Introduction

The sixth International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2022) was held in Cape Town, South Africa, from 03 - 05 October 2022. The Conference was the latest in a sequence of ICCRRR International Conferences (Cape Town 2005, 2008, 2012 and 2018, Leipzig 2015). The organization was a collaborative venture of the University of Cape Town in South Africa and Karlsruhe Institute of Technology (KIT) in Germany.

Across the globe, ever-increasing amounts of national construction budgets are spent on condition assessment, maintenance, monitoring, repair and strengthening of concrete structures. Considering this, substantial progress has been made in understanding concrete deterioration mechanisms, non-destructive assessment technologies, and repair and rehabilitation technologies. A large share of international research efforts in structural and materials engineering is dedicated to these topics, and we believe that international events such as the ICCRRR can contribute substantially to developing and implementing suitable solutions to address the above issues.

ICCRRR 2022 has received excellent support by researchers and practitioners from around the world, with authors being drawn from numerous research and industrial organisations. This book of abstracts contains the 2-page extended abstracts for the Keynote presentations and the short abstracts for all remaining presentations. The 2-page abstracts for all presentations are published on the conference website (you may find the link to the book of extended abstracts on the back cover of this booklet), and the full conference papers are published by MATEC Web of Conferences, a provider of open-access proceedings in Materials Science, Engineering and Chemistry. Again, the link to the full proceedings is provided on the back cover of this booklet.

The proceedings contain papers presented at the conference, classified into a total of 11 sub-themes which can be grouped under four main themes: (i.) Concrete durability aspects, (ii.) Condition assessment of concrete structures, (iii.) Concrete repair, rehabilitation and retrofitting, and (iv.) Developments in concrete material technology, assessment and processing. Only original contributions were considered for inclusion in the full conference proceedings and all papers submitted were subjected to a full process of peer review. The review of manuscripts was undertaken by members of the International Scientific Advisory Board, acting independently on one or more assigned manuscripts. This invaluable assistance, which has ensured that we can meet the high quality expected for the Proceedings of the ICCRRR, is gratefully acknowledged.

Like countless other events, the ICCRRR was supposed to be held during the Covid Pandemic and had to be postponed, in our case from 2021 to 2022. We decided to hold the conference in full contact mode as we believe that in-person contact forms an integral and essential part of the ICCRRR philosophy, which is based on exchanging the latest scientific knowledge and current industry developments in a personal, collegial atmosphere – both in the lecture venue and over a cup of coffee during the breaks and social functions. We are therefore grateful for the strong support we have received from all corners of the world and we wholeheartedly welcome our international and national guests to Cape Town.

We would like to give special acknowledgements to our valued supporters and partners in academia and industry:

- RILEM, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures
- *fib*, the International Federation for Structural Concrete
- ACI, the American Concrete Institute
- Cement & Concrete South Africa
- Deutsche Bauchemie
- Sika South Africa
- Mapei South Africa
- Afrisam
- Proceq and Screaning Eagle Technologies
- Sanika Waterproofing Specialists
- StonCor Africa
- Xypex Chemical Corporation
- a.b.e Construction Chemicals
- Kryton
- Euclid Chemical

Finally, we wish to thank the authors for their efforts at producing and delivering papers of high standard. We are sure that the Proceedings will be a valued reference for many working in this important field, and that they will form a suitable base for discussion and provide suggestions for future development and research.

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M G Alexander
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Contents

Introduction i

1. KEYNOTE PAPERS 1

Understanding the durability of concrete containing SCMs
Karen Scrivener . . . 1

Measuring, understanding, and forecasting reinforcing steel corrosion in concrete
Ueli Angst . . . 3

Damage management of concrete elements by crack mitigation and self-healing strategies
Nele De Belie . . . 5

Advances in predicting reinforcement corrosion damage on concrete structures
Mike Otieno . . . 7

Sustainability verification of deteriorating concrete infrastructure
Mette R. Geiker . . . 9

Understanding concrete biodeterioration mechanisms and resistance in sewer environments: recent progress and scientific and technical challenges
Alexandra Bertron, Amr Aboulela, Amaury Buvigner, Matthieu Peyre Lavigne, and Cédric Patapy . . . 11

Is sustainable rehabilitation of pavements possible with ultra-thin continuously reinforced concrete Pavement (UTCRCP) overlays?
Elsabe Kearsley . . . 13

Building repair and rehabilitation in a global paradigm of climate change, resource depletion and an increasing demand for building stock
Vernon Collis . . . 15

Cathodic protection of reinforcement in concrete structures - overview and experience over 30+ years
Rob B. Polder and Anthony W.M. van den Hondel . . . 18

2. CONCRETE DURABILITY ASPECTS 20

2.1. Concrete durability: innovative materials and influences of material composition . . . 20

Durability of untreated fine recycled aggregate concrete: a literature review
Areej Gamieldien, Hans Beushausen, and Mark Alexander . . . 20

Chloride penetration resistance of fine recycled aggregate concrete
I. G. Amadi, H. Beushausen, M.G. Alexander, and S. Surana . . . 20

Assessing the mechanical durability performance of concrete made using recycled clay masonry rubble bricks (CMRB) as course aggregates
Janina P. Kanjee, Thoba Sikhakhane, and Omphile Tejane . . . 20

The effect of cement reduction and substitution on the mechanical and durability properties of concrete
Kiran Ram, Diana Londono-Zuluaga, Marijana Serdar and Karen Scrivener . . . 21

The influence of different modifying polymers on the mechanical properties of cement mortar within a defined service temperature range
Alexander Flohr and Andrea Osburg . . . 21

Factors influencing the electrical properties of ettringite binders as repair materials
Atolo Tuinukuafe, Lamiya Noor, Jason H. Ideker, and O. Burkan Isgor . . . 21

Durability of concrete with Belite-Gehlenite clinker as fine aggregate
Arato Kobayashi, Hiromi Fujiwara, Masanori Maruoka, Mizuki Owada, and Kensuke Hayashi 22

Fly ash geopolymer concrete durability to sulphate, acid and peat attack
Yulin Patrisia, David W. Law, Chamila Gunasekara, and Arie Wardhono 22

Early-age effect of corn cob ash as a partial replacement for portland cement in concrete
Oluwadamilola A. Fadele and Mike Otieno 22

Development of sulfuric-acid resistant concrete with reduced carbon emissions
Shintaro Tanaka, Hiromi Fujiwara, Masanori Maruoka, Hiyori Ishiduka, and Tao Wang 23

Mechanical properties and self-sensing ability of amorphous metallic fiber-reinforced concrete
Théophile Bouillard, Anaclet Turatsinze, Jean-Paul Balayssac, Ahmed Toumi, Olivier Helson, and Xavier Bourbon 23

Towards understanding the influence of metakaolin in the prevention of alkali-silica reaction
Grant Prinsloo, Mohammad S. Pourbehi, and Adewumi J. Babafemi 23

Optimization of dune sand-slag blended geopolymer mortar using Taguchi method
Abdulkader El-Mir, Hilal El-Hassan, Amr El-Dieb, and Abdelrahman Alsallamin 24

Effects of sodium oxide content on the durability of alkali-activated mortar utilizing Botswana copper mine tailings and fly ash
Abraham V. J. Sannoh, Goitseone Malumbela, and Victor S. Gilayeneh 24

Effect of styrene-acrylic latex polymer on the dimensional and mechanical stability of ettringite accelerated binders composed of CAC-PC-C$
Lamiya Noor and Jason H. Ideker 24

2.2. Service life modelling and prediction of durability 25

Probabilistic service life design of reinforced concrete structures via free web application
Ueli Angst, Marc Zintel, and Christian Linden 25

Durability aspects of chloride-affected cracked concrete structures reinforced with 1.4003 rebars
Christoph Dauberschmidt, Andreas Fraundorfer, and Frederik Ripa 25

The influence of temperature on the cracking of plastic concrete
Marnu Meyer, Juandré van Zyl, and Riaan Combrinck 25

A numerical modelling framework to predict the effects of self-healing on chloride penetration in ultra high performance concrete (UHPC)
Antonio Cibelli, Hamza Ahmed, Giovanni di Luzio, and Liberato Ferrara 26

Modelling the cracking of fresh concrete
Riaan Combrinck, Marnu Meyer, and William P. Boshoff 26

Performance based approach to assess the spalling resistance of concrete under freeze-thaw attack
Muhammed Basheer, Yang Kai, and Adrian Long 26

Salt frost scaling of concrete – new insights regarding the damage mechanism
Matthias Mueller and Horst-Michael Ludwig 27

Impact of slag on carbonation rate of concrete based on calcium aluminate cement
Alma-Dina Bašić, Marijana Serdar, Ingrid Mikanovic, and Gunther Walenta 27

A critical evaluation of the use of crack width requirements in the durability design of marine reinforced concrete structures
Nicholas Elias and Hans Beushausen 27

2.3. Modelling and prevention of reinforcement corrosion 28

Stability of Fe^{2+} in cementitious media
Shishir Mundra, Dominik Kunz, Jan Tits, Erich Wieland, and Ueli M. Angst 28

Toward a digital twin of the steel-concrete interface for numerical corrosion studies
T. Schmid, Z. Zhang, N. Ruffray, M. Griffa, O.B. Isgor, and U.M. Angst 28

Thermodynamic and kinetic considerations of corrosion product formation in cementitious media
F.E. Furcas, B. Lothenbach, O.B. Isgor, S. Mundra, Z. Zhang, and U.M. Angst 28

Testing the Bromide penetration resistance of concrete: substitution of NaCl by NaBr in Rapide Chloride/Bromide migration test (RCM/RBM)
Christoph Langer and Gesa Kapteina . . . 29

Influence of alternative binders on the passivation of steel in mortar
Rebecca Achenbach and Michael Raupach . . . 29

Reinforcement corrosion of circular concrete columns under sustained load
Samer Jabbour, Beatriz Martín-Pérez, and Michelle Liu . . . 29

Moisture sorption behaviour of concrete mixtures containing chlorides and the resulting electrolytic resistivity in relation to the estimated corrosion risk
Andreas Fraundorfer, Thomas Heilmayer, Christoph Dauberschmidt and Christoph Gehlen . . . 30

Updating the prediction of chloride-induced corrosion in RC structures by considering cracks detected by a CNN
Patrick Pfändler, Thilo Schmid, and Ueli Angst . . . 30

Influence of red mud addition in alkali-activated mortars on corrosion resistance of steel
Ivana Vladić Kancir, Vinko Radoš, and Marijana Serdar . . . 30

Chloride profiles with a peak – why and what are the consequences for predictions?
Lars-Olof Nilsson . . . 31

Sustainable reinforced concrete for chloride exposures
Sylvia Keßler, Julia Wünsch, and Daniel Cassiani . . . 31

A comparison between uniform and galvanic corrosion rate in carbonation induced corrosion of reinforced concrete
Thi-Thu Trang Nguyen, Raoul François, Tru Ngoc Vu, and Myriam Carcasses . . . 31

Corrosion-induced concrete cracking - a poromechanical, multiscale approach
Mohit Pundir, David Kammer, and Ueli Angst . . . 31

Chloride threshold and service life of prestressed concrete with various supplementary cementitious systems
Dyana Joseline and Radhakrishna G. Pillai . . . 32

3. CONDITION ASSESSMENT OF CONCRETE STRUCTURES **33**

3.1. Degradation and condition assessment . . . 33

Forensic investigation concerning inspection and diagnosis of condition of water storage systems in the Gulf
Michael Grantham and Rob Polder . . . 33

Assessment of cantilevered concrete balconies by means of practically oriented evaluation tools
Bart Craeye, Lydia Wittocx, Neel Renne, Peter Minne, and Robby Caspeele . . . 33

Corrosion monitoring of reinforced concrete structures – actual research results and new guidelines
Andreas Fraundorfer and Christoph Dauberschmidt . . . 34

Condition assessment of two prestressed concrete slabs after 60 years in service
Dana Tawil, Leah Kristufek, Beatriz Martín-Pérez, Leandro Sanchez, and Martin Noël . . . 34

A case study on concrete testing for accurate assessment and maintenance of concrete structures
Kerusha Ayer, Andries van der Merwe, and Kevin Volmink . . . 34

Evaluation of corrosion damage in reinforced concrete structures in terms of the rebar's residual cross-section
Victor S. Gilayeneh and Sunday O. Nwaubani . . . 35

Preliminary evaluation of pier cap from an ASR-affected bridge in Central Canada
Leah Kristufek, Andisheh Zahedi, Dana Tawil, Leandro Sanchez, Beatriz Martín-Pérez, and Martin Noël . 35

Approach to the development of a model to quantify the quality of tendon localization in concrete using ultrasound
Stefan Küttenbaum, Stefan Maack, and Alexander Taffe . . . 35

Afrisam Ulco Preheater – digital audit through unmanned technology – a DeltaScan and SpecCon case study
Darryl Epstein . . . 36

3.2. Non-destructive measurement and assessment techniques . . . 37

An artificial intelligence approach to detection and assessment of concrete cracks based on visual inspection photographs
Mufaro Gomera and Yunus Ballim . . . 37

Imaging of results in NDT-CE: strength and limitations in the use of radar vs. ultrasonic echo
Alexander Taffe . . . 37

Recent advances in (ultra)sonic active and passive monitoring of reinforced and prestressed concrete structures
Ernst Niederleithinger, Niklas Epple, Chun-Man Liao, and Stefan Maack . . . 37

Testing methods for concrete-to-concrete interfaces as pathways for corrosive attack
Jan P. Höffgen, Matthias Mohs, Sarah Lamparter, Viktória Malárics-Pfaff, and Frank Dehn . . . 38

Microscopic assessment of ASR-affected columns after 20 years in service
Hesham Ahmed, Andisheh Zahedi, and Leandro Sanchez . . . 38

A framework for non-destructive assessment and monitoring of 3D printed steel fibre reinforced concrete (SFRC) tunnel segments
Andrea Marcucci, Stefano Guanziroli, Francesco Muscolino, Alberto Negrini, Roberto Felicetti, and Liberato Ferrara . . . 38

Practical procedure for the precise measurement of geometrical tendon positions in concrete with ultrasonic echo
Stefan Maack, Stefan Küttenbaum and Ernst Niederleithinger . . . 39

Sewer concrete subjected to biogenic acid corrosion: analysis of concrete deterioration phases using QEMSCAN
Alice T. Bakera and Mark G. Alexander . . . 39

Laser induced breakdown spectroscopy – a tool for imaging the chemical composition of concrete
Gerd Wilsch, Tobias Völker, Tim Klewe, and Sabine Kruschwitz . . . 39

Determination of surface properties of treated cement pastes by acoustic methods and scratch test - pilot experiments
Libor Topolář, Lukáš Kalina, Dalibor Kocáb, Valeriia Iliushchenko, Petr Bílý, and Josef Fládr . . . 40

