider investigations would be instigated to determine the scope, severity and urgency of the issue.

Historically there was no formal national policy for proactive investigations of corrosion but such work could have been promoted by the New Zealand Transport Agency (NZTA) and/or the regional bridge inspection engineer.

A research project to investigate the condition of bridges deemed to be at higher risk of corrosion was completed in 2013, as outlined in Section 3 below.

NZTA has also recently developed a screening process to identify bridges with the potential for failure under live load. This includes bridges at a high risk of corrosion. The screening process has been implemented through the regions but the results have not yet been completed and considered. It is anticipated that the results will provide a prioritised schedule of structures that will then require more detailed investigations of individual bridges.

3. Research Project

3.1 Project Outline

An NZTA research project was carried out entitled “Assessing Pre-tensioned Reinforcement Corrosion within the New Zealand Concrete Bridge Stock” (Rogers et al, 2013). The primary aim of the project was to obtain an accurate assessment of the severity, prevalence and distribution of corrosion damage to all of New Zealand’s pre-tensioned prestressed concrete bridges.

The project was initiated because a large number of pre-tensioned concrete bridges had been constructed between 1950 and the 1970s, and it was recognised that many of these designs did not meet current durability criteria and also included design characteristics that predispose them to corrosion of the pre-tensioned reinforcement. In addition, it is recognised that corrosion of pre-tensioned concrete is more critical than corrosion of conventional steel reinforced concrete.

The project identified 137 bridges as having a high likelihood of being at risk of pre-tensioned reinforcement corrosion either now or in the future. These bridges were identified as being actually in a saline environment or being within 1km of the coast. A sample of 30 of these bridges was then selected for more detailed inspection and investigation.

In summary, 29 of the 30 inspected bridges were found to be affected by chloride ingress with eight of these predicted to experience reinforcement corrosion within their 100 year service life as a result of that chloride ingress. In four of these cases the corrosion was of the shear reinforcement and in the other four it was corrosion of the pre tensioned reinforcement.

The research project also found cast-in chlorides in the prestressed bridges due to the use of chloride-based set accelerating admixtures. More specifically, of the 30 coastal bridges they investigated, 21 of the 29 affected included cast-in chlorides.

3.2 Project Examples of Affected Bridges

The Tiwai Bridge is located near Bluff in Southland and crosses Awarua Bay. It was constructed in 1969 and comprises 27 spans of T beams. The bridge is located in a coastal saline environment and inspection in 2004 identified serious corrosion of the pre-tensioned strands, refer photo at Section 9.1. The cause of the early failure was attributed to very low concrete cover and also the fact that the shear reinforcement did not enclose the strands. The super-structure was replaced in 2010.

The Boundary Bridge was constructed in 1963 and comprises a single span of precast, pre-tensioned concrete I beams. The bridge is located north of Thames at the base of the Coromandel Peninsular in the North Island, and specifically in the coastal exposure zone. Visual inspection had already identified severe corrosion of the pre-tension reinforcement within the I-beams, refer photo at Section 9.2, with the entire cross section of several wires in the bottom layer of pre-tensioned reinforcement being lost. This was attributed to low cover and the fact that the shear reinforcement did not enclose the pre-tension reinforcement. Extensive remediation works were completed in 2010.

The Fox River Bridge is located south of Westport in the West Coast region of the South Island. It was constructed in 1969 comprising multiple spans of I beams located in the coastal zone, refer photo at Section 9.3. Inspection indicated that the bridge was generally in good condition with no visible signs of any significant defects. Chloride ingress measurements and modelling indicated that the initiation of corrosion of the stirrups would occur after about 43 years and pretensioned reinforcement about 12 years later. Subsequently more detailed investigations demonstrated that corrosion had not actually initiated and that it was probable that the structure could be managed to achieve the 100 year design life. The structure continues to be monitored (Lee, 2017).

The Ngakawau Bridge was constructed in 1992 and comprises 5 spans of U beams, refer photo at Section 9.4. The bridge is located north of Westport in the West Coast region of the South Island, also in a coastal saline environment. Inspection indicated that the bridge was in excellent condition with no apparent signs of corrosion of reinforcement or strand. Initial investigations and modelling showed that there were no cast-in chlorides but that chloride ingress could result in corrosion initiation levels at the pre tension reinforcement after just 18 years. Subsequent more detailed investigations demonstrated that corrosion had not actually initiated and the structure continues to be monitored (Lee, 2017).

The Hamanatua Bridge was constructed in 1966 and comprised 3 spans of I beams. It is located near Gisborne on the east coast of the North Island. The bridge is 200m from a surf beach and is nominally in the B2 exposure zone but at the more aggressive end of that zone. Concrete cover to the prestressing steel was specified at 25mm, well below the current code requirements. In addition, the transverse reinforcement does not fully enclose the pretensioned strands.

Routine inspection of the Hamanatua Bridge identified splitting cracks in the lower flanges of some of the I-beams and subsequent investigation revealed the cracking was as a result of corrosion of the prestressing steel, refer photo at Section 9.10. The cause of the corrosion was atmospheric chloride ion contamination. Structural analysis was carried out to assess the impact of the prestressing strand corrosion which showed the bridge capacity was not significantly affected due to the short lengths of corrosion and the fact that the worst affected beam was under the footpath. It was subsequently decided to repair the beams using a proprietary cement-based patch repair system incorporating galvanic zinc anodes to guard against incipient anode formation.

3.3 Research Conclusions

In summary the key conclusions of the research project were:

- Corrosion occurs primarily in the coastal exposure zone but can also occur in adjacent zones,
- Cast-in chlorides due to the use of chloride-based set accelerating admixtures were identified in 21 out of the 29 bridges in the coastal zone affected by chloride contamination. Cast-in chlorides occurred in some beams but not in others on the same bridge.
- Chloride build up on the surface of a structure varies significantly even in apparently the same conditions of location and exposure.
- The critical location for chloride ingress (i.e. the location with the highest level of chloride ingress), varies significantly even in apparently the same conditions of location and exposure. The critical location for chloride on any bridge cannot therefore be predicted.
- Similar designs in similar exposure zones performed quite differently.
- Some bridges have poor chloride resistance for unknown reasons.
- Some bridges had low surface chloride concentrations in the Coastal exposure zone for no apparent reason.

4. Corrosion of Reinforced Concrete Bridges

4.1 Introduction

Almost half of the bridges on NZ state highways are constructed from conventional steel reinforced concrete and these are generally also the older bridges on the network.

There are hundreds of conventionally reinforced concrete T beams that were constructed to standard designs of the time (1930s'), across the full range of exposure zones. The standard specification for concrete cover varied from 1.5 – 2 inches (38-50mm) with concrete strength specifications between 17 and 21MPa. The actual concrete strength often exceeded 30MPa thus enhancing the durability performance. However concrete quality of these bridges was variable with segregation and lack of compaction being a common issue around congested reinforcement at the base of the beams.

A formal systematic review of durability performance has not been undertaken to date. Typical examples of reinforced concrete bridges with known corrosion issues are outlined in the next section.

4.2 Examples of Reinforced Concrete Bridges

The old Mangere Bridge is located in the Auckland urban area and was constructed in 1914. It comprises 17 spans of reinforced concrete beams and piers located in the coastal marine environment of the Manukau Harbour. The bridge was closed to vehicular traffic in 1985 but remained open for pedestrians and fishermen since then. The bridge has suffered from reinforcement corrosion in the form of extensive cracking, delamination, loss of steel section and concrete spalling as well as ship impact damage, refer photos at Section 9.5. Various maintenance and strengthening works have been carried out since 1985 to maintain the structure with sufficient strength to ensure the safety of pedestrians and other users. These works have included, reinforced concrete jackets to columns, patch repairs, external prestress, partial deck overlay and so on. More recently the access to the deck has been physically restricted in order to limit live load due to pedestrians and fishermen to only those areas of the bridge that can actually support such loads. Other areas are limited to structure dead load only.

The Whirokino Trestle Bridge is located on state highway 1 just north of Levin on the west coast of the North Island. It comprises 90 spans of reinforced concrete beams and piers in exposure zone B1 but is exposed to salt borne prevailing winds. Chloride contamination levels at the depth of the reinforcing steel exceeds 0.1% by weight of concrete, which is surprisingly high considering the bridge is 6 km from the coast. There is no significant carbonation. The high contamination levels are attributed to the onshore prevailing westerly wind and the lack of any sheltering topography. The concrete spalling on the beams (refer photo at Section 9.8), deck and piers is now extensive and a detailed condition assessment in 2014 showed the bridge had an estimated patch repair volume of about 90 cubic metres. However there has been very little loss of cross sectional area of reinforcement and the structural capacity of the bridge has not yet been directly affected. Repairs have been carried out reactively since about 1985 starting with locally formulated concrete and mortar repairs which later evolved into the use of proprietary cement-based patch repairs. Various patch repairs have been undertaken since then. The maintenance costs over the last 30 years or so have been reasonable despite the patch repairs required and were insufficient to justify replacement of the bridge. The bridge is now being replaced for a combination of durability and functional reasons.

The old Kopu Bridge is located near Thames at the base of the Coromandel Peninsular in the North Island. It comprises 25 spans of steel plate girders with a reinforced concrete deck on reinforced concrete piers in the coastal marine environment. Refer photo at Section 9.9. The bridge was constructed in 1927 and was replaced with a new bridge in 2011 built for functional reasons. The old bridge is a Category 1 heritage structure and currently remains intact. The piers are in poor condition with spalling due to corrosion of the reinforcement and some loss of steel section. High chloride ingress has been recorded in the tidal zone of the structure. Extensive remediation works have not been undertaken to date but will be required if the bridge is to be retained for heritage purposes. It is thought that any form of patch repair would be expensive and futile due to rapid failures and ongoing deterioration. One potential remedial option being considered is some form of partial reconstruction involving jacketing where the piles would be broken out to remove all loose or spalling concrete then jacketed with an 80mm thick jacket reinforced with stainless steel reinforcement. The jackets would be designed to provide the structural support to the bridge with no contribution from the original reinforcing.

4.3 Conclusions

These bridges have generally performed well but in coastal locations some have been replaced already and others are currently being maintained using repeat cycles of patch repairs. The above three examples are typical of the experience across the wider network and support the following conclusions for reinforced concrete bridges:

- Corrosion occurs primarily in the coastal zone but can also occur in adjacent zones under the right circumstances.

- Corrosion results in spalling concrete that usually provides clear signals for inspectors.

- Loss of steel section only occurs slowly often over a period of many years. Therefore remediation works can be delayed and/or managed to extend the life of the bridge for decades at a relatively low cost. This approach usually provides good value for money compared with a bridge replacement.

- The performance of apparently similar bridges in similar circumstances can vary significantly.

5. Patch Repair Techniques

Conventional patch repair involves the removal of unsound concrete at visibly obvious locations, such as spalls and cracks, to a depth of at least 20 mm behind the reinforcement to eliminate chloride-contaminated concrete. After replacing or treating the steel, as appropriate to the level of corrosion damage, the concrete is reinstated by hand-application, casting or spraying, depending on the volume of the repair. Best practice for conventional patch repairs indicates hydro-demolition for removal of the concrete, use of proprietary Portland cement-based repair materials from reputable manufacturers for reinstatement, and the provision of galvanic zinc anodes to guard against incipient anode corrosion cells developing adjacent to the newly completed repairs.

Well-executed patches are a viable strategy for extending the life of a deteriorating reinforced concrete structure and the repairs should remain durable for at least 10-15 years if protected with galvanic zinc anodes. However where there is more widespread chloride ion contamination it can be expected that other areas of concrete not repaired, may begin to fail within 10 to 15 years and further repairs will be required.

6. Protective Coatings

A New Zealand Transport Agency research project was carried out into protective coatings to delay corrosion damage of concrete structures (Freitag and Bruce, 2010). The primary findings of the study are summarised below.

- Current design and construction standards should deliver a 100 year service life without surface treatments for concrete.

- In the atmospheric and occasional splash zones, silane and siloxane have the potential to extend the service life of bridges if applied before corrosion damage occurs.

- Surface treatments should not be applied to newly built structures because they might not be able to penetrate the surface sufficiently and may result in concrete drying prematurely reducing potential performance. However they may be used for remedial works by exception, when new concrete does not meet the specified requirements.

- Silicon based penetrants are most cost effective when applied immediately prior to the initiation of corrosion and are most likely to benefit bridges in the most severe exposure classifications B2 and C.

- The justification for protective coatings should be based upon a combination of economic analysis and engineering judgement.

Generally current practice is that surface coatings are only usually applied when other repairs are being carried out and the incremental cost of a coating is small.

7. Cathodic Protection

The original Causeway Bridge is located on state highway 16 in the Auckland urban area and was constructed in the 1950s using reinforced concrete. The bridge is in a coastal marine environment. The bridge was duplicated in the 1960s using pre-tensioned reinforced concrete I beams and piles. It was then widened in the 1990s using pre-tensioned reinforced concrete U beams and piles. Further widening is now required and so the condition and longevity of the existing structures is a key factor in determining the optimum long-term solution.

A durability assessment was undertaken to establish the current condition and to determine probable future durability performance over a period of 50 years. The assessment was conducted on representative samples of the substructure and included the following tests: visual examination; chloride content sampling at varying depths; depth of carbonation; compressive strength of concrete; cement content and type; reinforcement continuity and concrete resistivity.

The test results indicated the following:

- The cover to reinforcement varied between 40 mm and 80 mm in the piers depending upon their age of construction with newer piles having the higher cover.
- Cement content varied from 12.8 to 17% by weight with an average of 14.2%.
- The chloride content at the level of reinforcement was higher than general industry accepted lower threshold of 0.06% by weight of concrete for plain steel and 0.03% by weight of prestressed steel. Maximum chloride values of up to 0.32% were measured.
- Visual inspection indicated minor pitting in the reinforcement at selected breakouts but no cracking of concrete as yet. There were also isolated cases of concrete cracking and rust staining on piles.

It was concluded that cathodic protection was required on the existing structures to ensure a remaining life of at least 50 years without significant maintenance.

A hybrid cathodic protection system (HCP) has been designed and commissioned for both the Causeway and the adjacent Whau bridges. The HCP system comprises discrete zinc anodes which were installed on both the reinforced and prestressed concrete piles from Lowest Astronomical Tide (LAT) level up to the soffit of the crossbeams. The anodes operate in two phases, initially energised using low voltage DC power to arrest ongoing corrosion and thereafter in galvanic mode to provide corrosion prevention for the residual service life. HCP minimised physical works on site, negated the requirement for extensive replacement of chloride contaminated concrete, allowed work to take place accommodating incoming and outgoing tides and offers protection against chloride induced corrosion to the substructures.

8. Discussion And Conclusions

Experience has clearly shown that there are some key factors that contribute to the corrosion of concrete bridges. These factors include:

- The exposure zone.
- Concrete cover and design detailing.
- Design and construction quality of concrete.

Experience has also shown that there are significant unexplained differences in real life that can result in durability performance that is significantly better or worse than would initially be predicted. However they may be at least partially explained by concrete quality, construction quality and exposure microclimates.

Corrosion of reinforced concrete in NZ bridges is generally obvious and takes many years before significant structural deterioration occurs that might impact on the structural performance of the bridge. Traditional inspection regimes will identify corrosion and a reactive remediation programme is a low risk and good value option in most circumstances.

Corrosion of pre and post tensioned reinforcement is potentially less obvious and can result in significant structural deterioration in a relatively short period of time. Such corrosion therefore has an inherently higher risk in terms of consequences. It is also more difficult and costly to remedy. Therefore a more proactive approach to identification and management of this corrosion is warranted.

In cases where longer term durability performance is required and corrosion has already initiated then cathodic protection techniques provide potentially viable solutions.

9. Photographs

9.1 Tiwai Point Bridge

9.2 Boundary Creek Bridge

9.3 Fox Bridge

9.4 Ngakawau Bridge

9.5 Mangere Bridge

9.7 Tutaekuri Bridge

9.8 Whirokino Trestle Bridge

9.9 Kopu Bridge

9.10 Hamanatua Bridge

General view of the Fox River Bridge & environs.

View of the underside of Fox River Bridge showing the simply-supported pre-stressed I-beams.

General view of the Ngakawau River Bridge & environs.

Underside of the Ngakawau River Bridge showing the good condition of the U-beams.

Spalling at base of the hammerhead on Pier C on the Fox River Bridge.

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Up-to-date Review of Aspects of Steel Reinforcement Corrosion in Concrete

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1. Introduction

Professor Brian Cherry in his education of students and practitioners had always ensured that fundamental aspects were conveyed. Following the Cherry mantra, it is appropriate to begin this symposium with an overview of key fundamentals and mechanisms when it comes to the protection of reinforcement by concrete. There are several degradative processes which affect some reinforced concrete structures and amongst these, the most common cause of deterioration is the corrosion of steel reinforcement. An up-to-date review of the key fundamentals and mechanisms of corrosion of steel reinforcement in concrete is also warranted.

Much is expected of some of our concrete structures and buildings, some are in extremely aggressive environments, they may be many decades of age, they are of critical importance in terms of function or location, it is impossible to replace them, etc. such that some require repair and protection during their service lives. Dr John Broomfield provided an overview of repair and protection aspects relating to corroding steel in concrete in the second paper of this symposium.

The subsequent papers and speakers at the symposium then addressed other aspects of reinforced concrete corrosion, protection repair and durability that Professor Brian Cherry has taught, researched and provided innovative solutions to over many decades, including:

- Condition assessment of structures;
- Modelling and deterioration prediction;
- Concrete repair and protection;
- Cathodic protection;
- Corrosion inhibitors; and
- Alternate metallic reinforcement.

2. Steel Reinforced Concrete

Concrete is the most widely used material of construction in the world, with 25 gigatonnes/year consumed globally. Since concrete is strong in compression but weak in tension this fault is remedied by reinforcing the structures with steel. The steel reinforcement can take the form of conventional carbon steel (black steel), prestressing steel, post-tensioned steel and steel fibres and its widespread utility is primarily due to the combination that produces the best features of concrete and steel. The two components complement each other and so by combining them the composite has good tensile strength, shear strength and compressive strength combined with durability and fire resistance.

When suitably designed, constructed and maintained, reinforced concrete provides service lives of numerous decades to structures and buildings. Concrete provides reinforcing steel with excellent corrosion protection. The highly alkaline environment in concrete results in the spontaneous formation of a stable, tightly adhering, thin protective oxide film (passive film) on the steel reinforcement surface, which protects it from corrosion. In addition, well proportioned, compacted and cured concrete has a low penetrability, thereby minimising the ingress of corrosion-inducing species via the aqueous phase. It also has a relatively high electrical resistivity, which reduces the corrosion current and hence the rate of corrosion if corrosion is initiated.

There are however, several degradative processes which affect some reinforced concrete structures leading to loss of functionality, unplanned maintenance/remediation/replacement, and in the worst cases, loss of structural integrity and resultant safety risks. Amongst these, the most common cause of deterioration is corrosion of conventional carbon steel (black steel), prestressing steel and post-tensioned steel reinforcement.

3. Protection Afforded to Steel Reinforcement by Concrete

3.1 Portland Cement and Blended Cement Binders

The hydraulic binder of concrete commonly consists of Portland cement or of mixtures of Portland cement and one or more of fly ash, ground granulated iron blast-furnace slag or silica fume (Standards Australia, 2010). The latter are referred to as Blended cements.