The effect of curing, specimen thickness, and saturation on surface resistivity of concrete
Saarthak Surana, Hans Beushausen, and Mark Alexander . . . 40

Mortar resistivity as a parameter for monitoring steel corrosion in alkali-activated materials
Antonino Runci and Marijana Serdar . . . 40

4. CONCRETE REPAIR, REHABILITATION AND RETROFITTING **41**

4.1. Repair methods, materials and techniques . . . 41

Application of RFID corrosion environment sensing system to repair work and results of 10-year study
Akira Eriguchi, Hiromi Fujiwara, and Yukitoshi Isaka . . . 41

Investigating the effects of anti-corrosive coatings on the bond between corrosion-damaged rebar and concrete repair materials
Moolla Muhammad Ameen, Nicholas Jarratt, and Hans Beushausen . . . 41

Re-using existing prefabricated prestressed concrete girders
Rob Vergoossen, Gert-Jan van Eck, and Danny Jilissen . . . 42

Repair of a hydraulic structure with different strain-hardening cement-based composites
Steffen Müller, Michaela Reichardt, and Viktor Mechtcherine . . . 42

Crack control for repair and strengthening of reinforced concrete structures using the multi-cracking behaviour of ultra-high performance fibre reinforced shotcrete (UHPFRSC)
Andre Strotmann and Jörg Jungwirth . . . 42

Concrete substrate moisture requirements for durable concrete repairs – a field study
Benoit Bissonnette, Alexander M. Vaysburd, Kurt F. von Fay, Shannon J. Harrell, Luc Courard, and Andrzej Garbacz . . . 43

History, diagnosis and repair of the Corniche Kennedy in Marseilles
Loriana Pace, Renaud Leconte, and Tancrède De Folleville . . . 43

Sustainable concrete repair & protection products – the impact on renovation works
Michel Donadio, Josefa Nüsslein, Katherine Agapitos, Wayne Smithers, and Johannes Lohner . . . 43

A long-term study on the effect of a hydrophobic treatment on the moisture balance and durability of a reinforced concrete structure in a road tunnel
M. Brem, J. Lohner, and M. Büchler . . . 44

Emergency rehabilitation of Selby interchange on M2, in Johannesburg, South Africa
Johnnie Strydom, Jared da Silva, and Odilon Kongolo . . . 44

Product data templates of repair products for Building Information Modeling (BIM)
Norbert Schröter . . . 44

Use of fibres in improving the mechanical properties of a multifunctional cement for structural repair purposes
Chinedu A. Ajoku, Anaclet Turatsinze, Ariane Abou-Chakra . . . 45

The use of hydrophobic treatments to extend the service life of deteriorated marine RC structures
Joanitta Ndawula, Hans Beushausen, and Mike Otieno . . . 45

4.2. Concrete patch repairs and bonded overlays . . . 46

Journey through time - concrete repair mortar
Klaus Bonin . . . 46

Rehabilitation and repair of concrete overlays
Dan King and Peter Taylor . . . 46

UHPC overlay as sustainable solution to preserve old concrete structures
Ankit Kothari, Magdalena Rajczakowska, and Andrzej Cwirzen . . . 46

Volume change behavior of cement-based repair materials labelled as shrinkage-compensating, shrinkage-compensated or nonshrink
Benoît Bissonnette, Laurent Molez, Pierre-Vincent Certain, Charles Lamothe, Marc Jolin, and Richard Gagné . . . 47

Strain-hardening limestone calcined clay cement-based (SHLC3) composites for strengthening concrete elements against impact loadings
Cesare Signorini, Mirza A.B. Beigh, Marko Butler, and Viktor Mechtcherine . . . 47

Investigating the structural contribution of patch repairs to reinforced concrete elements
Nicholas Jarratt, Vafa Naraghi, and Hans Beushausen . . . 47

Thin bonded overlays with carbon reinforcement for concrete pavements
Julia Neumann and Rolf Breitenbücher . . . 47

Carbonation and chloride penetration of repair mortars with water treatment plant sludge and sugarcane bagasse ash sand
Thiago A. Hemkemeier, Fernando C.R. Almeida, Almir Sales, and Agnieszka J. Klemm . . . 48

4.3. Structural repairs and strengthening . . . 49

Actual achievements and future challenges of HPFRC for structural rehabilitation of bridges
Adriano Reggia, Ivan Trabucchi, Alessandro Morbi, and Giovanni A. Plizzari . . . 49

Shear strengthening of concrete T-beams with lateral layers of UHPC
Tongxu Liu and Jean-Philippe Charron . . . 49

Numerical modeling of deep beams strengthened in shear with fabric-reinforced matrix composites
Nour Khir Allah, Tamer El-Maaddawy, and Hilal El-Hassan . . . 49

Study on the application of inorganic resin-based micro-FRP bars in strengthening marine concrete structures
Shuai Yang, Lingwang Su, Zongquan Ying , and Meimei Liu . . . 50

Experimental testing on the structural capacity of coupling beams with non-anchored longitudinal rebars
Torrealva Daniel and Arzapalo Joel . . . 50

Flexural behaviour of RC beams strengthened using hybrid combination of CFRP laminates and UHPC overlay
Taraka Malleswara Rao Balla, Rahul Reddy Morthala, and S. Suriya Prakash . . . 50

Partial reconstruction and lengthening of a continuous post-tensioned concrete bridge deck: case study of emergency rehabilitation of the Seaward Road Bridge after partial collapse
Peter Fenton, Jitesh Harripershad and Luke Reid . . . 51

CFCM for strengthening potentials
György L. Balázs, Ferenc Csurgai, and Sandor Solyom . . . 51

4.4. Service life extension: methods and materials . . . 52

Numerical study of galvanic anode systems used for patch repair of reinforced concrete structures
Christian Helm and Michael Raupach . . . 52

Current distribution and throwing power of galvanic cathodic protection with discrete anodes in reinforced concrete beam or column elements
Bjorn Van Belleghem, Mathias Maes, and Tim Soetens . . . 52

Field performance of hybrid and galvanic anodes in reinforced lime concrete heritage structure using electrochemical studies
Ananya Ajayan and Radhakrishna G. Pillai . . . 52

A rapid test to screen the functionality of galvanic anodes for cathodic protection of reinforced concrete
Ryan Cobbs, Rene Brueckner, Chris Atkins, and Arpit Goyal . . . 53

Ion distribution in concrete overlay, mapped by laser induced breakdown spectroscopy (LIBS), modified by an embedded zinc anode
W. Schwarz, Gerd Wilsch, N. Katsumi, G. Ebell, and T. Völker . . . 53

The performance of cement-based coatings for drinking water reservoirs: a case study
Christian Paglia, Cristina Mosca, and Albert Jornet . . . 53

Practical service life assessment and rehabilitation strategy development for hyperbolic shell natural draft cooling towers
Matthew B. Gries, Kevin A. Michols, John S. Lawler, Elizabeth I. Wagner, Anthea Dennis, Koketso Kgatle, and Marita Pretorius . . . 54

The environmental impact of service life-extending repair for corrosion damaged reinforced concrete balconies: a case study in a coastal context
Neel Renne, Bart Craeye, Matthias Buyle, and Amaryllis Audenaert . . . 54

Extending the service life of existing concrete structures to last beyond 100 years
David Whitmore . . . 55

Galvanic corrosion of prestressed strands in re-grouted post-tensioned concrete systems
Karthikeyan Manickam and Radhakrishna G. Pillai . . . 55

Long-term performance parameters influencing the service life of galvanic anodes in reinforced concrete systems
Karthikeyan Manickam, Deepak K. Kamde, and Radhakrishna G. Pillai . . . 55

Performance assessment of galvanic anodes in cathodic protection systems in reinforced concrete structures
Keerthi V. T., Naveen Krishnan, and Radhakrishna G. Pillai . . . 56

5. DEVELOPMENTS IN CONCRETE TECHNOLOGY, ASSESSMENT AND PROCESSING **57**

Feasibility of using clays from Southeast European deposits in limestone calcined clay cements
Matea Flegar, Marijana Serdar, Diana Londono-Zuluaga, and Karen Scrivener . . . 57

The investigations on properties of self-healing concrete with crystalline admixture and recycled concrete waste
Fallon Clare Manhanga, Žymantas Rudžionis, Ernestas Ivanauskas, and Algirdas Augonis . . . 57

Interactions between hydrated cement pastes and aggressive ammonium: experimental batches characterization
Marie Giroudon, Cédric Roosz, Mehdi Bista, Matthieu Peyre Lavigne, Laurie Lacarrière, and Alexandra Bertron . . . 58

Stability of synthetic calcium silicates hydrates in chemically aggressive conditions
Cédric Roosz, Marie Giroudon, Mehdi Bista, Laurie Lacarrière, and Alexandra Bertron . . . 58

Influence of alkali content and silica modulus on the carbonation kinetics of alkali-activated slag concrete
Olivera Bukvic and Marijana Serdar . . . 58

High-performance reactive magnesium cement incorporating hollow natural fiber and silica sand
Bo Wu and Jishen Qiu . . . 59

Quantified point clouds and enriched BIM-models for digitalised maintenance planning
Hendrik Morgenstern and Michael Raupach . . . 59

Case Study: implementation of photoluminescent polymer concrete elements on bridge and infrastructure projects
Kevin Volmink, Josiah Padayachee, and Nalini Nulliah . . . 59

Design of smart cementitious composites based on multi-walled carbon nanotubes (MWCNTs) using probe ultrasonicator for dispersion
Shaban Shahzad, Ahmed Toumi, Jean-Paul Balayssac, and Anaclet Turatsinze . . . 60

Early age properties of high-performance concrete
Derek Mostert and Elsabe Kearsley . . . 60

The tensile deformation and capillary pressure build up in fresh concrete
Marnu Meyer, Yaseen Khan, and Riaan Combrinck . . . 60

Effects of high and very temperatures on blast furnace slag concrete
Marcin Zyzak, Hans Hedlund, John L. Provis, and Andrzej Cwirzen 61
Using simple soil water content sensors to measure water availability in fresh concrete
Martha S. Smit, William P. Boshoff, and Luke, G. Warren 61
Effectiveness of concrete curing compounds in extreme windy and dry conditions
Zelda Spijkerman, William P. Boshoff, and Martha S. Smit 61
Preventing plastic shrinkage cracking by monitoring the capillary pressure build-up in self-compacting concrete
Renier Deysel, William P. Boshoff, and Martha S. Smit 61
Investigation of the influence of fine recycled sand on the setting behaviour of cement when used as supplementary cementitious material (SCM)
Benjamin Wolf, Johannes Paule, and Andrea Kustermann 62
Application of mine tailings sand as construction material – a review
Jacob Ikotun, Rhoda Adeyeye, and Mike Otieno 62
A novel approach for the consolidation of sand by MICP single treatment
Brigitte Nagy, Savannah Baptist, and Andrea Kustermann 62
Towards sustainable building materials through lithium silicate densifiers
Lukáš Kalina, Vlastimil Bílek, Jiří Smilek, František Soukal, Libor Topolář, Petr Bílý, and Josef Fládr 63

5.1. Fibre reinforced cementitious materials 64
A textile reinforcement method for 3D printed concrete
J. J. Janse van Rensburg, Adewumi J. Babafemi, and Riaan Combrinck 64
Textile reinforced concrete for free-form concrete elements: influence of the binding type of textile reinforcements on the drapability for manufacturing double-curved concrete elements
Shantanu Bhat, Matthias Kalthoff, Patrick Shroeder, Thomas Gries, and Thomas Matschei 64
Study on fundamental properties of the spraying ultra high strength fiber reinforced concrete cured at normal temperature
Kotaro Yoshikawa, Hiromi Fujiwara, Masanori Maruoka, Katsuhiko Yamada, and Junon Yoshikawa . . . 64
Performance of high-strength strain-hardening cement-based composites (HS-SHCC) under cyclic loading
Dominik Junger and Viktor Mechtcherine 65
Flexural strength of fibre reinforced concrete in relation to the angle of magnetically orientated fibres
Kristýna Carrera, Karel Künzel, Václav Papež, Radoslav Sovják, Přemysl Kheml, Jindřich Fornůsek, Michal Mára, and Petr Konrád 65
Behaviour of steel fibre reinforced concrete pavements on a single fibre level
Nyane Makara, Riaan Combrinck, and Humaira Fataar 65

6. Alkali-aggregate reaction migration (RILEM TC 300-ARM) **66**
Actions to mitigate alkali-aggregate reaction in affected structures
Luís Oliveira Santos 66
Non-traditional alkali-silica reaction mitigation products in new and affected concrete
Diego Jesus De Souza, Leandro F. M. Sanchez, and Medhat H. Shehat 66
Test procedures and strategies to evaluate non-traditional mitigation products in concrete
Leandro F. M. Sanchez, and Diego Jesus De Souza 66
Mitigation of the alkali-aggregate reaction
Esperanza Menéndez and Antonio Santos Silva 67

Author Index **68**

1. KEYNOTE PAPERS

Understanding the durability of concrete containing SCMs

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Increasing the use of supplementary cementitious materials (SCMs) in concrete remains by far the most practical way to reduce the CO_2 emission associated with cement and concrete. Supplies of the traditional SCMs, blast furnace slag and coal fly ash, are limited and will continue to decrease due to efforts to reduce global warming. Calcined clays can be produced in effectively unlimited quantities and open up new possibilities to increase substitution levels. To use all these materials with confidence we need to understand their durability from a generic, mechanistic standpoint.

In general, SCM improve most aspects of durability – chloride ingress, alkali silica reaction and resistance to sulfate ions. On the other hand, carbonation rates will be more rapid due to the reduced buffer to react with incoming CO_2. Nevertheless carbonation rates fulfil the requirements in most standards and in the vast majority of applications moisture levels are much too low to allow active corrosion even once the concrete is carbonated.

Understanding the resistance to chloride penetration is particularly interesting, as the corrosion of reinforcing bars due to chloride ions is by far the number one cause of durability issues with concrete. Traditionally chloride ingress is considered to be a function of the porosity of the concrete. Of course, porosity is a major factor, but our recent studies show that it is far from the whole story. For example, LC3-50 paste with a w/b ratio of 0.5 has a higher porosity than OPC with a w/b ratio of 0.3, but an effective diffusion coefficient of chloride 3-4 times lower (Figure 1).

Researchers frequently attribute the lower diffusion to the "tortuosity" of the pore structure, but this is in fact a circular argument as "tortuosity" figures are derived from the ratio of ion diffusion (or conductivity) in free solution to the diffusion (or conductivity) in the sample. The figures derived are far higher than can be explained by simple geometric arguments. It must be appreciated that even for concrete cured under water the saturated pore network is made up of pores in the range of 10 nm. There may be some refinement of the connected pore sizes in blended systems, but this is not enough to explain the large difference in diffusion rates.