AS 3972 (2010) defines Blended cement as a hydraulic cement containing Portland cement and a quantity comprised of one or both of the following:

a) Greater than 7.5% of fly ash or granulated iron blast-furnace slag, or both.

b) Up to 10% silica fume.

Furthermore, AS 3972 (2010) designates cements as general purpose and special purpose. By definition general purpose cements may be Portland cements (Type GP) or blended cements (Type GB). Special purpose cements are also defined in AS 3972 (2010) and may be Portland or blended cements with restrictions being placed on their composition.

Portland cement consists (nominally) of a mixture of oxides: CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, Na_2O and K_2O. These are combined together as a series of cement compounds. The cement compounds are then themselves combinations of the principal oxides (Cherry & Green, 2017).

Fly ash (FA) is the solid material extracted from the flue gases of a boiler fired with coal (Standards Australia, 2016). Fly ash for use in cement needs to comply with AS 3582.1 (2016). The fly ash content of a FA blended cement based concrete varies but is commonly in the range 20-35%. For example, some Road Authorities in Australia stipulate in their structural concrete specifications a minimum 25% FA content (Roads & Maritime Services, 2013; VicRoads, 2017) so as to achieve increased durability.

Granulated iron blast-furnace slag is the glassy non-metallic granular material, essentially consisting of silicates, aluminosilicates and calcium, resulting from the rapid chilling of molten iron blast-furnace slag (Standards Australia, 2016). Ground granulated iron blast-furnace slag (BFS) for use in cement needs to comply with AS 3582.2 (2016). The slag content of a BFS blended cement based concrete varies but is commonly in the range 50-70%. For example, some Road Authorities in Australia stipulate in their structural concrete specifications a minimum 50-65% BFS content (Roads & Maritime Services, 2013; VicRoads, 2017) to achieve increased durability.

Silica fume is a very fine pozzolanic material produced by electric arc furnaces as a by-product of the production of elemental silicon or ferro-silicon alloys. Silica fume is also known as ‘condensed silica fume’ and ‘microsilica’. The amorphous silica content of a silica fume (SF) blended cement based concrete typically varies between 5-15%. For example, some Road Authorities in Australia stipulate in their structural concrete specifications a 10% SF proportion (VicRoads, 2017).

Triple blend cement based concretes are also used for increased durability. For example VicRoads in their “Structural Concrete Specification 610” (2017) stipulate that in a triple blend concrete mix, the Portland cement shall be a minimum of 60% and the individual contribution of Slag, Fly Ash or Amorphous Silica shall be a maximum of 40%, 25% or 10% respectively. For marine durability, triple blend cement based concretes such as 52% shrinkage-limited (SL) cement, 25% FA and 23% BFS have been used (Green et al, 2009).

3.2 Alkaline Environment in Concrete

As mentioned above, the highly alkaline environment in concrete results in the spontaneous formation of a passive iron oxide film on reinforcing steel which protects it from corrosion.

The reaction of the cement compounds of Portland cement or Blended cement with water results in the setting and hardening of the cement paste so that it binds the aggregate (coarse and fine) of the concrete together. A product of the hydration of Portland and Blended cements is $Ca(OH)_2$ together with NaOH and KOH.

As a result, the pH of the pore solution of concrete is normally in the range of 12-14 (Page & Treadaway, 1982; Tuutti, 1982; Tinnea & Young, 2000; Tinnea, 2002; Broomfield, 2007; Abd El Haleem et al, 2010; Ghods, et al, 2011; Cherry & Green, 2017), and maintained due to the CaO-$Ca(OH)_2$ pH buffer until this is overcome by carbonation, leaching, or neutralised (acidified) by chloride ion induced pitting corrosion reactions. All these mechanisms involving loss of alkalinity will be discussed in detail in subsequent sections of the paper.

For iron (steel) in a pH 12-14 alkaline environment, the Potential - pH diagram, see Figure 1, tells us that the metal will be in a passive state.

3.3 Physical Barrier Provided by Concrete

In addition to providing a high pH passivating environment for reinforcing steel, concrete also provides a physical barrier against the ingress of corrosion-inducing substances. The quality of concrete as a physical barrier may be assessed from penetrability data (and chemical data, i.e. blended cements have better chloride ion binding/adsorption capacity as well as improving the porosity of the aggregate-paste transition zone).

Penetrability data is collected from a variety of measurements of a concrete’s water absorption, water permeability, chloride diffusion and gaseous diffusion/penetration of O_2 and CO_2. (Concrete Institute of Australia, 2015). The factors affecting concrete penetrability include the type and quality of aggregates, type of cement (binder), cement (binder) content, water/cement (binder) ratio and production variables such as mixing uniformity, placement, degree of compaction and adequacy of cure.

3.4 Passivity and the Passive Film on Steel Reinforcement in Concrete

3.4.1 Thermodynamics of Passivity

Thermodynamics, the science of energy changes, is applied to corrosion studies to determine why a particular metal does or does not tend to corrode in a particular environment. Chemical and electrochemical thermodynamic data [chemical potential (μ_0) values, standard free energy change of reaction (ΔG_0) values, and standard electrode potential (E^0) values] provides the means for deciding which of a set of reactions is thermodynamically favoured and for predicting the most stable reaction products under specified conditions of electrode potential and solution composition. Marcel Pourbaix (1904-1998) recognised that the corrosion state of a metal could be represented by a point on a diagram the two axes of which are potential (voltage) and the pH. These diagrams are axes now often termed ‘Pourbaix’ diagrams in his honour. The Pourbaix diagram plots electrochemical stability for the different redox states of an element as a function of pH. The Fe-H_2O system at 25°C, shown in Figure 1, is of most relevance to reinforcing steel in concrete. Typically, the concentrations of dissolved ions, other than H^+ and OH^-, are taken to be 10^{-6}M and solid phases are assumed to be pure.

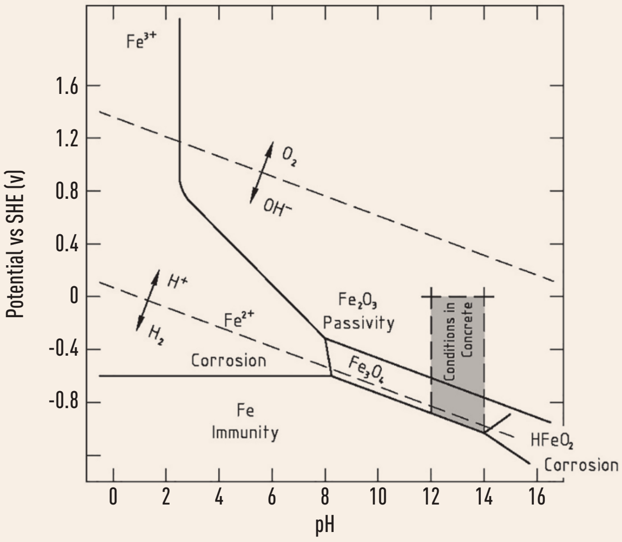


Figure 1. Potential-pH (Pourbaix) diagram for Fe-H_2O at 25°C and $[Fe^{2+}]$, $[Fe^{3+}]$ and $[HFeO_2^-] = 10^{-6}$M (Green, 1991)

If the potential of iron immersed in neutral water (pH about 7) is measured using a standard hydrogen electrode (SHE), it will be seen in Figure 1 to have a typical value -0.3V, which indicates that it is in a state of active corrosion. An examination of the Pourbaix diagram suggests three possible means of achieving a reduction in the corrosion. First, the metal can have its potential so changed in the negative direction that it enters the domain of immunity, i.e. it can be cathodically protected. Secondly, the potential can be changed in the positive direction so that it enters the passive domain. This is anodic protection and is only applicable to some metals such as iron but not for example to zinc. Thirdly, the pH of the electrolyte can be so adjusted that the metal enters the passivity domain, and this process is considered to be inhibition.

To summarise, Figure 1 shows us that there are three basic zones of behaviour representing states of lowest energy for iron (steel):

1. Immunity – iron metal is thermodynamically stable and is immune to corrosion.
2. Corrosion – Fe^{2+}, Fe^{3+} and $HFeO_2^-$ ions are thermodynamically stable and corrosion will occur at a rate which cannot be predicted thermodynamically.
3. Passivity – iron oxides are thermodynamically stable. These oxides give rise to a condition termed passivity since significant corrosion may be stifled owing to the formation of a protective oxide layer on the metal surface (see shaded area on Figure 1 in the high pH region).

Having described the information that can be gleaned from Pourbaix diagrams with respect to deciding which of a set of reactions is thermodynamically favoured and which reaction products are most stable, it is necessary to recognise that certain limitations apply to the use of thermodynamics and Pourbaix diagrams. The kinetics (rates) of possible reactions are not considered, and therefore, it is impossible to predict whether a particular reaction, which is thermodynamically favoured, will occur at a significant rate in practice. The aqueous solution composition in the vicinity of the corroding surface also needs to be known. This presents difficulties when considering real corroding systems in which concentration gradients may be developed and involves the use of microscopic flat surface pH electrodes inserted into pores that have been drilled into the structure.

3.4.2 Kinetics of Passivity

Figure 2 shows the anodic polarisation curve for a passive metal, such as reinforcing steel in the alkaline environment of concrete.

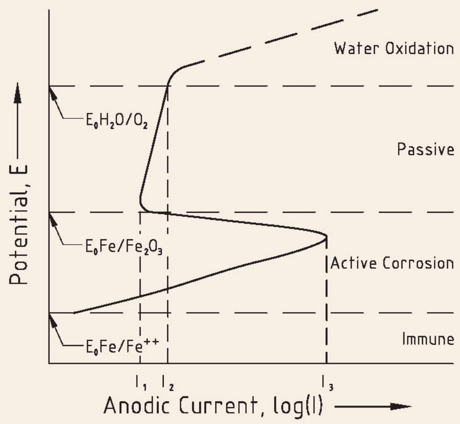


Figure 2. Anodic polarisation curve showing a transition from active dissolution to passivation (Green, 1991)

At potentials more negative than the equilibrium potential or reversible potential for Fe/Fe^{2+} (i.e. E^0 Fe/Fe^{2+}), iron is immune to corrosion or dissolution. Raising the potential to values more positive than E^0 Fe/Fe^{2+} leads to active corrosion at a rate which initially increases with increasing overpotential (maximum corrosion current, I_1). At some potential more positive or noble than the equilibrium potential for the formation of a surface oxide film (i.e. E^0 Fe/Fe_2O_3) active corrosion practically ceases (i.e. I_2) owing to surface oxide film formation which renders iron passive and allows the passage of a small 'leakage current' (i.e. $I_2 \rightarrow I_3$). This 'leakage current' results from the necessity to reform the surface oxide passive film at points of local breakdown and to replace oxide lost by dissolution to the environment.

3.4.3 Passive Film Formation

The corrosion of steel reinforcement in concrete is, initially at least, a very slow process. As a result of the hydration reactions of the cement (binder) compounds as previously noted, the pore water surrounding the steel has a high pH (in the range 12-14) and so the steel is completely covered with a dense gamma ferric oxide (γ-Fe_2O_3, maghemite) protective passive film. This is formed by the anodic reaction (1):

$$4Fe + 12OH^- \rightarrow 2\gamma Fe_2O_3 + 6H_2O + 12e^- \qquad (1)$$

Once the film has formed, the reaction continues (at a very slow rate) at the metal/oxide interface as a result of hydroxyl ions diffusing through the film of iron oxide. The cathodic process is ascribed to the reaction (2):

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (2)$$

This reaction takes place on the surface of the passive film. The cathodic process requires that oxygen molecules diffuse through the concrete to the passive film surface and are there reduced to hydroxyl ions. The electrical circuit is completed by the ionic transport through the passive film of the hydroxyl ions resulting from the cathodic reaction moving towards the metal/film interface and by electronic transport through the protective film to the film/electrolyte interface. Corrosion is proceeding in this state corresponding to the conversion of iron to iron oxide.

Passive (leakage) corrosion current densities (i_{corr}) measured for steel reinforcement in concrete are of the order of 0.1μA/ cm² (Andrade & Gonzalez, 1978; Hansson, 1984). This current density therefore corresponds to an insignificantly slow corrosion (penetration) rate of 1μm/year. This corrosion rate is of the order of 1mm in 1000years and so it can be seen that the reinforced concrete structure or building element may be regarded as unaffected by corrosion. The steel in this state is said to be "passive" or protected by a "passive film" (Cherry & Green, 2017).

Since the passive film maintains a constant thickness (it dissolves from the outside as quickly as it is formed on the inside) no great swelling stresses are applied to the concrete and so no cracking of the concrete takes place (Cherry & Green, 2017).

3.4.4 Passive Film Composition

The precise nature of the passive film which is formed by the reaction of iron with the highly alkaline environment of the pore water in concrete varies. As above, it can be considered to be generally a dense gamma ferric oxide (γ-Fe_2O_3, maghemite).

The characteristics of oxides formed on steel under alkaline conditions and their electrochemical behaviour have been examined by, for example, Nasrazadani (1997), Cornell and Schwertmann (2000) and Freire et al (2009). Iron-oxy-hydroxides like goethite (α-FeOOH), lepidocrocite (γ-FeOOH) and akagenite (β-FeOOH) were amongst the products formed. There were also the more protective forms of iron oxides including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3) and haematite (α-Fe_2O_3) formed as the constituents of the passive film on steel electrodes under alkaline conditions.

There is still significant debate about the true nature of the passive film on iron. Cohen (1978) indicated that the composition of the passive oxide layer is a spinel α-Fe_3O_4-γ-Fe_2O_3 solid solution. Sagoe-Crentsil and Glasser (1989) attributed the passive action of pH>12 concrete pore solution to the formation of a surface layer of Fe_2O_3-Fe_3O_4. Ghods et al (2011) have more recently also reported two-layer oxides in passive films, with an inner Fe^{2+} and Fe^{3+} layer and an outer pure Fe^{3+} layer. Al-Negheimish et al (2014) have also proposed a two-layer oxide passive film but the top layer was composed of FeO and FeOOH with Fe_2O_3 close to the steel surface.

More recently Ghods et al (2013) report of a tri-layer model of oxides for the passive film on the steel when exposed to simulated concrete pore solution namely a layer of FeO at the metal surface, then a layer of Fe_3O_4 and then an outer layer of Fe_2O_3.

MnS inclusions are often found in steels and their effect is to change the Fe_2O_3 in the passive film from γ-Fe_2O_3 to α-Fe_2O_3 according to Al-Negheimish et al (2014).

3.4.5 Passive Film Thickness

Singh and Singh (2012) proposed that the passive film formed in simulated concrete pore solution is of "ultra thin thickness" (i.e. <10 nm). Ghods et al (2013) reported that the thickness of the tri-layer ($FeO/Fe_3O_4/Fe_2O_3$) passive oxide film was uniform between 5 and 13 nm. Al-Negheimish et al (2014) have determined thicknesses of 6 to 7 nm for the passive film on steel in simulated concrete pore solution.

3.4.6 Models and Theories of Passive Film Development on Iron

Veluchamy et al (2017) indicate that the understanding of the passive state of metals started with Faraday (1844). Though several theories, models and experimental works on passivity have been published in the literature, the mechanisms underlying the stability of the passive oxide over the metal still remain a mystery according to Veluchamy et al (2017). They undertook a detailed review of theoretical and experimental results for the iron/electrolyte system invoking the high field model (HFM) (ion-migration mechanism), modified high field model, point defect model (PDM), variants of PDM (VPDM), diffusion Poisson coupled model (DPCM) and the density functional theory based atomistic model. The experimental and model-predicted dependencies on applied voltage, pH, chloride and temperature have also been presented and discussed by Veluchamy etl al (2017). Suffice to say that the models and theories of passive film development on iron are complex and still not clear. Any more detailed discussion is beyond the scope of this paper.

4. Corrosion of Steel Reinforcement

4.1 General

The passivity provided to steel reinforcement by the alkaline environment of concrete may be lost if the pH of the concrete pore solution falls because of carbonation or if aggressive ions such as chlorides penetrate in sufficient concentration to the steel reinforcement surface. Carbonation of concrete occurs when atmospheric CO_2 gas (and atmospheric SO_x and NO_x gases) neutralises the concrete pore water (lowering its pH to 9) and thereby destroying the passive film. Leaching of $Ca(OH)_2$ (and NaOH and KOH) from concrete also lowers pH to cause corrosion of steel reinforcement. Stray electrical currents, most commonly from electrified traction systems, can also breakdown the passive film and cause of corrosion of steel reinforced and prestressed concrete elements. The corrosion mechanisms by chlorides, carbonation, leaching and stray electrical currents is provided in subsequent sections but discussion of the different forms of corrosion, composition of reinforcing steel corrosion products (rusts) and the consequence of the corrosion products is first provided.

4.2 Uniform (Microcell) Corrosion and Pitting (Macrocell) Corrosion

According to the different spatial location of anodes and cathodes, corrosion of steel in concrete can occur in different forms (Elsener, 2002) namely:

- As microcells, where anodic and cathodic reactions are immediately adjacent, leading to uniform steel (iron) dissolution over the whole surface. This uniform (or general) corrosion is typically caused by carbonation of the concrete or by very high chloride content at the steel reinforcement.

- As macrocells, where a net distinction between corroding areas of the steel reinforcement (anodes) and non-corroding passive surfaces (cathodes) is found. Macrocells occur mainly in the case of chloride induced corrosion (pitting) where the anodes are small with respect to the total (passive) steel reinforcement surface.

Cherry and Green (2017) also suggest that uniform or general corrosion of steel reinforcement in concrete where the cathodic and anodic sites may be separated by millimetres (rather than microns), can be termed minicell corrosion.

4.3 Corrosion Products Composition – Chloride Induced Corrosion

The exact nature of reinforcing steel corrosion products (rusts) associated with chloride induced corrosion varies markedly depending on conditions. Corrosion products are of various layers and of various compositions. Generally speaking they will be layers and combinations of ferrous and ferric hydroxides, hydroxyl/oxides and oxides each with possible varying degrees of hydration.

Melchers and Li (2008) and Pape and Melchers (2013) have identified goethite (α-FeOOH), akagenite (β-FeOOH), lepidocrocite (γ-FeOOH) as corrosion products within chloride contaminated reinforcing steel samples from concrete structures. "Green rusts" can also occur. Melchers and Li (2008) and Pape and Melchers (2013) have identified compounds such as iron oxide chloride (FeOCl), hibbingite (α-$Fe_2(OH)_3Cl$), iron chloride hydrate ($FeCl_2.4H_2O$), "Green Rust I" (carbonate variety) and "Green Rust II" (sulphate variety) within the corrosion products (rusts) of samples taken from steel reinforced and prestressed structures in chloride-rich environments. Discussion of chloride induced corrosion mechanisms is provided at Section 5.

For corroding mortar specimens subject to chloride ingress, Koleva et al (2006) identified corrosion products mainly consisting of highly crystallised goethite (α-FeOOH), lepidocrocite (γ-FeOOH) and akagenite (β-FeOOH). Depending on the ratio of iron and chloride ions, the iron oxychlorides and iron oxyhydroxides present different morphologies and exert influences on steel/mortar interface microstructure and on material behaviour.