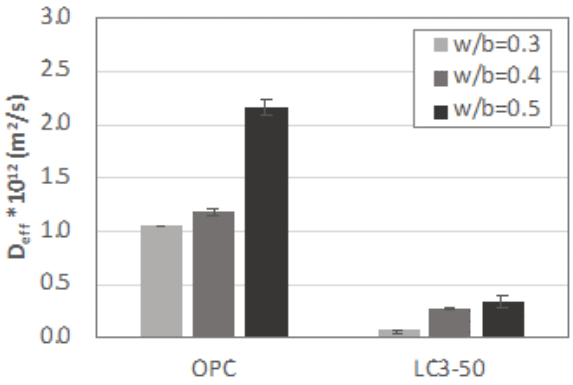

Figure 1: *Effective Cl diffusion for OPC and LC3 pastes adapted from Wilson et al. [1]*

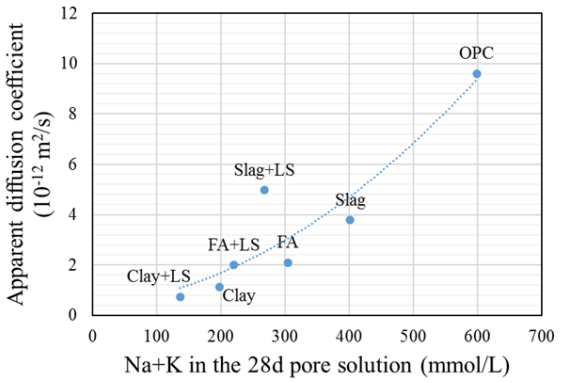

Figure 2: *Relation between apparent diffusions coefficient for various blended systems with the alkali concentration in the pore solution, from Sui et al [2]*

Our recent work indicates two other factors play a major role. First the ionic concentration of the pore solution. As shown in Sui et al [2] the diffusion seems to be strongly correlated this the concentration of [Na

+ K]. On a simplistic level it higher numbers of charge balancing Na^+ and K^+ allow higher levels of Cl^- in solution.

A second factor, which is not yet well understood, is the composition of the C-(A)-S-H, which changes significantly between OPC and blended systems. The simulations from the recently completed thesis on Khalil Ferjoui in our group indicates this may explain the difference, but critical information on the actual surface structure of C-(A)-S-H is still lacking.

This work illustrates that we need to change our thinking of the factors affecting durability and evolve our use of “durability indicators” accordingly. With respect to resistance to chloride ingress the bulk resistivity, which can be measured very quickly and easily seems to be the best indicator.

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Measuring, understanding, and forecasting reinforcing steel corrosion in concrete

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Abstract. This contribution reviews recent advances in the areas of measuring, understanding, and forecasting reinforcing steel corrosion in concrete. The overall goal is to promote scientific discussion and progress to allow for technological innovations in the fields of non-destructive testing, structural health and corrosion monitoring, as well as modelling of the performance of reinforced concrete structures and maintenance strategies in actual service environments. *Improved Condition assessment as well as Concrete Repair, Rehabilitation and Retrofitting* (ICCRRR) technologies are needed to face the challenge of ageing infrastructure and to meet the "net zero by 2050 target".

1 Motivation

Corrosion of reinforcing steel in concrete is the primary cause for the degradation of civil infrastructure [1]. It is a common challenge of the industrialized countries that the asset of structures contains an increasing portion of relatively old structures, which need to be maintained to ensure safety and availability. Projections for the number of structures needing repair in the coming decades are in the order of an increase by a factor of 3–5 by 2050 with respect to now [2]. Already today, however, leading industry nations are confronted with the need to close bridges for heavy traffic due to safety concerns, and – fortunately more rarely – cases of structural collapses.

Against this background, there is an urgent demand for *Improved Condition assessment as well as Concrete Repair, Rehabilitation and Retrofitting* (ICCRRR) technologies. Without technological progress, it will be extremely difficult to tackle the challenge of ageing infrastructure.

Another concern relates to the pressing issue of global warming and the need to reduce the construction sector's environmental footprint. Ambitions such as the "net zero by 2050 target" call for dramatic changes in both the materials used (e.g. low-emission cements, recycled mineral waste and aggregates) and construction processes (e.g. digital/additive construction). Such new technologies not only needed to have a low environmental footprint at the time of construction, but to prove durability over long time scales.

For the reasons given above, it is vital to be able to measure, understand, and forecast corrosion of steel in concrete. This contribution will highlight recent advances in these three areas and how they can contribute to address the societal/environmental challenges outlined above.

2 Measuring corrosion

The measurement of corrosion means that corrosion processes can be followed and quantified in both laboratory studies and, more importantly, in-situ in structures. While a number of techniques have been developed that may allow for the detection of corrosion-onset and the quantification of corrosion rates under certain well-controlled conditions – in particular, specially designed samples in the laboratory (e.g. segmented bars for macro-cell corrosion studies [3, 4]) – reliable measurements of corrosion processes under actual exposure conditions in structures are still a major challenge. Such quantification, however, is crucial for the understanding of corrosion processes, as existing models need to be expanded to better take into account the dynamic behaviour under generally time-variable exposure conditions [5, 6].

New opportunities may be seen in recent advances in sensing technologies, allowing for the placement of embedded sensors to characterize environmental changes such as chloride concentrations and pH during the life of a structure [7]. Such sensing techniques not only allow for a better characterization of the exposure conditions but also to relate corrosion processes to the actual changes in the pore solution chemistry.

Additional opportunities for the in-situ quantification of corrosion rates, especially for localized corrosion, are related to combining advanced numerical corrosion models with on-site measurements, such as [8]. Here, the progress in computational power may facilitate the development of a new generation of non-destructive techniques.

3 Understanding and forecasting corrosion

One of the prevailing key open questions is related to the factors that lead to corrosion of steel in concrete in chloride-exposure environments. Various assessments have revealed that the concept of the critical chloride threshold is not adequate in scientifically explaining corrosion initiation [6]. A number of studies have highlighted that different features at the steel-concrete interface play important roles [9-11]. Nevertheless, it is still not possible to reliably predict the initiation of corrosion.

Similarly, the rate at which corrosion processes occur is an important parameter, especially for the assessment of the life or residual life of a structure. Recent fundamental understanding about the relevance

of concrete microstructure and moisture [12] opened new perspectives, both for the decarbonization of cement and concrete and for new models to forecast the performance of reinforced concrete. Such models may also be useful on implementing and generating confidence in repair and rehabilitation methods deviating from mainstream approaches, such as the use of concrete surface treatments [13]. Nevertheless, more research is needed to develop engineering models that can reliably predict the rate of corrosion of steel in concrete under actual exposure conditions and on the basis of parameters available in engineering practice.

Finally, corrosion-induced concrete cracking and spalling is a common limit state in engineering practice, but so far no model is available to reliably predict this [14]. This may be related to the fact that most models are centred on mechanical considerations, e.g. on the basis of the assumption of a rebar idealized as an expanding cylinder. On the other hand, little attention is paid on the transformation of dissolved ferrous ions in the pore solution, resulting from (electro-)chemical reactions, including considerations of the thermodynamic stability and the kinetics of different reactions in competition with transport. A recent compilation of literature data on the speciation of iron in cementitious systems [15] may be a useful starting point in this regard, but certainly more scientific studies are needed to fully reveal the "fate" of dissolved iron in a cementitious matrix.

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Damage management of concrete elements by crack mitigation and self-healing strategies

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Abstract. Small cracks in concrete elements that are allowed by structural design codes will not hamper the functionality of the element initially, but do provide an easy access for aggressive agents into the concrete and to the reinforcement. Therefore, cracks will lead to an acceleration of degradation processes and reduce the service life and sustainability of concrete structures. Crack mitigation strategies like the incorporation of superabsorbent polymers, and self-healing methods can help to reduce the maintenance frequency and increase service life, however, their efficiency in realistic environments needs to be properly evaluated.

1 Occurrence of cracks in concrete

The occurrence of small cracks in concrete is almost unavoidable. Shrinkage phenomena and temperature effects can induce early age cracks and at later ages the intrinsic brittleness and low tensile strength of the material in many cases leads to cracking in service. For many structural elements, this results in the need to introduce reinforcement, mostly steel rebars. In design codes, cracks of limited width (200-300 µm) are allowed for most structural elements if water tightness is not a prerequisite. Fib Model Code 2020, Eurocode 2 and ACI 318, propose equations to calculate crack widths as a function of reinforcement bar diameter and reinforcement area ratio, concrete cover, concrete tensile strength, steel-concrete bond strength and the induced stress in the reinforcement. Small cracks will not hamper the functionality of the element initially, but do provide an easy access for aggressive agents into the concrete and to the reinforcement. Therefore, cracks will lead to an acceleration of degradation processes and reduce the service life and sustainability of concrete structures. Recently developed high performance and extremely low porosity concrete types are mostly even more brittle and sensitive to early age cracking than normal strength concrete. Degradation models rarely include the crack pattern as a durability parameter, because the effects of cracks on the kinetics of the degradation mechanisms are generally not well-known or too complex to introduce into simple calculation models.

2 Effect of cracks on concrete durability

It is clear that the presence of cracks in the concrete cover zone provides easier access for various aggressive agents. For instance, it has been found that cracks above a certain critical crack width allow a faster penetration of chloride ions into the matrix. This critical width could be around 10 to 50 µm, as stated by Maes [1] and Van den Heede et al. [2] respectively. Based on in situ inspections on a concrete bridge, Kušter Marić et al. [3] mentioned that above the crack width of 100 µm the time to depassivation of the reinforcement was significantly reduced, independent of the cover thickness. Cracks can also increase the CO_2 penetration through the concrete cover, thus triggering an earlier start of the reinforcement corrosion. Alahmad et al. [4] found that CO_2 penetrated freely in cracks with a width above 60 µm, while the carbonation rate in the crack decreased for smaller crack widths. Also, Van Mullem et al. [5] showed that carbonation was significantly affected by the crack tortuosity for crack widths below 100 µm.

3 Crack mitigation and self-healing strategies

To increase durability and the service life of the structure, different mitigation and crack treatment methods can be applied. Superabsorbent polymers (SAPs) possess the ability to take up a significant amount of liquids from the environment and due to their ability to absorb and retain water from the cementitious mixture, they have been successfully used as internal curing agents preventing self-desiccation and reducing autogenous shrinkage. In a recent study [6], commercial acrylate based and in-house developed NaAMPS (2-acrylamido-2-methyl-1-propanesulfonic acid sodium salt) based superabsorbent polymers have been proven to effectively eliminate early age shrinkage cracks in reinforced concrete walls (14 m x 2.75 m x 0.80 m), while reference walls without SAPs presented through-going cracks in the first 7 days after casting.

The so-called passive crack treatments are manually applied if inspection indicates that crack widths have exceeded allowable values for the structure and environment in which it has to function. They only treat surface cracks and the application is dependent on the accessibility of the affected area. Active methods on the other hand are incorporated at the construction stage. Those methods, also called self-healing techniques, will be activated when the cracks are formed and may fill both interior and surface cracks.

3.1 Autogenous and autonomous healing

A further distinction can be made between autoge-

nous healing and autonomous or autonomic healing. Autogenous healing relies on the conventional constituents of the concrete matrix, and is mainly induced by continued hydration of yet un-hydrated binder particles near the crack walls, and precipitation of calcium carbonate crystals in the crack. Methods to limit crack width (fibre addition), provide the water that is needed for hydration reactions to occur (e.g. addition of super-absorbent polymers), or enhance hydration or crystallization (e.g. by mineral additions or crystalline admixtures) can be used to stimulate or improve autogenous healing. Autonomous healing uses unconventional engineered additions to provide the self-healing function and includes the application of encapsulated minerals and polymeric healing agents, and of encapsulated or granulated micro-organisms. Various microbes have been shown to induce precipitation of $CaCO_3$ as a result of their metabolism and the nucleation properties and zeta-potential of the cell wall. Regarding encapsulated agents, micro-encapsulation, macro-encapsulation, and vascular networks have been applied. The choice will determine the magnitude of the healable damage, the repeatability of healing, and the recovery rate. In these systems, the formation of the crack is mostly the trigger to activate the self-healing, because it ruptures the capsules and releases their content.

3.2 Self-healing under realistic conditions

Several review papers have been published, giving an overview of the different autogenous and autonomous technologies [7], test methods to assess their effectiveness [8] and models to predict the result of the self-healing process [9]. However, many of the results were obtained in ideal conditions, often environmental conditions in laboratories. At the moment, there is a need for further insights into the behaviour of self-healing concrete in real service scenarios, including cases where structures are functioning in extreme or aggressive conditions and in the case of dynamic cracks. An overview of the current knowledge regarding the efficiency of self-healing concrete under realistic conditions has been recently compiled [10].

Ideal conditions vary according to the considered self-healing mechanism. For (improved) autogenous self-healing to happen, liquid water should be available. SAPs can capture moisture from the air and in this way activate autogenous healing [11]. The swelling of SAP particles in contact with moisture leads to immediate crack sealing and the release of water to yet unhydrated binder particles at the crack faces activates autogenous healing. The efficiency of bacterial self-healing will depend on the characteristics of the microorganisms that are used. Aerobic bacteria are not only in need of water, but also of oxygen, of which the availability could decrease from the crack mouth to the crack tip. This could be overcome by using nitrate-reducing bacteria together with nitrate as an alternative electron acceptor that enables bacterial $CaCO_3$ precipitation without O_2 being available. These bacteria could provide the added functionality of corrosion inhibition by nitrite produced as an intermediate metabolite [12]. Other autonomous mechanisms, based on encapsulated polymeric healing agents, may be independent of water availability. Still, one-component polyurethane precursors need humidity to polymerize [13]. On the other hand, in unsaturated specimens, the release and distribution of healing agent can be positively affected by the capillary action of the crack. Temperature changes will affect the rate of chemical and enzymatic reactions and lead to a variation in polymer viscosity thus affecting the crack filling efficiency [14]. Therefore, the best self-healing strategy will depend largely on the conditions in which the concrete element will function.

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Advances in predicting reinforcement corrosion damage on concrete structures

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Abstract. Steel corrosion-induced damage in reinforced concrete (RC) structures is a pervasive problem that affects minor and major infrastructural developments alike. In the recent past, focus has shifted from prediction of corrosion rate which is affected by several inter-related factors, to the prediction and management of corrosion-induced damage in the propagation phase. Much focus has also been placed on the prediction of the residual life of these structures. These developments have been facilitated by a number of developments in the field including advancements in materials technology, impact of climate change, improved laboratory testing / simulations, real-time in-situ remote monitoring, and capacity / people development. This paper discusses the main drivers that have shaped and provided impetus for the advances in the management of steel corrosion damage in RC structures.

1 Introduction

Steel corrosion-induced damage in reinforced concrete (RC) structures, especially in the marine environment [1], is a pervasive problem that has persisted for decades despite the numerous studies in this field. The damage takes different forms that stretch across both the serviceability and ultimate limit states of the affected RC structures, and include cover cracking (initiation and propagation), delamination and spalling, increased deflection, and loss of steel cross-sectional area. Even with relatively good durability design, specification and in-situ quality control, steel corrosion is inherently difficult to completely eliminate, and most approaches resort to the management of the risk thereof.