The corrosion products generally detected by Vera et al (2009) from embedded steel in concrete cylinder samples exposed to simulated marine and industrial conditions and a natural marine atmospheric environment were:- lepidocrocite (γ-FeOOH), goethite (α-FeOOH) and magnetite (Fe_3O_4); but in the chloride contaminated environments the presence of akagenite (β-FeOOH)was detected; and, in the natural marine atmospheric environment the formation of siderite ($FeCO_3$) was also observed.

4.4 Corrosion Products Composition – Carbonation Induced Corrosion

Attack of concrete by carbon dioxide is termed carbonation and the mechanisms of such are provided at Section 6. Carbonation-induced corrosion products were mostly hydroxide type of rusts (i.e. goethite/α-FeOOH and lepidocrocite/γ-FeOOH) identified on existing reinforced concrete facades of 12 buildings that had been in use for 30-43 years (Kolio et al, 2015).

Huet et al (2005) identified corrosion products mainly composed of magnetite (Fe_3O_4) and lepidoocrocite (γ-FeOOH) in laboratory-based studies of mild steel in carbonated concrete pore solution.

4.5 Corrosion Products Development – Cracking, Delamination and Spalling

The process of reinforcement corrosion will lead to corrosion products which will generally occupy a greater volume than the iron dissolved in its production, refer Figure 3 (Jaffer & Hansson, 2009). Furthermore, when the corrosion products become hydrated the volume increase is even greater (Broomfield, 2007), refer hydrated haematite (α-$Fe_2O_3.3H_2O$) (red rust) in Figure 3.

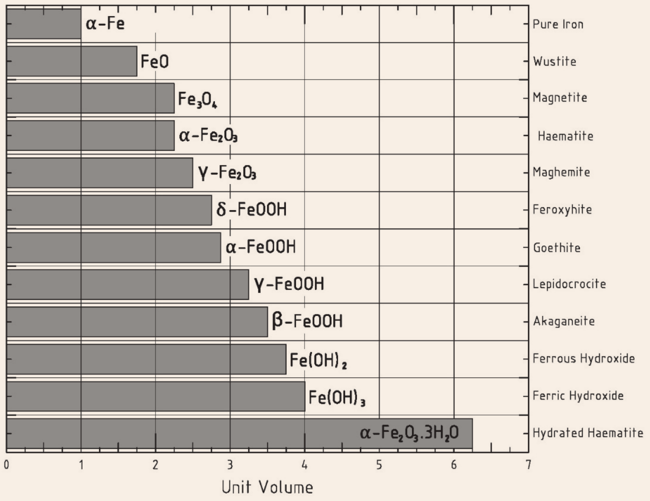


Figure 3. Relative volume of iron and some of its oxides (adapted from Jaffer and Hansson, 2009).

The consequence of higher volume corrosion products is the development of tensile stresses in the concrete covering the reinforcement. Concrete, being weak in tension, will crack as a consequence of the corrosion. Continuing formation of corrosion product(s) will enhance the expansion which will ultimately lead to cracked pieces of concrete cover detaching, leading to delamination and then spalling. Rust staining of the concrete may or may not occur together with the cracking or as a prelude to delamination and spalling. Section loss, bond loss and anchorage loss of the reinforcement also occurs as a result of the corrosion.

Kolio et al (2015) describing work they had carried out on carbonation-initiated corrosion on concrete façade panels, determined that the corrosion products (i.e. as previously discussed, goethite/α-FeOOH and lepidocrocite/γ-FeOOH) had a unit volume increase of roughly 3 times the volume of iron. By taking into account the relative volume of the corrosion products, they determined that the required corrosion penetration (metal loss) to initiate visually observable cracks in the studied building façade panels was an average of 54 µm with a corresponding corrosion (rust) products thickness of 112 µm.

Hydrated haematite (α-$Fe_2O_3.3H_2O$) (red rust) induced cracking, delamination and spalling of cover concrete can be frequently seen in deteriorated reinforced concrete structures and buildings, an example of which is provided at Figure 4 for a marine structure.

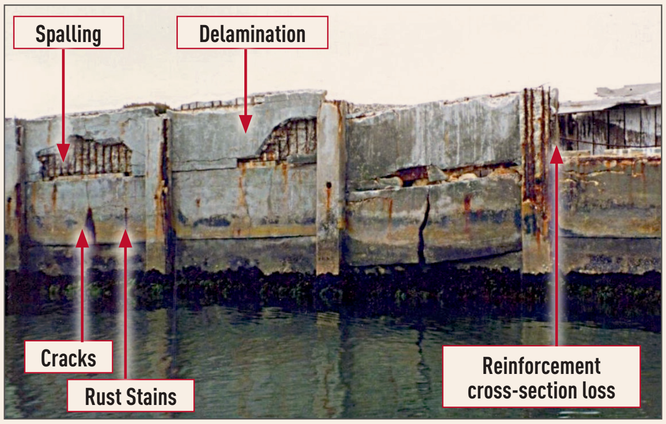


Figure 4. Reinforcement corrosion induced deterioration.

4.6 Corrosion Products Development – No Visible Damage

It is most important to note however, that not all corrosion of reinforcement leads to rust staining, cracking, delamination or spalling of cover concrete. Localised pitting, localised corrosion at cracks, localised corrosion at concrete defects, etc can result in marked section loss (loss of bond, loss of anchorage) and ultimately structural failure without the visible consequences of corrosion on the concrete surface, i.e. no rust staining, cracking, delamination or spalling of cover concrete (Green et al, 2013). This form of decay is inherently more insidious. An example of marked localised section loss of reinforcement due to chloride induced pitting (macrocell) corrosion is provided at Figure 5. The definition of macrocell corrosion being as at Section 4.2 where a net distinction between corroding areas of the steel reinforcement (anodes) and non-corroding passive surfaces (cathodes) is found.

Figure 5. Example of marked localised pitting (macrocell) corrosion and section loss (corrosion penetration) of steel reinforcement. Here pits would have started out narrow but with time have coalesced to result in section loss over a greater (anodic) area.

Elsener (2002) pointed out that macrocell (pitting) corrosion is of great concern because the local dissolution rate (reduction in cross-section of the conventional/prestressing/post-tensioned steel reinforcement, loss of bond, loss of anchorage) may greatly be accelerated due to the large cathode/ small anode area ratio. Indeed, values of local corrosion (penetration) rates of up to 1 mm/year have been reported for bridge decks, sustaining walls or other chloride contaminated steel reinforced concrete structures (Elsener, 2002).

Broomfield (2007) also notes that 'black rust' or 'green rust' (due to the colour of the liquid when first exposed to air after breakout) corrosion can also be found under damaged waterproof membranes and in some underwater or water saturated structures. He states that it is potentially dangerous as there is no indication of corrosion by cracking and spalling of the concrete and the reinforcing steel may be severely weakened before corrosion is detected. Reinforcement bars may be “hollowed out” in such deoxygenated conditions.

5. Chloride Induced Corrosion Mechanisms

5.1 General

It is known that chloride ions in sufficient concentration can destroy the passivity of steel reinforcement (conventional, prestressed and post-tensioned) in concrete leading to pitting corrosion. Pitting corrosion is localised accelerated dissolution of metal that occurs as a result of breakdown of the otherwise protective passive film on the metal surface (Frankel, 1998). Various mechanisms of chloride ion induced corrosion of steel reinforcement in concrete are proposed in the literature.

Frankel (1998) comments that many engineering alloys, such as stainless steels and aluminium alloys, are useful only because of passive films, which are thin (nanometre scale), oxide layers. Furthermore, that such passive films are often susceptible to localised breakdown resulting in accelerated dissolution of the underlying metal and if the attack initiates on an open surface, it is called pitting corrosion and at an occluded site it is called crevice corrosion.

Fundamental studies of pitting corrosion on such engineering alloys appear to have typically focused on the various stages of the pitting process, namely: passive film breakdown, the growth of metastable pits (which grow to about the micron scale and then repassivate) and the growth of larger, stable pits (Frankel, 1998). Like Frankel (1998), Angst et al (2011) propose from a fundamental viewpoint that chloride induced pitting corrosion of steel reinforcement in concrete can be considered to occur as a sequence of distinct stages:- pit nucleation, metastable pitting and stable pit growth.

The mechanisms of pitting corrosion of steel in chloride contaminated concrete will therefore be considered on this basis as well as discussion of some other mechanistic aspects relating to the reinforcing steel quality itself.

5.2 Passive Film Breakdown/Pit Initiation

The American Concrete Institute (ACI) Committee 222 on ‘Corrosion of Metals in Concrete’ (1985) proposes three theories to explain the effects of chloride ions on passive steel reinforcement:

a) The Oxide Film Theory – postulates that chloride ions penetrate the passive film through pores or defects in the film, thereby “colloidally dispersing” the film.

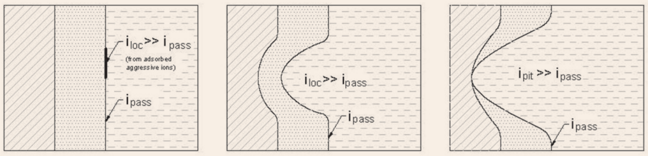
b) The Adsorption Theory – postulates that chloride ions are adsorbed preferentially on the metal surface in competition with dissolved oxygen or hydroxyl ions. The chloride ion promotes the complexation of the metal atoms, thus facilitating anodic dissolution.

c) The Transitory Complex Theory – postulates that chloride ions form a soluble complex with ferrous ions which then diffuses away from the anodic sites. Thereafter, the complex decomposes, iron hydroxide precipitates, and the chloride ions are released to transport more ferrous ions from anodic sites.

Frankel (1998), in a comprehensive review paper of pitting corrosion of metals, indicates that theories for passive film breakdown and pit initiation of pure metal systems (i.e. not alloys where pitting may also be associated with inclusions or second-phase particles) have been categorised in three main mechanisms that focus on passive film penetration, film breaking, or adsorption (Figure 6).

a) Penetration Mechanism

b) Adsorption Mechanism



c) Film Breaking Mechanism

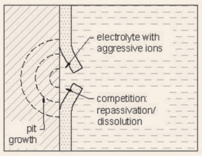


Figure 6. Schematic diagrams representing pit initiation by (a) penetration, (b) adsorption and thinning, and (c) film breaking (Frankel, 1998).

Soltis (2015) reviewed the three main mechanisms that focus on passive film penetration, film breaking, or adsorption together with mechanisms such as the ‘percolation model’ and ‘voids at the metal-oxide interface’. Soltis (2015) proposes that despite a number of theories for passive film breakdown/ pit initiation, this aspect of localised pitting corrosion remains still the least understood, with a generally accepted theory yet to come. Soltis (2015) then surmises that it is entirely possible that we may fail to develop a single theory and will need to focus on the development of system-specific models, purely because of differences in passive film properties.

Given the Soltis (2015) proposition that there may not be a single theory for passive film breakdown and pit initiation and that development of system-specific models may be necessary, in the remainder of this sub-section, literature has been reviewed with the aim of proposing a system-specific mechanism(s) for chloride ion induced depassivation and pit initiation of reinforcement steel in concrete. The ultimate health of reinforced concrete can be seen as an analogy to human health – there are a multitude of causes for “illness”.

Bird et al (1988) in laboratory-based solution studies in the pH range 10-14 and containing NaCl in the range 10^{-3} – 10 M, supports the idea that the first stages of localised passive film breakdown depend upon the competition for adsorption, at the oxide/liquid interface, between hydroxyl ions and aggressive ions such as chloride ion. Leek and Poole (1990) for steel in concrete suggest that the breakdown of passivity by chloride ions is achieved by disruption of the passive film to substrate adhesive bond. An initial bond breakdown occurs beyond which internal pressure within the film due to surface tension effects, acts to disband chemically unaltered film, thereby expanding the size of the site of depassivation. Little or no chemical dissolution of the passive film occurs.

Sagoe-Crentsil and Glasser (1990) for steel in chloride contaminated concrete show evidence for the ‘Transitory Complex Theory’ above. X-ray diffraction analysis of steel from chloride contaminated cement paste samples showed the formation of an intermediate, soluble, $FeCl_2.4H_2O$ complex. Visually, they advise this was evident as a greenish-blue hue.

As noted previously, Pape and Melchers (2013) identified FeOCl, α-$Fe_2(OH)_3Cl$, $FeCl_2.4H_2O$, “Green Rust I” (carbonate variety) and “Green Rust II” (sulphate variety) compounds within the corrosion products of samples from reinforced and prestressed structures in chloride environments. It is then proposed that the presence of “green/greenish-blue rusts” may be evidence of the ‘Transitory Complex Theory’ above.

Figures 7 and 8 at Section 5.4.2 show schematically the reactions within a propagating chloride induced pit (Treadaway, 1988; 1991), and as such may also be considered further evidence of the ‘Transitory Complex Theory’.

Ghods et al (2013) have recently stated that the underlying mechanism for the depassivation process by chloride ions for steel in concrete is still not fully understood. They propose that one of the reasons behind this lack of understanding is the unavailability of data on the compositional and nanoscale morphological characteristics of the passive oxide film before and after exposure to chlorides. They advise that nano- scale surface chracterisation techniques are required since traditional electrochemical and most microscopic techniques do not provide such specific data. Although such techniques have been widely used to characterise metal and metal alloy oxides, their application to study carbon steel and stainless steel in alkaline environments that are representative of concrete pore solution has been limited.

In the study by Ghods et al (2013), nano-scale transmission electron microscopy (TEM) samples prepared with a focused ion beam were used to investigate the passivity and depassivation of carbon steel reinforcement in simulated concrete pore solutions. It was found that the addition of chlorides at concentrations lower than the depassivation thresholds did not change the physical appearance of the passive oxide films. After exposure to chlorides in concentrations greater than depassivation thresholds, passive oxide films were no longer uniform, with some regions of the surface bare and some pit initiation sites formed on the surface of the steel.

It is proposed that the study by Ghods et al (2013) is evidence for both or either the ‘Adsorption Theory’ or ‘Transitory Complex Theory’ for chloride ion induced passive film breakdown of steel reinforcement in concrete.

Based on the majority of the above opinions, it is proposed that the ‘Transitory Complex Theory’ is the dominant mechanism for the chloride ion induced depassivation/pit initiation of steel reinforcement in concrete and that the ‘Adsorption Theory’ may also be a contributing mechanism.

5.3 Metastable Pitting

Frankel (1998) advises that metastable pits are pits that initiate and grow for a limited period before repassivating. For metals in solutions, large pits can stop growing for a variety of reasons, but metastable pits are typically considered to be those from micron size at most with a lifetime of the order of seconds or less. Angst et al (2011) indicate for chloride induced reinforcement corrosion that once a pit has formed, the anodic dissolution reaction has to be sustained, otherwise the pit might cease growing and repassivate within a short time. Nucleation /repassivation events occur during the phase of so-called metastable pitting.

These authors also propose that it is generally accepted that many of the nucleated pits never achieve stability and that for a pit to survive the metastable state, it is necessary that the solution within the pit cavity (anolyte) maintains an aggressive chemical composition. This requirement is met by hydrolysis of the dissolving iron cations and the resulting increase in H^+ ion concentration as well as migration of chloride and other anions into the pit to maintain charge neutrality. So long as dilution of the aggressive pit chemistry is prevented, pit growth is self-sustaining and likely to achieve stability.

This mechanism of localised acidification due to metal ions hydrolysis is attributed to Galvele (1976). Newman (2010) then highlights that definition of the pit propagation process by the localised acidification model has had an enormous influence on the development of corrosion science.

Pit growth and pit propagation together with the chemical conditions within propagating pits including localised acidification is discussed specifically at Section 5.4 and illustrated in Figures 7 and 8. Lin et al (2010) utilised a scanning-micro reference electrode (SMRE) technique to monitor localised corrosion processes of reinforcing steel in NaCl-containing solution by in situ imaging of the corrosion potential and corrosion current. Metastable micro-pits occurred randomly and instantaneously on the surface when the reinforcing steel was first immersed in the chloride-containing solution. The number and size of active micro-pits changed with immersion time; some micro-pits lost their activity and some micro-pits gathered into groups to form visible corrosion holes that were covered by yellow-brown corrosion products.

Furthermore, whether metastable pitting nuclei developed into macro-corrosion pits or lost their corrosion activity, was closely associated with the local chloride concentration. Once stable pitting nuclei were formed, further hydrolysis reactions of Fe^{2+} ions continued to lower the local pH, which accelerated dissolution of Fe at pits (Lin et al, 2010).

A porous cover of corrosion products and remnants of the passive film have also been reported for carbon steel and iron in chloride solutions (Alvarez & Galvele, 1984). Loss of this pit cover will result in dilution of the anolyte and might stop anodic dissolution. The pit can survive rupture of the cover and continue to grow in a stable manner only if the pit geometry has already developed in such a way that the pit depth sufficiently limits transport of ionic species to and from the pit bottom, in other words: that the pit geometry (transport path) imposes a resistance against diffusion and migration (Angst et al, 2011).

5.4 Pit Growth/Pit Propagation

5.4.1 General

Green (1991) has proposed that for chloride-induced pit growth to be sustained for reinforcing steel in concrete, the following conditions must be maintained:

a) A sufficient concentration of chloride ions at the pit;

b) The recycling of chloride ions during the corrosion process (i.e. from the hydrolysis of the intermediate iron chloride/ oxy-chloride complexes);

c) Diffusion of chloride ions to the pit from the bulk pore solution;

d) Development of acidity within the pit;

e) Cathodic processes on the steel surface; and

f) A continuous electrolytic path between cathodic sites and the pit.

Angst et al (2011) advise that studying the transition from nucleation to stable pit growth for the case of reinforcement steel embedded in concrete is much more difficult owing to experimental reasons. For instance, the reference electrode cannot be placed as close to the pit as in the case of solution experiments, or the IR drop through the concrete might disturb electrochemical measurements. Also, visual examination of an electrode embedded in concrete is impossible during an experiment. In addition, concrete is an inhomogeneous material and thus local chemistry is not as well defined as in solutions. Corrosion kinetics are also clearly different for steel embedded in concrete compared with experiments in solution.

Angst et al (2011) proposed that in principle the localised pit growth/propagation mechanisms valid for stainless or carbon steel in solution can be expected to apply also for reinforcement steel in concrete, namely: acidification of the anolyte and migration of chloride ions into the pit are required to maintain the aggressive local pit chemistry, which in turn is required to sustain anodic dissolution. In concrete, convection as a mechanism that promotes dilution of the anolyte can be neglected when compared with the situation of a metal surface directly exposed to bulk solution. However, considering the presence of soluble alkaline cement (binder) hydration products (i.e. NaOH, KOH and $Ca(OH)_2$) providing a pH buffering capacity, local acidification can be considered a critical step (Angst et al, 2011). Particularly lime/portlandite ($Ca(OH)_2$), segregated at the steel/concrete interface, and its ability to retain a fall in pH, as it has been suggested as a major reason for the inhibitive properties of concrete (Page, 1975). As long as OH^- ions migrate preferentially into the pit cavity to maintain charge balance, they will inhibit the pH of the anolyte from falling too fast.

Alvarez and Galvele (1984) reported that for iron in alkaline solutions, acidification of the anolyte is the rate controlling step; once a low pH in the pit is reached, the behaviour becomes equal to that found in acid solutions where chloride accumulation in the pit is the rate limiting process.