It is unavoidable to talk of steel corrosion damage without referring to corrosion propagation. This is because steel corrosion-induced damage is directly associated with the corrosion propagation phase in the service life of a corrosion-affected RC structure. More than a decade ago, Otieno *et al.* [2] stated that "the impetus to include corrosion propagation in the design service life of RC structures can be attributed to a number of reasons including, among others, (i) the rapid increase in the number of deteriorated RC structures due to steel corrosion, (ii) the need to safely utilize the residual serviceability and strength of the RC structure with or with-out remedial measures [3], and (iii) the propagation phase may in some instances be sufficiently long to merit consideration and quantification. These statements are still valid today!

2 Prediction of corrosion damage

Prediction of steel corrosion damage in RC structures is intrinsically linked to the prediction of the progress of steel corrosion in the propagation phase i.e. corrosion rate. The latter, in addition to the lack of a unified method for its quantification, is not easy to predict even though several models have been proposed to date [4]. Furthermore, corrosion rate is affected by a number of inter-related factors including cover depth and condition (cracked or uncracked), concrete quality (including binder type), temperature, concrete resistivity, relative humidity and specimen design [1, 5]. These pose challenges to the prediction of corrosion rate.

It is however clear that to date, due to the aforementioned challenges, there has been no consensus on the universal applicability of the various corrosion rate prediction models, and focus seems to have shifted to the prediction and management of corrosion-induced damage in the propagation phase. Much focus has also been placed on the prediction of the residual life of these structures.

The prediction of steel corrosion damage in RC concrete structures is hinged on adopting limit states for corrosion-induced damage. A limit state refers to a state beyond which a structure or part of it no longer satisfies the desired performance criteria [6]. In order to depict the different stages of corrosion-induced damage in the propagation phase, the propagation phase is usually sub-divided into sub-phases, the boundaries of which are denoted by different limit states [4, 7].

3 Focus areas - drivers for advancement

The advancements in the management of corrosion damage have been realized due various reasons. Salient ones are briefly discussed in the following sections.

3.1 Developments in materials technology

Advances in the field of materials used to manage and repair corrosion damage such as surface coatings, corrosion inhibitors and sacrificial anodes [8] cannot be ignored. These need to be further exploited to minimize corrosion damage and maximize the total service life of these structures.

3.2 Impact of climate change

The impact of climate change on the deterioration of RC structures cannot be overlooked. The increasingly harsher exposure environments due to, e.g., global

warming [9], require a corresponding response from engineers not only in terms of reducing the carbon footprint of concrete structures and focusing on the need for net zero energy infrastructure but also in mitigating the short- and medium-term needs. There is need for further work on climate adaptation of corrosion-affected RC structures.

3.3 Improved laboratory testing / simulations

Empirical laboratory tests are invaluable in the development of steel corrosion deterioration prediction models. We therefore need to be acutely careful in the experimental designs to simulate exposure environments, and be even more careful in generalizing the applicability of the results and models thereof.

3.4 Real-time in-situ remote monitoring

The technological advancements such as artificial intelligence and data analytics should be exploited in the monitoring of in-service corrosion-affected RC structures, and more importantly, the associated damage. This is critical for some critical ageing RC structures such as nuclear power plants. This will help immensely in the validation and calibration of existing models and forecasting of the performance of RC structures in the long-term.

3.5 Forecasting corrosion-induced damage

Advancements in time-dependent reliability analyses have made it possible to predict and forecast cumulative corrosion damage in RC structures.

3.6 Capacity / People development

It is incumbent upon researchers to capacitate engineers – especially novice ones – with the advancements in knowledge relating to steel corrosion damage in RC structures.

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Sustainability verification of deteriorating concrete infrastructure

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Abstract. Sustainable asset management is becoming increasingly important, both due to aging population of buildings and infrastructure and due to more restrict policies. Management optimization requires sustainability quantification and verification. The development in *fib* guidelines is summarized and supplemented with further suggestions for sustainability quantification. Methods for including depreciation rates in sustainability quantification need be established.

1 Introduction

A necessity for sustainability verification is combined quantification of the time dependent performance of the considered structure (or stock of structures) and the various impacts of relevance. Limit states for sustainable reinforced concrete structures were discussed by Geiker et al. [1] stressing the need for considering the whole life cycle of a structure, and both engineering and sustainability limit states.

2 Guidelines

The European-funded DuraCrete project provided a durability design framework resembling the established structural design approaches [2]. This framework was further developed and formalized in the *fib* Model Code for service life design [3] and the ISO standard 16204 [4].

The *fib* Model Code for concrete structures 2010 [5] also provides design principles for sustainability (environmental impacts, social impacts, and aesthetics) (see [5] Section 3.4), and suggests life cycle assessment methods adhering to ISO 14040 [6] be used for verification (see [5] Section 7.10). However, [5] provides no specific design guidelines.

Addressing the intention of [5], a design and management framework considering environmental impacts was, based on Lepech [7], proposed by Lepech et al. [8, 9].

The *fib* TG 6.3 "Sustainability of precast structures" presents in [10] the Sustainable Structural Design (SSD) method, which considers both environmental and structural performance in a life cycle perspective. The SSD method combines in economic terms input from life cycle assessment with structural performance assessment. Emphasis is placed on the SSD method being modular, portable, and scalable to facilitate general applicability. The *fib* TG 6.3 further advocate for the use of the "MIVES" method, a multi-criteria decision-making method "capable of defining specialized and holistic sustainability models to obtain sustainability indexes". Reference is in [10] made to the Spanish Structural Concrete Code, where MIVES is proposed used for assessing the sustainability of concrete structures. Adopting MIVES, the *fib* TG 6.3 proposes a set of criteria be considered: economic: total costs, quality, dismantling, service life; environmental: consumption, emission, energy; and social: third parties; health and safety. Despite "health and safety" could include structural performance, this appears not explicitly mentioned neither in the general description nor in the cases.

The draft of the *fib* Model Code 2020 (MC2020) [11] fully integrates structural performance verification in "sustainable and through-life management & care". Structural performance is treated as the basic aspect of social performance of any concrete structure. In addition to stating requirements and criteria, the draft of MC2020 provides guidelines for evaluation/verification. To account for difference in performance of alternative concretes Müller and Boumaaza [12] introduced the "Concrete Sustainability Potential", CSP= $(f_{ck.tSL})$/GWP, where the characteristic concrete strength is multiplied by the service life divided by the global warming potential.

3 Further sustainability quantification

3.1 Sustainability development space

For sustainability assessment Holden et al. [13] introduced the "sustainability development space" limited by threshold values (acceptance criteria) illustrated in a radar chart/spider web diagram. Linnerud et al. [14] recently applied the concept and used the distance between "headline indicator" values and corresponding thresholds to quantify the sustainable development gap at different times and locations.

3.2 Age and use classes

Kohler and Hassler [15] introduced age classes and use classes to provide an integrated system analysis approach for assessment of larger building stocks. The approach was applied by Brattebø et al. [16] for sustainability assessment of building and infrastructure stocks. The authors claimed that (i) when using use-age matrices, the stock can be examined and documented over time considering changes in use characteristics and aging of the stock and (ii) when applying lifetime probability functions together with materials density and energy intensity coefficients of the system, life cy-

cle environmental impact patterns can be quantified.

Considering infrastructure stocks, it is the present author's expectation that the division into age classes with benefit could be based on changes in the requirements to durability related properties (e.g., cover thickness and w/b ratio, alkali reactivity of aggregates, air entrainment for frost resistance) and construction practices (e.g., duration of curing and mitigation of early age cracking). Furthermore, it is suggested that for similar structures (e.g., highway bridges) the use class could be subdivided into type classes reflecting the condition of the structures. An example of such a subdivision is given in Figure 1. Using the concept according to Kohler and Hassler [15] and data from Osmolska et al. [17] the stock of Norwegian standard I-beam girders are subdivided into age and type classes based on regulations and observed corrosion damage.

Use/type class		Age class				
		≤ 1972	1973-80	1981-87	1988-93	≥ 1994
1: Inner coastal	1.1 Non-conformancies					
	1.2 Environmental attack					
	1.3 Non-conf. & env. attack					
	1.4 Other damage					
	1.5 No registred corr. damage					
2: Coastal	2.1 Non-conformancies					
	2.2 Environmental attack					
	2.3 Non-conf. & env. attack					
	2.4 Other damage					
	1.5 No registred corr. damage					
3: Harsh coastal	3.1 Non-conformancies					
	3.2 Environmental attack					
	3.3 Non-conf. & env. attack					
	3.4 Other damage					
	1.5 No registred corr. damage					

Figure 1: *Division of stock into age and type classes to support sustainable asset management: Suggestion for subdivision of Norwegian standard I-beam girders based on regulations and observed corrosion damage. Concept according to Kohler and Hassler [15], data from Osmolska et al. [17].*

3.3 Modelling approach

When uncertainty is characterized in life cycle assessment (LCA), Monte Carlo Simulation is the standard approach [18]. In a recent thesis, Wu [19] developed a method that uses neural network to generate simulations statistically equivalent to simulations based on multi-physics models, with much less computational time and resource. Such surrogate models enable optimization of design and maintenance for real world application. Furthermore, it enables generating probabilistic profiles of deterioration performance of real structures and thus supports probabilistic sustainability analysis.

3.4 Depreciation of impacts

Using climate gas emission as the only measure, the Norwegian Public Roads Administration recently compared alternatives for maintaining a marine crossing and demonstrated that cathodic protection resulted in only 10% of the emissions of a new marine bridge [20]. The gain would be less if extending the CSP-concept [12] and taking account for differences in expected service life. However, it is of high importance also to consider the urgent need for up-front emission lowering. Methods for such sustainability quantification, including depreciation rates, need be discussed and established.

The author is grateful to Professor Helge Brattebø, NTNU, and Professor Mike Lepech for discussions and suggestions.

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Understanding concrete biodeterioration mechanisms and resistance in sewer environments: recent progress and scientific and technical challenges

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The durability of concrete in sewer systems notably related to the biogenic acid attack is a major economic, societal and health issue in developed and emerging countries. Strong deterioration occurs in the aerial part of the pipes because of biological activity and notably the production of sulfuric acid by sulfur oxidising bacteria (SOB) developed in the biofilm in direct contact with the concrete surface.

There are several major scientific and technical challenges to develop durable and sustainable cementitious materials intended for the construction of new sewer systems, but also for the maintenance and rehabilitation of old ones, and adapted to different level of aggressiveness encountered in the sewers. Calcium aluminate cements (CAC) have proven high resistance in sewers compared to Portland-cement based (PC) materials, the reason for their resistance (biological, chemical) still being discussed. More generally the intrinsic characteristics, particularly chemical and mineralogical, of cementitious materials, which are responsible for their resistance to the biogenic acid attack in sewerage systems, are not yet fully understood. Also, few studies in the literature investigated the resistance of low-CO_2 cementitious materials to the biogenic acid attack so far. To make progress on these various issues, the question of the assessment of cementitious materials in laboratory using representative and accelerated biological tests is also crucial, as notably chemical tests, currently prescribed in some standards, were proven not to be relevant in some conditions.

The presentation will aim to review the latest progress obtained from the work carried out at INSA Toulouse in the last decade, (i) in the understanding of the mechanisms of biodeterioration and of the resistance of cementitious materials exposed to sewer-like environments, and (ii) the development of a representative accelerated laboratory biological test method (BAC test) [1–3] together with a universal performance indicator and (iii) their exploitation to assess the performances of a wide range of cementitious materials in such conditions.

The studies investigated different types of binder systems, including conventional binders, PC-based cements, and CAC, and low-CO_2 binders (blast-furnace slag cements (BFSC), calcium-sulfoaluminate (CSA) and alkali-activated (AA) based binders). In order to identify the key factors responsible for the resistance of cementitious materials in sewer, a comparative evaluation of cementitious materials made of CAC, PC, BFSC (PC with 30 to 95% of slag), CSA and AA-based binders exposed to sulfur-oxidizing microbial activity in different conditions, was carried out.

Firstly, a possible mechanism often argued in the literature to explain the better resistance of CAC binders is the bacteriostatic effect on SOB linked to their aluminium leaching. Nevertheless, reactor tests conducted on acidophilic SOB, demonstrated their ability to acclimatise to high aluminium contents [4]. More generally, the nature of the material (CAC, PC, BFSC, CSA and AA-based binders) did not significantly affect the SOB selection on the surface of paste specimens exposed to the BAC test [5,6]. Moreover, the CAC materials seemed to favour the development of a higher SOB activity (and so acid production) than PC-based systems, leading to more aggressive conditions. The resistance of CAC materials to biodeterioration appeared to be mainly linked to the intrinsic chemical resistance of mineralogical phases initially present or precipitated during the deterioration process (AH3). Reactive transfer modelling using a home-made model developed on Aquasim software, showed that the transport phenomena limiting the dissolution of the cement matrix seemed to constitute a secondary process in the conditions of the BAC test [5,7].

Besides the very good resistance of calcium aluminate cement, certain calcium sulfoaluminate cement (CSA)-based materials have shown better behavior than Portland cements in the experimental conditions of the BAC test.

Calcium sulfoaluminate clinker (CSAC) and calcium sulfoaluminate clinker with gypsum (CSAG) showed better performance than calcium sulfoaluminate clinker with anhydrite (CSAC) (Figure 1). The evolution of the mineralogical phases of the three studied CSA-based materials consisted of the dissolution of AFt and AFm phases and the formation of gibbsite-like AH3 on the surface. The better resistance of CSA-based materials was mainly attributed to the presence of aluminium hydroxide (AH3) as well as its chemical stability in acidic environments. Moreover, the mineralogical form of aluminium-bearing phases was a key factor in the resistance of such phases; i.e. the increase of the aluminium content in the materials by non-reactive mineral additives was shown to be insufficient to improve the performance of cementitious materials.