5.4.2 Chemical Conditions within Propagating Pits
Schematic diagrams of the reactions that occur within a propagating chloride induced pit for steel reinforcement in chloride contaminated concrete are provided at Figures 7 and 8.

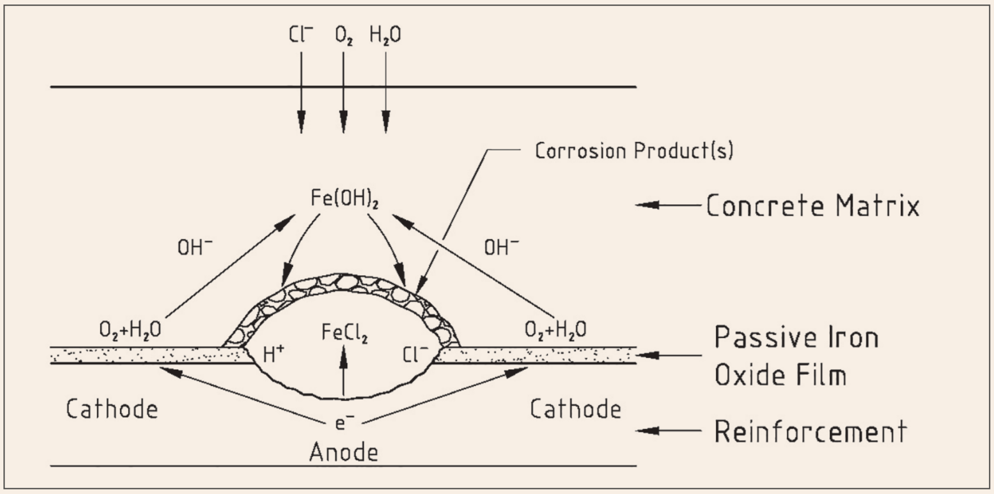


Figure 7. Schematic diagram of reactions associated with chloride induced pit growth/pit propagation (adapted from Treadaway, 1988).

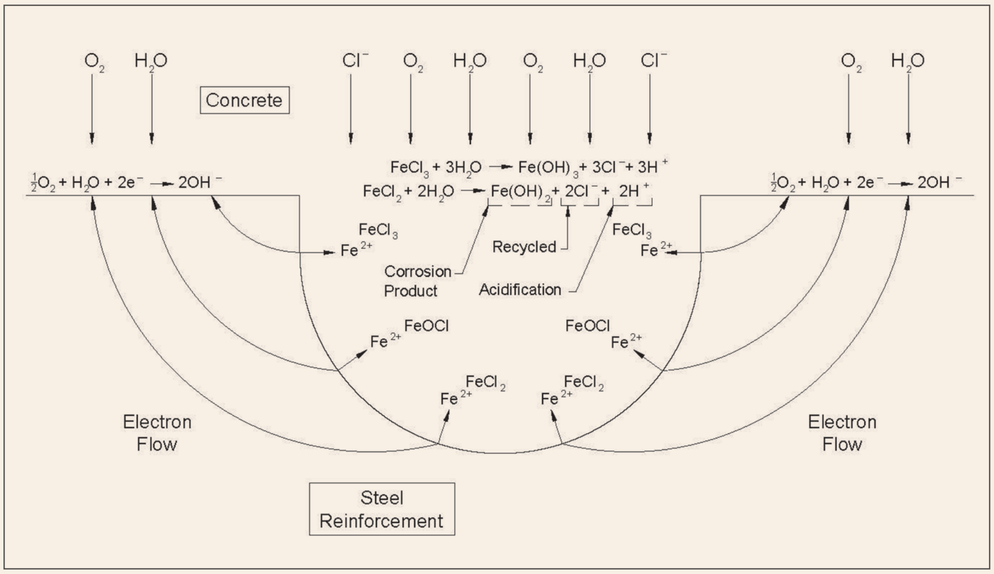


Figure 8. Schematic diagram of reactions within a propagating chloride induced pit (adapted from Treadaway, 1991).

The chloride ions enter the passive film (via predominantly the 'Transitory Complex Theory') and give rise to soluble products such that a small bare area of metal surface is formed. Ferrous ions (Fe^{2+}) diffusing away from the anodic area will react with the high pH environment to form a rust product ($Fe(OH)_2$ initially) which will shield the bare metal from oxygen. Further Fe^{2+} ions will no longer be able to be oxidised by the dissolved oxygen and so may be hydrolysed leading to the production of H^+ ions in the incipient pit. The production of H^+ ions reduces the pH in the pit. Tinnea (2002) has in fact measured reductions in pH to below 4 within pits for conventional steel reinforcement in chloride contaminated concrete.

A charge imbalance is also then generated by the H^+ ions production so that Cl^- ions will enter the pit which will now contain iron chloride (including the corrosive $FeCl_3$), iron oxy-chloride and iron chloro-hydroxyl compounds (Treadaway, 1991).

The rate of pitting corrosion is very large (locally) because the portion of the metal covered by the protective passive film is in general very much larger than the portion of the metal where the passive film has been damaged. The area over which the reduction of oxygen takes place is therefore very much larger than the anodic area where metal is dissolved. Consequently, as the metal loss that has to balance the oxygen reduction must all take place in the localised area where the passive film has been damaged, the rate of penetration of the metal in that local area is very fast. The net result is that rapid pitting is observed (Cherry & Green, 2017). As previously noted, values of pitting (penetration) rates of up to 1 mm/year have been reported for bridge decks, sustaining walls or other chloride contaminated steel reinforced concrete structures according to Elsener (2002).

5.5 Reinforcing Steel Quality

5.5.1 Metallurgy

Angst et al (2011) indicate that the metallurgy (physical surface heterogeneities such as inclusions, lattice or mill-scale defects, flaws, and grain boundaries) of the steel reinforcement also impacts the nucleation of chloride induced pitting.

Bhandari et al (2015) note that for engineering alloys, pits almost always initiate due to chemical or physical heterogeneity at the surface such as inclusions, second phase particles, solute-segregated grain boundaries, flaws, mechanical damage, or dislocations.

5.5.2 Reinforcing Steel Defects

Lin et al (2010) have undertaken work to image the chloride concentration on the surface of reinforcing steel, and to further study the effects of interfacial chloride ions on pitting corrosion in reinforcing steel by combining electron microprobe analyser (EMPA) ex-situ imaging of the morphology and chemical composition of reinforcing steel at the same locations. Both the electrochemical inhomogeneities in the reinforcing steel and the non-uniform distribution of chloride at the surface were considered the most important factors leading to various localised attacks. They also developed a scanning-micro reference electrode (SMRE) technique to monitor localised corrosion processes of reinforcing steel in NaCl containing solution by in situ imaging of the corrosion potential and corrosion current. Combining the data of the SMRE technique with that of the EMPA measurements they confirmed that among the electrochemical inhomogeneities (defects) in reinforcing steel, MnS inclusions play a leading role in the initial corrosion because chloride prefers to adsorb and accumulate at the MnS inclusions, resulting in pitting corrosion. Accordingly, dissolution of the MnS inclusion is generally accompanied by a local drop in pH around the MnS inclusion, as follows (Lin et al, 2010):

$$MnS + 3H_2O \rightarrow Mn^{2+} + HSO_3^- + 5H^+ + 6e^- \qquad (3)$$

Once a local reduction in pH and increase in chloride concentration is reached, nucleating pits can initiate and form occluded pits, such that H^+, Cl^- and HSO_3^- can accumulate inside pits. The metastable pitting nuclei either developed into large corrosion pits or lose their corrosion activity, which is largely dependent on whether the local chloride concentration exceeded the critical chloride concentration. If stable pitting nuclei were formed, further hydrolysis reactions of Fe^{2+} ions continued to lower local pH, which accelerated dissolution of iron at pits (Lin et al, 2010).

6. Carbonation Induced Corrosion Mechanisms

Attack of concrete by carbon dioxide is termed carbonation. The passivity provided to steel reinforcement by the alkaline environment of concrete can be lost due to a fall in the pH of the concrete pore solution because of carbonation and thereby destroying the passive film.

Carbonation may occur when carbon dioxide gas (and atmospheric SO_x and NO_x gases) from the atmosphere dissolves in concrete pore water and penetrates inwards or when the concrete surface is exposed to water or soil containing dissolved carbon dioxide.

Carbon dioxide dissolves in the pore water to form carbonic acid by the reaction:

$$CO_2(g) + H_2O(l) \rightarrow H_2CO_3(aq) \qquad (4)$$

Dependent on the pH of the surrounding solution carbonic acid can dissociate into hydrogen and bicarbonate ions. The carbonic acid reacts with $Ca(OH)_2$ (portlandite) in the solution, contained within the pores of the hardened cement paste, to form neutral insoluble $CaCO_3$. The general reaction is as follows:

$$Ca(OH)_2(aq) + H_2CO_3(aq) \rightarrow CaCO_3(s) + 2H_2O(l) \qquad (5)$$

and the nett effect is to reduce the alkalinity of the pore water which is essential to the maintenance of a passive film on any reinforcing steel that may be present. Whilst there is a pH buffer between CaO and $Ca(OH)_2$ that keeps the pH at approximately 12.5, the CO_2 keeps reacting until the buffer is consumed and then the pH will drop to levels no longer protective of steel.

The attack of buried concrete by carbon dioxide dissolved in the groundwater is a two-stage process. The calcium hydroxide solution that fills the pores of the concrete, first reacts with dissolved carbon dioxide to form insoluble calcium carbonate. However, it then subsequently reacts with further carbon dioxide to form soluble calcium bicarbonate which is leached from the concrete. The extent to which each process takes place is a function of the calcium carbonate/calcium bicarbonate concentration of the ground water (which in turn is a function of the pH and the calcium content) and the amount of dissolved carbon dioxide.