The presentation will finally review the pending questions and research needs for further years to develop more durable and low-environmental impact sewer structures. They are notably related to (i) which form of aluminium based phases should be promoted in low-CO_2 binders to increase their resistance to biogenic acid attack, (ii) the relation between environmental condi-

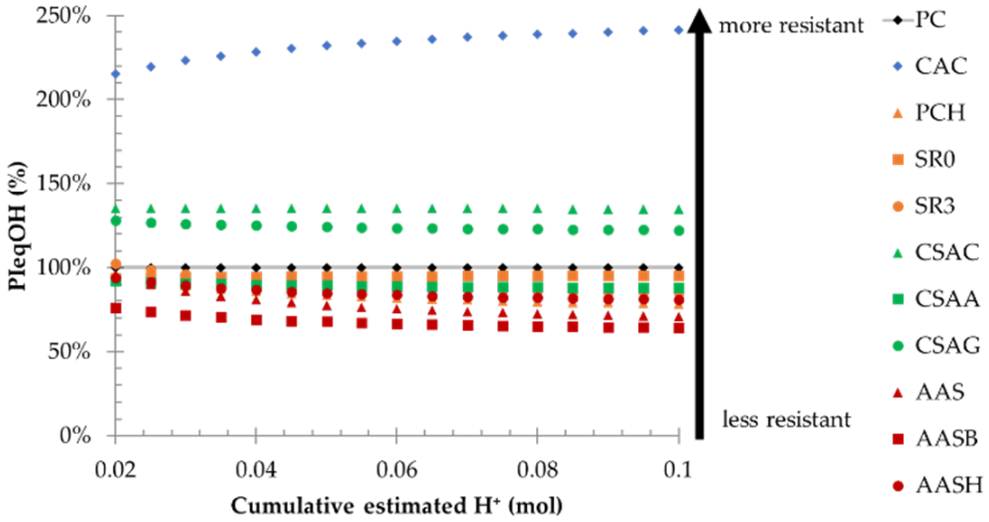

Figure 1: *Equivalent OH Performance indicator (PIeqOH) of cement pastes made with different binders and exposed to the BAC test, as a function of the cumulative leached sulfate (presented as estimated H^+, as H_2SO_4 is produced by the sulfur oxidizing microorganisms developed on the surface of the materials) in the leached solution of the BAC test [8]. The performance indicator (PIeqOH) is an indicator that assesses the resistance of cementitious materials tested in the BAC test compared to the reference material (Portland Cement based paste). Such indicator allows a classification of cementitious materials according to their resistance to biological attack in sewer conditions assimilated by the accelerated laboratory test. It is based on the evaluation of the leaching of chemical cementitious ions (in particular calcium, aluminium, iron, magnesium and sulfate) which define the neutralizing capacity of the materials. The novelty and interest of the indicator is that it allows to compare a range of materials with very different mineralogical and chemical natures. SR0 and 3: Sulfate resistant cements, PCH: Portland cement with iron rich addition, AAS, AASH and AASB: alkali activated slag alone, with iron or aluminium rich additions. The meanings of the other acronyms are provided in the text.*

tions in sewer pipes (including the H_2S concentration, the relative humidity, and the amplitude and frequency of their variations, the geometry of the sewer, etc.) and the aggressiveness of the environments, and how to consider them in the classification of the aggressiveness of sewer networks, and in the recommendations on material's design. (iii) We need also to establish reliable correlations between the rate of deterioration of the laboratory tests and on-site situation.

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Is sustainable rehabilitation of pavements possible with ultra-thin continuously reinforced concrete Pavement (UTCRCP) overlays?

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Abstract. Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP) overlays consist of a 50mm thick steel fibre reinforced concrete layer, reinforced with about 6mm thick steel bars spaced at 50mm centres, both lengthwise and breadthwise. The thin reinforced concrete layer is placed on top of layer works to extend the life of existing pavements damaged by overloaded heavy vehicles. The maintenance cost of this thin overlay is limited by the reduction in the movement joints. A number of UTCRCP trial sections have been constructed in South Africa, with varying levels of success. In this paper the behaviour of the heavily reinforced thin concrete layers under both environmental and rolling axle loads are discussed, based on experimental test results. It is concluded that UTCRCP overlays can only be used for sustainable rehabilitation of pavements if the behaviour of the thin concrete layer under both environmental and rolling axle loads are understood and taken into account when deciding on joint spacing, steel reinforcing, casting conditions and materials used in the concrete.

1 Background

Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP) overlays consist of a 50 mm thick fibre reinforced concrete surface layer, reinforced with about 6 mm thick reinforcing bars spaced at 50 mm centres, both lengthwise and breadthwise. The thin reinforced concrete layer is placed over pavement layers damaged by heavy vehicle axle loads. The long term maintenance cost of these thin concrete overlays should be limited due to the significant reduction in movement joints requiring regular routine maintenance [1]. Although a number of UTCRCP trial sections have been built, the question whether UTCRCP overlays can be used for sustainable pavement rehabilitation remains. In this presentation two major issues that threaten the sustainability of UTCRCP overlays are addressed. The first issue deals with the load spreading and failure mechanism design assumptions made during the design of UTCRCP overlays, while the second issue deals with the environmental load that the thin concrete overlay, with limited movement joints, is exposed to.

Rigid concrete pavements are normally about 250 mm thick concrete slabs with closely spaced movement joints. The slab thickness is determined based on the flexural strength of the unreinforced concrete and the concrete surface layer is deemed to behave according to the "beam on elastic support" principles as proposed by Westergaard in 1926 [2]. UTCRCP overlays are not only highly reinforced, resulting in ductile behaviour, but the thin concrete layer is also not rigid and differential movement across the width of the pavement, makes the design assumptions for rigid pavements not applicable for modelling the behaviour of UTCRCP overlays. Flexible pavements typically consist of a thin asphalt or bituminous layer and the failure mechanism of these pavements is typically rutting in the wheel path. The possibility that UTCRCP overlays act as flexible pavements when exposed to rolling axle loads should be investigated.

Rigid concrete pavements are prone to curling and warping as a result of temperature and humidity changes throughout the depth of the concrete layer. The UTCRCP concrete layer may be thin enough to limit the curling and warping effects, but the lack of thickness could result in increased length changes caused by daily and seasonal temperature and humidity variations. The magnitude of the effect of concrete thickness should be studied to ensure that designers can make appropriate assumptions in terms of spacing of movement joints and reinforcing bars.

2 Experimental setup

Here two aspects of UTCRCP behaviour are considered, with not only the effect of rolling axle loads, but also the effect of environmental loads are taken into account. In the first experiment reinforced concrete slabs with thicknesses of 50 mm, 75 mm and 100 mm were instrumented with temperature sensors and strain gauges to determine not only thermal gradients, but also strains that develop in free moving slabs. These measured strains, can give an indication of the stresses that would develop in UTCRCP, where movement is constrained. In the second experiment, a 1:10 scale UTCRCP model was built and tested at 10 G centrifugal acceleration in a Geotechnical centrifuge to qualitatively study the complex soil structure interaction behaviour of the thin, ductile and flexible concrete layer placed on compacted soil layers and exposed to a rolling axle load equivalent to that of a typical 8 ton axle load (E80) [3,4]. Figure 1 gives an indication of a cross section through the scale model.

By instrumenting each pavement layer in the wheel path and between wheel paths, the vertical displacements caused by the passing of a rolling axle load was measured. The shape of the deflection bowls of the pavement layers was used to develop a conceptual model of the load spreading and soil structure interac-

tion under a UTCRCP overlay.

3 Results

The test results from the thin concrete slabs clearly indicated that the effect of daily and seasonal temperature changes results in significant concrete deformation. The advantage of a 50mm thick concrete slab is however the lack of thermal gradient, which explains the lack of curling and warping caused by temperature changes. The thermal expansion of the thin slabs will however be more than that of thicker slabs and contractors may have to cast some parts of the UTCRCP overlay when the temperature is high to ensure that length reduction takes place, thus preventing longitudinal buckling of the thin overlay. Sufficient steel reinforcing in the length of the pavement can prevent wide cracks from opening up as a result of drying shrinkage and thermal contraction during cold winter nights. Rainfall has a significant effect on the behaviour of the thin concrete slabs as moisture absorbed on the surface results in a significant length change. UTCRCP pavements should be constructed using concrete that will not absorb water during rain storms. This would be possible by using a combination of fine fillers and pore blockers, reducing the water/cement ratio and water content of the concrete and sealing the running surface of the pavement. The scale model test results indicate that the flexible thin concrete overlay spans across the rut that forms in the layer works after the first load cycle. The permanent damage that the supporting layer works experience is not visible from the surface as the ductile concrete layer rebounds when the wheel load moves away. As long as the highly reinforced concrete layer is ductile and strong enough to withstand repeated load cycles, the thin ductile UTCRCP overlay will protect the layer works, maintaining a useable riding surface.

Test results indicate that steel reinforcing is required in the breadth of the pavement to resist the sagging moments that develop under the wheels of heavy vehicles. However, the UTCRCP overlay not only has to bridge rutting of supporting layers caused by heavily loaded vehicles, but also has to resist the hogging moments caused in the centre of the axles when the downward force of the vertical wheel loads is resisted by an equal and opposite upward reaction between the wheel paths. By limiting the thickness of the concrete to as little as 50 mm it is possible to place only one layer of steel in the concrete to handle both sagging and hogging moments. By placing this reinforcing at mid-depth, there is sufficient concrete cover to protect the steel from the negative environment effects if a suitable concrete mix composition is used. The longitudinal reinforcing in the UTCRCP is required to prevent cracks from opening up as a result of both drying shrinkage and length reduction caused by decreasing concrete temperatures. The lack of thickness of the concrete layer means that the stresses caused by the volume changes is significantly higher than what design engineers normally calculate. The spacing of movement joints has to be balanced with the volume of steel required. Buckling of UTCRCP can be prevented through not only careful selection of materials used in concrete, but also specifying permissible temperature ranges for casting concrete.

4 Conclusion

UTCRCP overlays can be a sustainable solution to rehabilitation of pavements damaged by overloaded heavy vehicles. Design engineers and contractors will however have to take not only the actual soil structure interaction behaviour under rolling axle loads into account, but also the significant negative environmental effects that determine the allowable distance between movement joints, as well as the volume of longitudinal reinforcing required in the thin concrete layer.

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Building repair and rehabilitation in a global paradigm of climate change, resource depletion and an increasing demand for building stock

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Abstract. The current industry processes to address the repair and rehabilitation of buildings are inadequate to provide an effective extension of serviceable life. This often leads to premature demolition. Developed in practice, an improved adaptation of the conventional new-build staged methodology is proposed to give buildings a second life which, if led correctly by the concrete repair specialist, can extend the life and keep the embodied CO_2 stored in the building for another generation.

1 Introduction

The successful repair and rehabilitation of concrete structures is to extend service life and to avoid demolition. This is imperative if we are to achieve zero atmospheric carbon by 2050 and to reduce resource depletion. Currently a 30 year old building embodies a similar amount of CO_2 as its operational energy if fossil fuel-based. Retrofitting existing buildings to reduce operational energy will become easier with new technologies. Therefore repairing and rehabilitating degrading buildings to avoid demolition and keep embodied CO_2 is critical for planetary health.

Too many buildings are being demolished, mainly due to poor assessments. This paper proposes an alternate assessment-design-repair methodology to the current approach for buildings.

2 The current approach

In civil engineering structures the concrete is generally exposed and concrete repair specialists are consulted as defects manifest. In buildings the structure is usually hidden by finishes with defects manifesting when degradation is advanced, the building condition curve taking a downward turn (Figure 1). This is prevalent in many concrete frame buildings designed and built in the 60s and 70s when durability was not understood. In degrading commercial buildings rental returns drop. Fewer funds become available for repair with further drops in rent. This leads to further degradation and an erosion of the building value (Figure 2). Demolition becomes an option.

Demolition of a listed building requires Heritage approval and cannot be demolished unless an engineer determines that it is not structurally safe nor capable of being made safe. The demolition of unlisted buildings is the owner's decision. Decisions are often made without sound engineering advice from concrete building specialists, as the process to make such building assessments is largely absent in South Africa. In contrast, the norm for new civil engineering and building projects is a rigorous design process. The appointed Principal Consultant ("PC"), assisted by specialist consultants, takes the project through 4 sequential Stages of Design [1] (Figure 3). Buildings require regulatory approval. If viable after the first two stages (brief/inception and concept design/viability) then the team 'builds' the project on paper during the next two stages (design development/regulatory approval and specifications/pricing documentation). The appointed Principal Contractor is assisted by specialist sub-contractors. In civil engineering structures the PC is an engineer, in buildings an architect. Determining feasibility and ensuring viability makes the Principal Consultant the project investment advisor.

The methodology for the assessment and repair and rehabilitation for ageing concrete buildings with advanced deterioration is relatively less well applied in the building industry, if at all. Such defects are incorrectly considered to be normal wear and tear with owners employing decorating contractors who double as concrete repair 'consultants'. Sometimes a non-specialist engineer is consulted who, after a visual inspection, incorrectly proposes demolition or provides a general repair specification extracted from product specifications. Pricing is similarly generic with the expected under-estimations. A proper condition assessment is only conducted during construction, the process similar to a geotechnical investigation being undertaken once the foundations have been dug, usually providing similar unwelcome surprises. Thus the extent of the concrete degradation is revealed during construction, and in cases is so complex that work has to be aborted. Demolition becomes a resigned option. At best concrete repair specialists are consulted to rectify the situation; the parties not initially aware that the assessment of the residual structural capacity of the degraded RC structure is a highly specialized field. The client bears the cost and time overruns.

However the specialist assessment and repair of such advanced deterioration in ageing RC structures is not part of regular maintenance or normal wear and tear as contemplated by the National Building Regulations ("NBR") [2] [3]. An application to the Local Authority ("LA") is required for structural repairs under the direction of an appointed competent person ("CP") who is *'qualified by virtue of his education, training, experience and contextual knowledge to make a determination regarding the performance of a building or part*

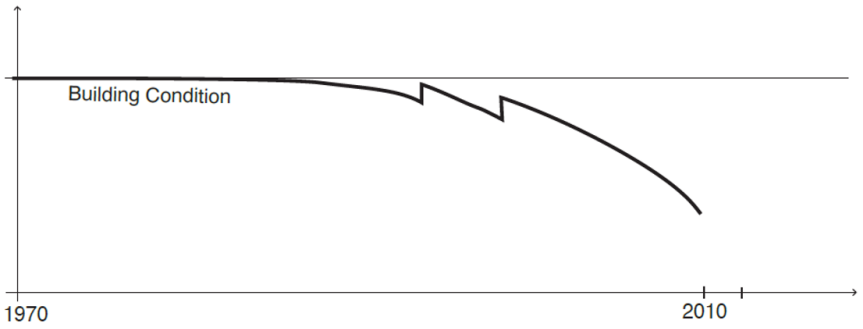

Figure 1: *Senator Park, Cape Town - a high rise apartment block*

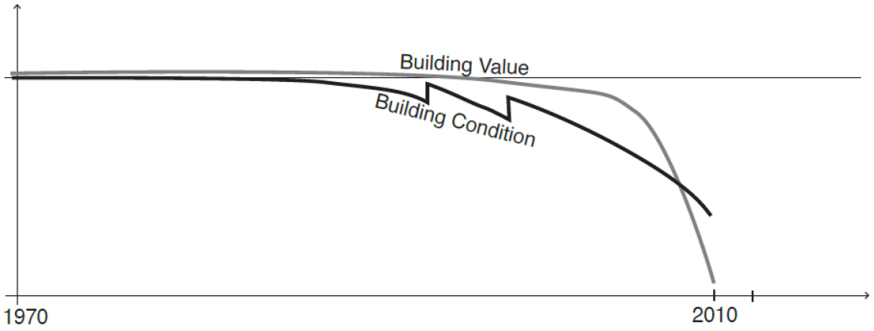

Figure 2: *Senator Park, Cape Town – the building value dropped as degradation manifested*

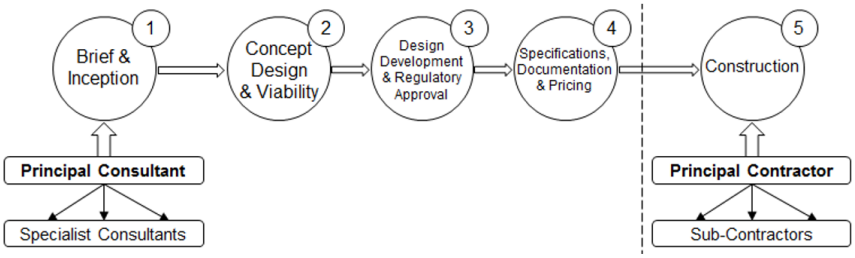

Figure 3: *The conventional 4 stages of design and construction*

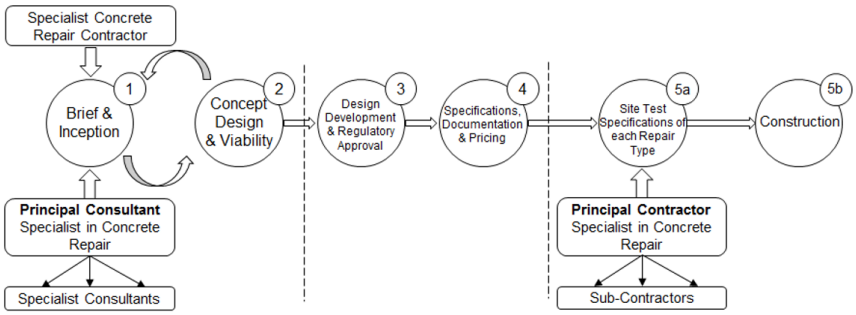

Figure 4: *Proposed adaptation to the conventional stages of design and construction*

thereof … ' [4]. This is a structural engineer (or two) who is a concrete repair and rehabilitation specialist. Without this appointment the owner fails to comply [5] [6], with neither the concrete defects adequately analysed nor the root cause of the problem and risks properly identified. Many ageing buildings are unnecessarily demolished or repairs not properly strategized.

3 An improved approach

A staged methodology developed and successfully tested in practice seeks to address the above shortfalls (Figure 4) to give the best chance to avoid demolition and to give the building a valuable working life.

Four essential adaptations are made to the conventional 4 Stage design methodology: 1. As per the NBR, the Stage 1 appointed competent person (Principal Consultant) is a RC repair specialist engineer [6]. Assisted by specialist consultants (engineers/architect/QS) they advise on the building asset and LA approvals. The historical plans, reports and maintenance records are researched and measured drawings prepared.
2. A RC repair specialist contractor (with abseiling specialists) is appointed during Stage 1 who makes the works safe and exposes and records as many of RC defects as possible to allow for a thorough Stage 2 condition assessment. As-built details of the defects are drawn. The defects are classified into types and mapped onto the plans. Site and laboratory testing enables a condition analysis. If repairs are feasible then preliminary repair strategies and specifications are developed with the specialist contractor for each defect type. Costs are estimated. 3. If repairs are viable the Brief is revised to enable a 2nd Stage 2 condition assessment and compliance check but of all the building systems including *inter alia* services, M&E, finishes, structures, openings, water proofing and energy efficiency. Costs are revised.
4. Outdated buildings may require an upgrade or repurposing to make the rehabilitation viable. If so, then Stage 1 and 2 are repeated until a feasible and viable solution is developed. An informed brief is thus developed with the client. An application is made to the LA with the repair and upgrade plans.

Two essential changes are made to construction Stage 5. 1. A new pre-contract Stage 5a is added where each defect type is repaired. This is to test the specifications and to agree on the procedures, measurement and certification of each type. The recorded testing is the bench mark for quality control.
2. During Stage 5, each defect (with co-ordinates) receives a quality control and claims record sheet with 4 photographs: before opening up, remedial work and closing-up, and after closing-up before painting. The engineer is called to inspect unique defects. These records are provided to the client for maintenance.

Case studies of two developments where demolition was averted by the author, one heritage and one 1970s high rise apartment where the methodology was applied to upgrade the building are presented in the keynote address.

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Cathodic protection of reinforcement in concrete structures - overview and experience over 30+ years

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Abstract. This paper gives an overview of long term performance up to 30 years in the field of cathodic protection of steel reinforcement in concrete in The Netherlands, focusing on impressed current systems based on activated titanium anodes. Case studies are presented including applications to large numbers of precast elements corroding due to mixed-in chloride with drilled in titanium anodes, parking garages with titanium strips in cementitious overlays and industrial floors with titanium mesh in overlay. Based on observed failures and replacements, analysis of working life of various types of systems and components and end-of-life considerations are given. CP has become a fully accepted method of securing safety and serviceability of buildings and infrastructure that are prone to corrosion. Observations show that with activated titanium based systems, very long service lives can be obtained. The activated titanium itself keeps working well beyond the observed period of 30 years. Some other components have relatively higher failure rates. The repairs that were required in the cases discussed are dominated by failing anode-copper connections and to a minor extent power sources and potential sensors.

1 Introduction

Cathodic protection (CP) of steel reinforcement has become the major and most successful method to stop or prevent corrosion in concrete. Over time, many reinforced concrete structures develop corrosion of the embedded steel, due to long-term exposure to aggressive influences such as chlorides from sea water and de-icing salts or the effects of mixed-in chlorides; in some cases aggravated by carbonation [1, 2]. Steel corrosion causes cracking and spalling of concrete and steel cross section loss, compromising serviceability and eventually structural safety. Consequently, repair and protection of concrete structures has become a major industry in the past 40 years. However, in many cases conventional methods of concrete repair have been found to be ineffective or not durable [3, 4]. CP on the other hand, provides an effective and durable method for corrosion protection of steel in concrete.

CP of concrete structures was developed in the USA in the 1970s [5] and introduced in Europe in the 1980s [6]. In the USA, a large number of concrete bridge decks was damaged by corrosion due to chloride ingress from de-icing salts. Early types of anodes were applied with varying results; many of these early anode types have been discontinued [7]. Later, new anode materials became available, such as activated titanium and conductive coatings, variants of which are still widely used today; sacrificial (galvanic) anodes were introduced in the late 1990s. From about 1985 in the UK [6], Italy [8], Norway [9, 10], Denmark, Switzerland [11, 12] and The Netherlands [13] application of CP to concrete increased. A growing numbers of systems have been installed more recently in Germany, France, Belgium and Switzerland. Long term performance and an overview of interventions have been analysed [14, 15].

This paper focuses on impressed current CP (ICCP) with anodes based on activated titanium. Essential elements of every CP installation are the anode system, comprised of the anode material itself, current feeders, anode-cable connections, cathode-cable connections, anode and cathode cables, junction boxes, a power source, and the monitoring system. This paper reports on observations and analysis of the long term performance of activated titanium anode systems based on the authors' involvement in maintenance of a large number of CP systems in The Netherlands. Another paper reports on long term experience with monitoring systems [16].

2 System working life

The working life of a CP system basically is the length of time over which sufficient current flows to all reinforcing steel that needs protection; the necessary controllability also requires the monitoring system to keep working properly. For ICCP systems this implies that the complete chain from power source to anode to steel and back needs to be conducting the current, as well as the monitoring circuit needs to transmit correct potential signals. Consequently, system failure can be caused by loss of anode material, loss of anode/concrete bond, anode-copper connection failure, cable failure and power source failure; or by failure of potential sensors and their cabling.

A previous study [15] has shown that failure of the following components occurred in a group of 105 ICCP systems: - Local attack of conductive coatings
- Anode-copper connections
- Power sources
- Potential sensors

In addition, in some cases loss of overlay/concrete

bond was reported. Long term behaviour of conductive coatings was described in [17]. Here the long term performance of titanium anode ICCP systems is illustrated from six case studies installed since the early 1990s, out of about 100 projects in The Netherlands and some additional observations.

3 Overview and conclusions

Cathodic protection reduces corrosion by injecting a current into the steel that depresses its potential. In concrete a negative shift of a hundred millivolts is sufficient to reduce the corrosion rate to insignificant values, essentially independent of chloride levels or carbonation. Potential shift is measured at least twice a year. This overview focused on long-term experience with ICCP systems based on activated titanium anodes and the following conclusions can be drawn.

A very long working life is possible with ICCP systems based on activated titanium, but it may be limited by failure of components of the electro technical installation. Manufacturers of activated titanium anodes claim lives for their material of 50 to 100 years, and no evidence was found of the contrary. However, several systems showed evidence of some kind of failure in the current providing circuit or the monitoring system.

The parts that are most sensitive for degradation are the connections between (primary) anodes and copper cables. Accelerated corrosion of copper occurs when even the smallest electrolytic path to the concrete and the cathode (steel), arises, as the copper cannot resist anodic polarisation at typical system operating voltages. Moisture entering embedded connections or junction boxes is the culprit. Perfect isolation is necessary, which requires good execution of connections and proper sealing and/or sheltered positioning of junction boxes. Repair or replacement of failed connections usually concerns many items, and can be costly.

Failure of power units has occurred due to lightning strike, moisture entering the cabinets or simple ageing of the electronics. Such failures will be detected during monitoring sessions. Power unit replacement is relatively simple and nowadays generally not very costly. Anticipating replacement of power units after around 15 years may be a good strategy [15].

Failure in the monitoring system may be due to potential sensors loosing electrolytic contact, damaged cabling, connections or measuring devices. General failure rates are low [16], but with the typical minimum of only two sensors in a zone, proper controllability is lost when a single electrode fails. Placing a few more sensors than strictly needed is a good strategy to maintain the ability of proper monitoring for a long time.

Summarising, effective working lives of documented ICCP systems have been found as long as thirty years, but some of the older systems in particular required some form of maintenance, i.e. repair of connections and/or replacement of power units or potential sensors.

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2. CONCRETE DURABILITY ASPECTS

2.1. Concrete durability: innovative materials and influences of material composition

Durability of untreated fine recycled aggregate concrete: a literature review

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Unlike natural aggregate particles, recycled concrete aggregates contain hardened cement paste phases and multiple interfacial transition zones. These differences in properties may be linked to a decrease in durability performance in recycled aggregate concrete. This paper presents a review of the literature published on the durability performance of concrete produced using untreated fine recycled concrete aggregate (fRCA). From the available literature, the durability performance of concrete made using fRCA is strongly linked to the w/b used and the porosity of the resulting concrete matrix. Water absorption, gas permeability, and chloride penetration were found to increase with fRCA replacement. A possible maximum replacement level of 30% was observed in this regard. Carbonation resistance was found to increase with fRCA replacement due to the presence of calcium hydroxide in fRCA samples.

Chloride penetration resistance of fine recycled aggregate concrete

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This study investigates the chloride penetration resistance of fine recycled aggregate concrete (FRAC). Six concrete mixes comprising 0.45 and 0.55 w/b were prepared using fine recycled aggregates (FRA) at 0, 25 and 50% by volume replacement of natural sand. The chloride penetration resistance of the concrete was tested using the surface electrical resistivity (SER), chloride conductivity index (CCI), and the bulk diffusion tests. The SER and CCI tests were conducted after 28 days and 180 days of wet curing, while the bulk diffusion test was carried out after 28 days of wet curing and 180 days of exposure to chloride solution. Results show that the SER of FRA concrete was comparable to the control concrete, at all ages tested. The 28-day CCI of the concrete was impacted as FRA replacement levels increased, whereas at 180 days of testing, the FRA concrete mixes showed more significant improvement in CCI than the control natural aggregate concrete (NAC). The bulk diffusion results indicate that, for each w/b, the chloride diffusion profiles of the control and FRA concrete are comparable.

Assessing the mechanical durability performance of concrete made using recycled clay masonry rubble bricks (CMRB) as course aggregates

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The South African construction industry is currently faced with mounting construction waste and overflowing landfills. Consequently, the feasibility of using of clay masonry rubble brick (CMRB) as a partial replacement for natural coarse aggregate in concrete was investigated. Three concrete mixes were made using a water-to-binder (w/b) ratios of 0.60. A control mix as well as a mix containing 50% and 100% replacement of coarse Andesite aggregate with CMRB as coarse aggregate was tested. The compressive strength, shrinkage and durability properties (with respect to oxygen permeability, water sorptivity and chloride conductivity) were assessed. The results show that the incorporation 100% MCR brick as coarse aggregate produced the lowest compressive strength result, the highest shrinkage rate and the least resistance to gaseous ingress and chloride conductivity. The concrete mix containing 50% MCR brick exhibited

the least resistance to water absorption through capillary action. The mechanical and durability properties of both concrete mix containing MCR brick was largely affected by the porous nature of coarse masonry rubble. The results can be attributed to a relatively high void ratio leading to the presence of more interlinked pathways within the CMRB aggregate.

The effect of cement reduction and substitution on the mechanical and durability properties of concrete

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There are now several initiatives to reduce the carbon footprint of cement production, such as the use of alternative binders for clinker. However, reducing the carbon emissions of the cement sector will only be possible when design optimization is combined with other measures. The construction industry is reluctant to reduce the cement content of concrete mixes and is not encouraged to use performance-based design for concrete. In most cases, these steps will negate the benefits of using alternative binders in concrete. The objective of this paper is to investigate the effects of lowering the cement content and additionally substituting part of the cement on the mechanical properties and durability of concrete. The reference mix was taken from a real bridge recently built in Croatia, and the alternative combination was prepared with a reduced cement content of 22%. All mixes were evaluated based on their mechanical strength and resistance to chloride penetration. The carbon footprint of each mix was also studied. The study concluded that the alternative mix with lower cement content had comparable durability and a significantly lower carbon footprint, meaning that the alternative mix proved to be a more sustainable option.

The influence of different modifying polymers on the mechanical properties of cement mortar within a defined service temperature range

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Within the scope of the research project “Experimental investigations and microstructure-based modelling of the elastic and viscoelastic behaviour of PCC as a function of temperature” the temperature-dependent influence of the polymers on the load-deformation behaviour of cement stone, mortars, and concretes is characterized by standard measurements as well as novel experimental campaigns and completed by microstructural investigations before and after the temperature influence to also provide information on changes in the morphology of single phases. The results of the study are bundled in a semi-analytical multiscale model based on the methods of continuum micromechanics. By means of a bottom-up approach, homogenized properties at the macroscale are determined using the specific microstructural behaviour. The microstructure changing as a result of the temperature influence can thus be directly correlated with the macroscopic material behaviour. After extending an existing multiscale model by considering principles of thermo-poro-elasticity, the temperature dependence of the mechanical properties of PCC will be predictable. Presented in this paper are selected experimental results of the mortar investigations of the research project, which is currently in process. This research has been supported by the German Research Foundation (DFG), which is gratefully acknowledged.