The iron oxide passive film formed on steel in alkaline conditions is stable at pH levels greater than 10 (Broomfield, 2007) or greater than around 9.5 (Savija & Lukovic, 2016). Since the process of the carbonation of concrete lowers the pH of concrete pore water to lower than 9 (as low as 8.3) (Savija & Lukovic, 2016), the passive film is simply dissolved. The steel surface is then exposed to a pH~9 environment and corrosion thereby propagates.

Carbonation of concrete causes general corrosion where anodic and cathodic reactions are immediately adjacent (microcells or minicells), leading to uniform steel (iron) dissolution over the whole surface.

Localised carbonation induced corrosion of steel reinforcement can however occur at cracks, concrete defects, low cover areas etc of reinforced concrete elements.

7. Leaching Induced Corrosion of Reinforcement

The passivity provided to steel reinforcement by the alkaline environment of concrete may also be lost if the pH of the concrete pore solution falls because of leaching of $Ca(OH)_2$ (and NaOH and KOH). Leaching from concrete can lead to a lowering of the pH below 10 to cause corrosion of steel reinforcement.

Natural waters may be classified as "hard" or "soft" usually dependent upon the concentration of calcium bicarbonate that they contain. Hard waters may contain a calcium ion content in excess of 10 mg/l (ppm) whereas a soft water may contain less than 1 mg/l calcium. The capillary pores in a hardened cement paste contain a saturated solution of calcium hydroxide which is in equilibrium with the calcium silicate hydrates that form the cement gel. If soft water can penetrate through the concrete (e.g. joint, crack, defect, etc) then it can leach free calcium hydroxide out of hardened cement gel so that the pore water is diluted and the pH falls. Since the stability of the calcium silicates, aluminates and ferrites that constitute the hardened cement gel requires a certain concentration of calcium hydroxide in the pore water, leaching by soft water can result in decomposition of these hydration products. The removal of the free lime in the capillary solution leads to dissolution of the calcium silicates, aluminates and ferrites and this hydrolytic action can continue until a large proportion of the calcium hydroxide is leached out, leaving the concrete with negligible strength. Prior to this stage, loss of alkalinity due to the leaching process will result in reduced corrosion protection to reinforcement.

Calcium hydroxide that is leached to the concrete surface reacts with atmospheric carbon dioxide to form deposits of white calcium carbonate on the surface of the concrete. These deposits of calcium carbonate may take the form of stalactites or severe efflorescence. Leaching induced corrosion of steel reinforcement can be localised and consequently more serious where it occurs at concrete joints, cracks, defects, etc. An example of localised corrosion of steel reinforcement in a potable water reinforced concrete tank is shown at Figure 9.

Figure 9. 'Black rust' (magnetite) localised corrosion of steel reinforcement due to leaching at construction joints in the wall of a reinforced concrete tank containing potable water. (Photo courtesy of Greg Moore)

8. Stray Current Corrosion and Interference of Reinforcement

8.1 General

Stray electrical currents, most commonly from electrified traction systems, can also breakdown the passive film and cause corrosion of steel reinforced and prestressed concrete elements.

Stray electrical currents are a potent source of corrosion problems in reinforced concrete. Currents flow through any environment in response to potential differences in that environment. If an extended reinforced concrete structure is immersed in such an environment, then these potential differences drive a current through the steel and this gives rise to corrosion. In the regions where the environment has the more positive potential, current will enter the metal by means of the reaction:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (6)$$

In the regions where the environment has the more negative potential, current will leave the metal by means of the reaction:

$$2Fe \rightarrow 2Fe^{++} + 4e^- \qquad (7)$$

and as the metal is polarised in the positive direction that part of the structure is corroded.

8.2 Ground Currents

Ground currents are particularly effective in causing corrosion in extended reinforced concrete structures such as concrete pipelines, tunnels and retaining walls because the potentials that can build up in the soil between the different portions of the structure are correspondingly larger. Although the driving force for the corrosion is greater, the resistance between the cathode and anode is not proportionately larger and so the corrosion currents are greater.

The commonest cause of stray current corrosion is electrified traction systems. In general, the DC power for an electric train or tram is supplied by a sub-station and drawn from a positive overhead cable. The negative return to the sub-station is either through the rails on which the train is running or through a separate conductor rail. Although most of the current driving the trains/trams returns to the sub-station from which it is drawn via the conductor rail of the traction system, it is inevitable that some of the current in the conductor rail leaks from that rail and goes back to the sub-station through the earth. This sets up potential gradients in the earth. If a low resistance path (such as metallic reinforcement to a concrete structure) is present, then the current may pass through the reinforcement. It can be seen from Figure 10 that where the current enters the structure, the reinforcement is cathodically protected. Where the current leaves the structure near the sub-station, corrosion is intensified.

The potential loss of reinforcing steel section due to stray current corrosion can be very serious and design measures may need to be developed to mitigate such corrosion. As an example, suitable mitigation systems needed to be designed, implemented and maintained for the Sydney Harbour Tunnel as calculations carried out indicated a potential corrosion problem existed on the steel reinforcing of the immersed tunnel units and up to 150 kg of steel could be corroded per year by stray current (McCaffrey, 1991).

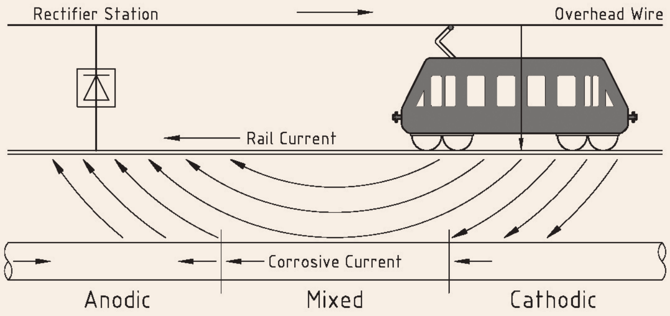


Figure 10. Ground currents set up by electric traction systems (Cherry & Green, 2017).

8.3 Interference Currents

Interference corrosion currents are typically associated with cathodic protection schemes. The application of remote anode impressed current cathodic protection system to (say) a buried pipeline involves the establishment of an anode(s) (anode groundbed) at some distance from the pipeline with the aim of passing current from the anode(s) (groundbed) to the pipeline. If there is a reinforced concrete structure within this potential field then voltage gradients associated with the passage of current through the soil give rise to interference corrosion of steel reinforcement. The effect on the buried reinforced concrete structure is to set up cathodic areas near to the anode groundbed and anodic areas closer to the structure which the cathodic protection system has been designed to protect.

8.4 Local Corrosion Due to Stray and Interference Currents

Dependent on the type of reinforced or prestressed concrete structure and elements that are near an electrified traction system or cathodic protection systems, stray current or interference corrosion of steel reinforcement may be localised. As such, structurally significant section loss of reinforcement may occur within short periods of time, since current density can be converted to an equivalent mass loss or corrosion penetration rate by Faraday's Law.

For example, a section of reinforcing steel receiving 1 uA/cm² of stray current equates to a mass loss or corrosion penetration rate of approximately 12 μm/yr because of Faraday's Law (Fontana, 1987). If the stray current is 1 mA/cm², then the corrosion penetration rate will be approximately 12 mm/yr. Consequently, significant section loss of reinforcement may occur within short periods of time for reinforced and prestressed elements suffering stray current corrosion from ground currents or interference currents.

9. Conclusions

Professor Cherry had always been a firm believer in understanding first the fundamentals of any aspects of corrosion science, then the mechanisms, before embarking on the engineering of solutions to the management of materials corrosion. So it has been with steel reinforced concrete. This paper has endeavoured to walk the reader through the fundamental and mechanistic aspects of the excellent protection afforded to steel reinforcement by concrete (including electrochemistry), corrosion of steel reinforcement (uniform (microcell/mini-cell) and pitting (macrocell) corrosion, corrosion products composition and development, chloride induced corrosion mechanisms (passive film breakdown/pit initiation, metastable pitting, pit growth/propagation, chemical conditions within propagating pits and reinforcing steel quality effects), carbonation induced corrosion mechanisms, leaching induced corrosion of reinforcement and reinforcing steel stray current corrosion and interference.

Concrete is a most wonderful material of construction. When suitably designed, constructed and maintained, reinforced concrete provides service-lives of numerous decades to structures and buildings. Concrete provides reinforcing steel with excellent corrosion protection. The highly alkaline environment in concrete results in the spontaneous formation of a stable, tightly adhering, thin oxide passive film on the steel reinforcement surface, which protects it from corrosion. In addition, well proportioned, compacted and cured concrete has a low penetrability, thereby minimising the ingress of corrosion-inducing species via the aqueous phase, and a relatively high electrical resistivity, which reduces the corrosion current and hence the rate of corrosion if corrosion is initiated. As Professor Cherry said many times “good steel in good concrete will not corrode”.

There are however, several degradative processes which affect some reinforced concrete structures leading to loss of functionality, unplanned maintenance/remediation/replacement, and in the worst cases, loss of structural integrity and resultant safety risks and amongst these, the most common cause of deterioration is corrosion of conventional carbon steel (black steel), prestressing steel and post-tensioned steel reinforcement.

10. Acknowledgments

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It is noted that the views expressed in this paper are those of the authors and are not necessarily of the organisations that they represent.

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INTERESTING CORROSION PHOTOS

Decaying sign at CSIRO Black Mountain site.
Courtesy Ian MacLeod.

Derelict Warehouse. Brooklyn Vic.
Courtesy Robert Slater.

St George's Anglican cathedral was reroofed in original Welsh slate eight years ago. During a rare rain event the beginnings of bacterial attack are showing other than the run-off from copper dormers which have a biocidal impact on the microflora
Courtesy Ian MacLeod.

Everyday Corrosion.
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