Factors influencing the electrical properties of ettringite binders as repair materials

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Ettringite binders are increasingly being used as rapid-repair materials to extend the service-life of reinforced concrete where rebar corrosion has caused deterioration and spalling. The transport properties of these ettringite binders are important in assessing the longevity of such repairs. This study demonstrates how the electrical properties of such binders can be interpreted to obtain meaningful results related to the transport properties. In addition to the pore solution chemistry, the degree of saturation in calcium sulfoaluminate (CSA) cement was found to be an important factor in the electrical properties since ettringite binders can have greater self-desiccation at earlier ages than ordinary portland cement (OPC). After one day of hydration, the electrical properties suggested that the CSA containing mixtures had greater pore network connectivity than the OPC mixture and this can be attributed to the varying phase compositions. Thermodynamic modelling confirmed a high amount of ettringite formation in the CSA

system and a lower capillary water and capillary porosity associated with this. The lower internal relative humidity of ettringite binders should be considered when using electrical measurements to evaluate their transport properties since it increases the total electrical resistivity.

Durability of concrete with Belite-Gehlenite clinker as fine aggregate

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The Japanese cement industry uses large quantities of industrial waste and by-products as raw materials in the production of cement clinker. Although the amount of industrial waste generated annually has remained almost constant, domestic demand for cement has been falling. In order to maintain the amount of waste re-used by the cement industry, there is a need to explore new ways of utilizing clinker besides in cement production. The proportion of waste used in the production of Belite-Gehlenite clinker featured in this study is about twice as much as in normal clinker. Previous studies have shown that when clinker is used as aggregate in mortar and concrete, clinker hydration products fill cracks as they occur for added self-healing performance. In this study, in addition to the basic characteristics of concrete containing Belite-Gehlenite clinker as fine aggregate, the resistance to cracking of specimens made with the concrete is investigated. Compared with concrete using natural sand, it is confirmed that compressive strength is improved, drying shrinkage is reduced, carbonation is suppressed, and freeze-thaw resistance is maintained. It is also demonstrated that resistance to cracking is improved.

Fly ash geopolymer concrete durability to sulphate, acid and peat attack

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The durability of concrete has a profound impact on the service life of structural elements. Indonesia has extensive peat soils, which provide a highly aggressive environment for concrete structures. Geopolymer concrete has demonstrated good durability when exposed to acid/sulphate conditions similar to those encountered in peat soils. This paper investigates the performance of geopolymer concretes produced using Indonesian type F fly ash under sulphate and acid chemical attack. Geopolymer concrete specimens have been exposed for 12-months in a range of solutions: 5% sodium sulphate, 5% magnesium sulphate, 1% and 3% sulphuric acid, and simulated peat solution. The mechanical and durability properties of specimens together with a control concrete have been monitored for compressive strength, change in mass, water absorption and volume of permeable voids, ultra pulse velocity, air and water permeability, pH profile, and microstructural analysis (XRD, SEM/EDS). The control immersed in water achieved 56.93 MPa at 12-months of age. Magnesium sulphate exposure had a significant deterioration impact on the compressive strength of geopolymer concrete, demonstrating an 11% reduction in strength, while those exposed to sodium sulphate had an 8.9% increase in strength. Specimens exposed to peat solution displayed a slightly increased strength and those in acid conditions a 1.2% and 4.5% decrease in 1% acid and 3% acid, respectively. In general, the geopolymer concrete displayed a high level of resistance against sodium sulphate, 1% sulphuric acid and simulated peat attack.

Early-age effect of corn cob ash as a partial replacement for portland cement in concrete

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One of the effects of supplementary cementitious materials (SCMs) in concrete is the dilution effect which is as a result of partially replacing Portland cement with SCMs. The dilution effect of corn cob ash (CCA) with respect to strength gain and transport properties of concrete is the focus of this study. 100 mm concrete cubes were prepared with corn cob ash partially replacing Portland cement at 15% and 30% using w/b ratio of 0.4 and 0.6. The effect of CCA replacement level on the compressive strength development between 3 and 28 days, and transport properties at 28 days of curing was done. This was compared to the effect of fly ash at the same replacement level and 100% Portland cement content. The results showed that compressive strength decreases with increasing ash content and increases with increasing curing age. The dilution effect of CCA was more pronounced at the two replacement levels than fly ash with a marginal gain or strength loss compared to w/c ratio corresponding to each w/b ratio. The oxygen permeability

index obtained for CCA concrete were lower compared to that of fly ash concrete at the same replacement levels and PC concrete at the same w/b ratio. Also, the water sorptivity index and chloride conductivity index for CCA concrete were higher than that of fly ash and PC concrete at the same w/b ratio.

Development of sulfuric-acid resistant concrete with reduced carbon emissions

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A recent social problem in Japan is the corrosion of concrete structures at sewerage facilities caused by sulfuric acid in the sewage, causing the structures to deteriorate before their expected life span. At the same time, low-carbon concretes using reduced amounts of cement are being developed as a response to concerns about global warming.The production of cement emits large amounts of carbon dioxide, so it is being replaced by blast furnace slag and fly ash, which are industrial by-products. In this study, low-carbon concretes with good sulfuric acid resistance are developed by replacing cement with various proportions of blast furnace slag fine powder, and fly ash. In particular, the concrete with 20% cement, 20% water-binder ratio has a high compressive strength of 60 N/mm^2 or more and shows good resistance to sulfuric acid as demonstrated by a reduced mass change rate and neutralization depth in sulfuric acid immersion tests.

Mechanical properties and self-sensing ability of amorphous metallic fiber-reinforced concrete

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The aim of this research work is to develop a corrosion resistant fiber-reinforced concrete for radioactive waste disposal structures. In the case of precast concrete, the use of fibers is a solution to reduce the amount of steel reinforcement while maintaining high mechanical performance and durability. Concrete has a low strain capacity and a limited tensile strength. Generally, reinforcing bars are used to ensure tensile strength. A fiber reinforcement can also help to overcome such a mechanical weakness. For this purpose, an amorphous metallic fiber (AMF), corrosion-resistant and suitable for application in severe environment conditions are used. The fresh and hardened properties of the self-compacting fiber reinforced concrete (SCFRC) are studied with volume fractions of AMF of 0% and 0.28% and with three different aspect ratios (82, 114 and 123). Flexural tensile tests according to European standard EN 14651 are conducted to quantify the contribution of the fiber reinforcement on the residual flexural tensile strength. Since these fibers are electrically conductive, they are also tested to design a smart concrete. For this purpose, electrical resistance of specimens submitted to cyclic flexural loadings are monitored using a Wheatstone bridge.

Towards understanding the influence of metakaolin in the prevention of alkali-silica reaction

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The role of supplementary cementitious materials (SCM) in the prevention and mitigation of the Alkali-Silica Reaction (ASR) in concrete materials and structures is becoming increasingly significant and relevant in the civil engineering. The use of SCMs in South Africa is limited to Ground Granulated BlastFurnace Slag (GGBS) and Fly Ash (FA) as they are readily available. With recent advancements in concrete technologies, it has been found that calcined clays such as Metakaolin (MK) have been useful in concrete to improve the chemical, mechanical, and physical properties of concrete material. Deposits of MK have been found in some regions of South Africa and are now available for consumption with various applications but have not yet been widely accepted as conventional SCM within the concrete ready-mix industry. This article aims to summarise state-of-the-art and existing knowledge gaps in the application of SCMs in concrete material and identify the feasibility and benefits of extending the use of SCMs with MK in a comparative study with FA Class F and SF. The performance of MK with respect to the key variables such as exposure conditions, reaction mechanisms and pore solution composition in the prevention of ASR in concrete material relative to the mentioned SCMs is discussed.

Optimization of dune sand-slag blended geopolymer mortar using Taguchi method

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Achieving optimum performance of geopolymer mortar intended for structural and repair applications is a complex task with various factors being considered prior to production. This study explores the influence of mix design parameters on the fresh and hardened properties of geopolymer mortar made with treated dune sand (TDS) and granulated blast furnace slag (BFS). A total of nine geopolymer mortar mixtures were designed following the Taguchi method for four factors, each with three levels. These factors included BFS replacement rate by TDS, alkali-activator solution to binder ratio (AAS/B), sodium silicateto-sodium hydroxide ratio (SS/SH), and sodium hydroxide (SH) molarity. The investigated performance quality criteria were flowability, compressive strength, water permeability, and carbon dioxide footprint. The effect of various factors on the responses was assessed through ANOVA while determining the signalto-noise (S/N) ratios to seek the optimum proportions of mixtures. Results revealed that a mix made with TDS replacement, AAS/B, SS/SH, and SH molarity of 25%, 0.5, 1.5, and 14 M yielded superior performance.

Effects of sodium oxide content on the durability of alkali-activated mortar utilizing Botswana copper mine tailings and fly ash

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This investigation aims to provide experimental data on the performance of alkali-activated mortar made of copper mine tailings (CMT) and fly ash (FA) exposed to acid-sulphate attacks and elevated temperature environments as a measure of durability. FA was used as a replacement material, substituting 20 to 40% of the CMT by mass, and sodium hydroxide was the alkaline activator, which was added in terms of Na_2O content by mass of the total binder at 5%, 10%, and 15%. The durability performance of alkali-activated mortar was evaluated against 5% and 10% concentrations of sulphuric and hydrochloric acids, and magnesium and sodium sulphates up to 180 days of exposure, as well as elevated temperature environment. The specimens were first visually examined, and weight change was measured before being exposed to an elevated temperature environment and the residual compressive strength was measured. It was observed that Na_2O content and elevated temperature environment influence the residual compressive strength of alkali-activated mortar. Increasing the Na_2O content for all CMT-FA-based mortar samples performed well in sulphates and acids mediums in terms of durability, but with a slight reduction in its durability performance in terms of residual compressive strength. However, these effects were more profound in samples exposed to acids, particularly those with lower FA replacement levels and sodium oxide content. For the high-temperature exposure, the residual compressive strength of all CMT-FA samples was much higher than the initial values. The findings also revealed that the partial replacement of CMT by FA significantly improved the residual compressive strength in terms of the durability performance of the alkali-activated mortar.

Effect of styrene-acrylic latex polymer on the dimensional and mechanical stability of ettringite accelerated binders composed of CAC-PC-C$

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Cementitious binder composed of CAC-PC-C$ (calcium aluminate cement- Portland cement- calcium sulfate) forms ettringite as the principal hydration product which promotes high early strength (~ 20 MPa) within a very short time (~ 3 hours). This property makes these materials suitable for many rapid repair applications as well as construction works where the required time for opening to service is nominally 3 hours or less. However, it is evident from previous literature that synthesized ettringite is susceptible to decomposition due to temperature and relative humidity (RH) raising the question of whether these materials would be long-lasting in outdoor applications. In this study, the effect of styrene-acrylic latex polymer on CAC-PC-C$ binder, specifically ettringite stability, for two different exposure conditions: i) 23˚C, 50% RH and ii) 50˚C, 50% RH was evaluated. Preblended CAC rich (60%) CAC-PC-C$ cementitious system, with and without polymer modification, were investigated by changes observed in dimensional and mechanical (i.e., flexural, and compressive strength). Results from this study will help to understand how the addition of styrene-acrylic latex polymer affects the stability of ettringite in CAC-PC-C$ cementitious systems exposed to different temperatures and relative humidity.

2.2. Service life modelling and prediction of durability

Probabilistic service life design of reinforced concrete structures via free web application

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The degradation of traffic infrastructure is to a large extent caused by chloride induced corrosion. Damage to highly exposed structural elements in the splash water zone often occurs before the planned service life and causes enormous costs in repair. Although recognized models for probabilistic service life design are available and anchored in regulations, their application and thus the verification of the design are currently reserved for experts only due to complicated and cost-intensive statistical software. With the help of the newly developed and freely accessible web application, target service lives can now easy be calculated already in the planning stage.

Durability aspects of chloride-affected cracked concrete structures reinforced with 1.4003 rebars

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The protection of reinforced concrete components exposed to chlorides is often ensured by coating systems, which are usually associated with high maintenance costs over the service life. A possible alternative is the use of high-alloy, stainless steel reinforcement. Through smart selection in areas subject to particularly high stresses and the possibility of using mixed reinforcement with black steel, this type of reinforcement can also be used for economical construction. In many areas, it is sufficient to use significantly cheaper chromium steel rebars instead of very expensive, highly corrosion-resistant austenitic chromium-nickel steels. An industrial research project was carried out at Munich University of Applied Sciences in which the resistance of a chromium steel reinforcement with material number 1.4003 in chloride-exposed separation cracks of RC-specimens was investigated. The results obtained formed the basis for the development of design variants for underground parking garages. Structural tests on a large number of existing structures show how a long service life can be achieved with such reinforcement even under high chloride loads

The influence of temperature on the cracking of plastic concrete

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High early age concrete temperatures can lead to many problems such as an increased rate of cement hydration, as well as an increased rate of moisture loss from fresh concrete which can ultimately lead to the occurrence of plastic shrinkage cracking. Concrete is also batched and cast at various ambient temperatures which greatly influences the temperature development of the concrete after placement. There is a need to understand the influence of concrete temperature on the plastic cracking of concrete. This study investigated the temperature development over the thickness of a concrete slab when exposed to different initial concrete and ambient temperatures as well as the effect these factors have on plastic shrinkage cracking. This was achieved by experiments on concrete samples at varying temperatures while measuring the concrete temperature, pore water evaporation, shrinkage, settlement, setting times and plastic shrinkage cracking magnitude. These tests were conducted in a climate controlled chamber. It was concluded that exposure to higher initial concrete and ambient temperatures significantly increases the average temperature over the thickness of the concrete. The evaporation of pore water was higher when exposed to higher evaporation conditions. The plastic shrinkage, settlement and plastic shrinkage cracking were more severe in the presence of higher initial concrete and ambient temperatures even though the critical period and setting times were reduced due to an increase in the concrete temperature. Finally, the surface temperature of the concrete as tested in slabs up to 100 mm in thickness can be used as a good indication of the temperature development in the lower layers of the concrete.

A numerical modelling framework to predict the effects of self-healing on chloride penetration in ultra high performance concrete (UHPC)

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In-service conditions, concrete develops cracks, favoring pathways for aggressive substances to penetrate and destroy the matrix and the reinforcement. Cementitious material's inherent ability to self-seal cracks – owing to delayed (secondary) hydration and calcium carbonate precipitation - may result in greater durability in aggressive environments. The effect of autogenous and stimulated healing – mixtures enriched with healing agents – on chloride penetration was recently investigated experimentally at the Politecnico di Milano for an Ultra-High-Performance Concrete. The entire laboratory campaign is simulated in this study using a numerical model based on the Multiphysics-Lattice Discrete Particle Model (M-LDPM), which can simulate autogenous and stimulated healing in ordinary and advanced cementitious materials. An improved version of the Hygro-Thermo-Chemical (HTC) model is used to simulate the healing process, which includes the effect of crack closure on permeability. The healing model is coupled and harmonized with an existing M-LDPM-based chloride diffusion model for saturated and non-saturated concrete in order to capture the results obtained through the aforementioned experimental campaign. The numerical results show that the model can capture both the reduction in chloride penetration due to crack sealing and the different degrees of crack closure that can be achieved with and without using crystalline admixtures as healing agents. The research activity from which this work stem was framed into the H2020 ReSHEALience project (GA 760824).

Modelling the cracking of fresh concrete

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The cracking of fresh concrete, while still in a plastic state, includes both plastic settlement and plastic shrinkage cracking, which starts once the concrete is cast to around the final setting time. The cracking process is complex and is influenced by numerous factors which include the climate, mix proportions, element geometry and construction procedures. Preventing these cracks therefore remains a problem in practice. One of the reasons for this is the lack of a model that can be used to determine the location, timing and severity of the cracking before the cracking occurs. The main challenges with such a model are the testing of the fresh concrete to determine the tensile material properties, the appropriate constitutive law needed, and the time dependency of material properties as well as the anisotropic volume change. This paper presents a finite element model that uses a total strain smeared cracking approach and accounts for both the time dependency of material properties and the anisotropic volume change. The model gives an adequate representation of the cracking behaviour of fresh concrete for extreme climates but not for normal to moderate climates, mainly due to the size discrepancy between the interior and surface cracks during experiments as well as the relaxation of stresses that are not accounted for in the model. A parameter study showed that both the settlement and shrinkage strains significantly influence and therefore govern the size of the final plastic crack, while the material mechanical properties only influence the time of crack onset and rate of crack widening.

Performance based approach to assess the spalling resistance of concrete under freeze-thaw attack

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Assessment of resistance against freezing-thawing (F-T) attack using the performance-based approach remains a conundrum. Most techniques require many specimens and a long test duration. This study intends to search for an easy, inexpensive, and rapid performance-based approach to examine the F-T resistance of concrete. Performance parameters measured include mechanical strength, permeation properties, porosity along with general material characteristics. Theoretical aspects were considered, and two fundamental factors, tensile strength and inner stress caused by freezing, were considered. After numerous trails, a multi-parameter index using tensile strength and sorptivity is given to assess resistance of concrete. It is believed that use of the proposed approach can reduce the test duration and relevant cost involved in FT resistance evaluation by 80% at least and presented findings encourage the movement from the current prescriptive design criteria to performance-ensuring specifications. The results also indicate that in situ permeation test methods should be improved to give basic characteristic of concrete, so that the

evaluation can be performed rapidly and reliably on concrete in structures

Salt frost scaling of concrete – new insights regarding the damage mechanism

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To achieve the important goal of clinker reduction for concretes in cold and temperate climates, it is important to understand the underlying mechanisms for salt frost scaling. Two conflicting damage theories dominate the current State of the Art – the glue spall theory and the cryogenic suction theory. In this study, important aspects of both theories were evaluated experimentally using salt frost scaling tests on concrete and low temperature differential scanning calorimetry. It was found, that the generation of scaling in a salt frost attack could be better explained by the cryogenic suction theory, which is based on the uptake of highly concentrated brine at sub-zero temperatures. However, this theory cannot account for the pessimal effect of low de-icing salt concentrations in salt frost scaling tests, as it does not consider the moisture uptake during the thawing phase of a freeze-thaw cycle. By expanding the cryogenic suction theory by that aspect, a comprehensive theory for salt frost damage was obtained. In that theory the cryogenic suction of highly concentrated brine during frost is responsible for the generation of scaling. The moisture uptake during the thawing phase balances the de-icing salt concentration in the concrete and accounts for the pessimum effect.

Impact of slag on carbonation rate of concrete based on calcium aluminate cement

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Throughout their service life, concrete structures are exposed to various environmental conditions that affect their durability. The cementitious matrix inevitably comes into contact with air, which leads to a progressive carbonation reaction. As a result of carbonation, changes occur in the microstructure and porosity of the cementitious matrix. Calcium aluminate cement is produced to increase the resistance of composites to aggressive environments, but its application is limited by the occurrence of conversion process. The addition of slag inhibits the conversion process of calcium aluminate cement and prevents a reduction in compressive strength due to the formation of C_2ASH_8 hydrate, while contributing to the net zero commitment of the cement industry. It remains an open question how these changes in microstructure caused by the addition of slag affect the carbonation rate of calcium aluminate cement-based concrete. Therefore, the objective of this study was to determine the effects of slag on the microstructure and porosity of calcium aluminate-based concrete before and after accelerated carbonation. For this purpose, the mechanical properties, porosity, and reaction product of a concrete mix containing 30% calcium aluminate cement replacement by slag were compared to calcium aluminate cement-based concrete before and after exposure to 3% CO_2 for 7 and 28 days. Thermogravimetric analysis (TGA) and mercury intrusion porosimetry (MIP) were tested to understand the changes in reaction products and pore size distribution, respectively.

A critical evaluation of the use of crack width requirements in the durability design of marine reinforced concrete structures

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Crack width requirements play a significant, and often dominant, role in the design of marine reinforced concrete structures. However, there are several issues with both the theoretical basis and the practical application of these requirements. This paper discusses some of these issues, in order to highlight the need to evaluate the overall effectiveness of the crack width requirements.

2.3. Modelling and prevention of reinforcement corrosion

Stability of Fe^{2+} in cementitious media

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Service-life models developed for reinforced concrete structures have worked under the assumption that once corrosion initiates, the precipitation of corrosion products occurs predominantly at the steel-concrete interface (SCI) generating expansive stresses, subsequently leading to the spalling of the concrete cover. Recent work has explicitly shown that corrosion products could also precipitate a few hundred microns away from the SCI. The development of corrosion products further away from the SCI has been hypothesised to be due to competition between the kinetics of diffusion, precipitation/sorption and oxidation of aqueous Fe^{2+}, once dissolved due to corrosion. This study experimentally assesses the stability of Fe^{2+} in solutions representative of conditions where the steel reinforcement is undergoing carbonation-induced corrosion. We use spectrophotometric techniques to quantify the kinetics of iron oxidation in solutions with pH ranging between 5 and 9. This data would feed into a reactive transport model enabling us to develop a better understanding of the propagation phase of corrosion in reinforced concrete structures.

Toward a digital twin of the steel-concrete interface for numerical corrosion studies

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Modeling reinforcement corrosion in concrete relies on numerically solving the governing reactive transport equations in a domain of interest. Traditionally, such domains are simplified by homogenizing the physical characteristics of the porous media and material properties over a representative volume. Relatively recent studies have put additional emphasis on the role of the steel-concrete interface in the corrosion behavior because this region has a microstructure significantly different from that of bulk concrete. It is questionable if the homogenization technique is the correct approach to investigate corrosion phenomena at the steel-concrete interface. This study explores a novel approach of obtaining a three-dimensional discretized domain directly from SEM images of a concrete or mortar specimen with embedded steel. The images are obtained by SEM imaging of consecutive surfaces prepared by focused ion beam (FIB) nano-milling. This produces an image stack that allows reconstructing the three-dimensional microstructure of the original sample's steel-concrete or steel-mortar interface. This procedure achieves a resolution of 30 nm along all directions in space, i.e. the resulting dataset consists of isotropic voxels of 30×30×30 nm^3. Therefore, it is possible to reconstruct pore sizes down to capillary pores with diameters of about 100 nm. Since the capillary porosity plays an important role for the transport properties of porous materials, this approach provides access to more realistic modeling of transport phenomena at the capillary scale.

Thermodynamic and kinetic considerations of corrosion product formation in cementitious media

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The complexity of cementitious systems as well as a multitude of deterioration mechanism make the accurate service-life predictions of reinforced concrete structures inherently challenging. Existing deterministic and statistical service life models rely on a prior knowledge of transport properties and other input parameters that project the evolution of structural damage far into the future. Whilst there is a general consensus regarding the mechanism by which corrosive agents induce steel corrosion in concrete, it is yet unclear whether model parameters governing carbonation, chloride ingress and corrosion product formation can reliably predict corrosion. It is consequently paramount to combine corrosion science principles, crystalline phase assemblage and the kinetic and mass transfer limitations thereof.

Testing the Bromide penetration resistance of concrete: substitution of NaCl by NaBr in Rapide Chloride/Bromide migration test (RCM/RBM)

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The chloride migration coefficient of concrete describes the resistance of concrete against chloride ingress. This important material variable can be determined with the rapid chloride migration test (RCM). During the test, chloride ions penetrate concrete by means of an applied electrical field. If the concrete has already been exposed to chlorides before the test starts, the test set up has to be adapted to achieve reliable results. Due to repeated exposure to the same salt (e.g. NaCl), there is no direct possibility to distinguish the chloride ions from the test procedure and the exposure before this, within the initial test procedure. Therefore, the RCM-test setup has been adapted by replacing NaCl through NaBr in the same molar amount. Consequently, this adapted test setup is called the rapid bromide migration test (RBM). The indicator silver nitrate $AgNO_3$ forms sparingly soluble silver salts (AgCl, AgBr) in the presence of halogen ions (e.g. Cl^-, Br^-), which form a white precipitate in areas with Cl^- or Br^- ions. The penetration depths are measured at two split cylinder halves. In case the RBM-specimen has previously been exposed to NaCl, an analyzation technique has to be available for the two elements Cl and Br to enable a differentiation. As the white precipitate areas - a result of the formation of AgCl and AgBr - have a quite similar visual appearance, a differentiation cannot be achieved and other analytical techniques have to be considered. With laser-induced breakdown spectroscopy (LIBS), it is possible to determine the depth-dependent ion quantity (wt.-% of Cl or wt.-% of Br). In this study, it is shown by test results that it is possible to exchange NaCl by NaBr in the RCM test, since the penetration behavior of both ions (Cl^-, Br^-) is very similar in the migration test.

Influence of alternative binders on the passivation of steel in mortar

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Against the background of the high CO_2 emissions generated in the production of Portland cement (OPC), research is being carried out worldwide into alternative types of cement that can be produced in a more climate-friendly way. These alternative binders have a lower clinker-cement ratio or contain no Portland cement at all. To allow for widespread use in reinforced concrete components, an understanding of how they affect the corrosion behaviour of embedded steel is necessary. The first step in effectively protecting steel from corrosion is passivation. In the study presented here, various alternative binders from the following groups were investigated: OPC with the supplementary cementitious materials (SCMs) calcined clays or modified steel mill slag, alkali-activated materials (AAMs), a calcium sulfoaluminate ($C\bar{S}A$) cement and the C-S-H binder Celitement®. An OPC and a CEM III/B have been investigated as reference materials. Mortar samples were prepared with all of these binders and the passivation behaviour of embedded steel was observed in electrochemical studies on three-electrode test specimens. In addition, the pH values of the pore solutions were determined, since it is an important parameter for assessing passivation ability.

Reinforcement corrosion of circular concrete columns under sustained load

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This paper presents the results of an experimental study of the axial capacity of circular spirally-reinforced concrete columns that were subjected to accelerated corrosion while sustaining a constant compressive service load. Two sets of columns of five columns each were designed with different spiral pitch to investigate the effect of concrete confinement on the corrosion propagation. Columns with non-confining spiral reinforcement had only their longitudinal reinforcing steel corroded, whereas in the other set of specimens, the spiral reinforcement was corroded and isolated from the vertical reinforcing steel. The cracking initiation, pattern, and widening of the concrete cover were monitored for a period of 4-10 months, and relations obtained between the crack widening and propagation and the elastic shortening of the column and steel mass loss were established. After the accelerated corrosion period, eight columns were tested to failure under either concentric or eccentric load; the vertical deformation, cracking pattern and failure type were monitored and recorded. The failure of specimens with non-confining spiral reinforcement was characterized by sudden crushing of the concrete and longitudinal reinforcement buckling, with a reduction in load capacity of 30-40%. Columns with confinement reinforcement failed in a ductile manner by progressive spalling of the concrete cover, maintaining their load capacity in spite of the corroded spiral reinforcement.

Moisture sorption behaviour of concrete mixtures containing chlorides and the resulting electrolytic resistivity in relation to the estimated corrosion risk

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When using corrosion monitoring on reinforced concrete structures exposed to chloride, self-corrosion can play a decisive role in the interpretation and evaluation of the results. Only a part of the corrosion current can be measured electrochemically as element current. A significant proportion of the cathode process takes place on the measuring anode electrode itself. With decreasing water content of the concrete, the ratio of self-corrosion current to measurable element current increases. Corrosion tests on this topic are currently being carried out at the Munich University of Applied Sciences in cooperation with the Technical University of Munich. The moisture sorption isotherms determined at the beginning of the corrosion tests for the concrete mixtures investigated are presented here. Additionally, the electrolytic resistivities of the concrete mixtures in dependence on their water and chloride contents have been evaluated. In consideration of literature results, a moisture range can be evaluated that is associated with harmless corrosion processes.

Updating the prediction of chloride-induced corrosion in RC structures by considering cracks detected by a CNN

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Reinforced concrete (RC) structures are generally inspected visually at regular time intervals. Due to the continuous ageing of infrastructure, particularly in industrialised countries, there is an ever-increasing need for efficient and reliable condition assessments, which maximise the information gained during an inspection. This allows for improved planning of maintenance works. Recent developments in the field of machine learning, in particular in deep learning, have the potential to allow the analysis of a vast amount of data in a short time. In the case of chloride-induced corrosion, an a-priori depassivation probability can be estimated (e.g. by the fib model code for service life design in non-cracked concrete) and later spatially updated following Bayes Theorem to approximate the remaining service life of the structure. The update process is composed of two steps: (i) Detection of cracks through image-based inspection by a pre-trained convolutional neural network (CNN) and (ii) modifying the chloride ingress model based on the inspection and detection of cracks. In such a case, the chloride ingress model is modified to account for cracked concrete locally. This contribution will describe the process of updating corrosion predictions based on image analysis in detail and apply it to an example.

Influence of red mud addition in alkali-activated mortars on corrosion resistance of steel

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Alkali-activated materials (AAM) consist of a precursor, which is a source of aluminosilicates, and an alkali source. The precursors are usually waste materials from various industries such as fly ash from thermal power plants and slags from the metallurgical industry. Due to the increasing use of these materials in the cement industry and strategies for decommissioning coal-fired power plants, alternative raw materials from waste streams are increasingly being explored. One of these materials is waste from the aluminium industry, known as red mud. Due to its chemical composition, which is similar to that of other cementitious materials, red mud is suitable for use in the cement industry. It can also be used as a source of aluminosilicates in the synthesis of AAM. In this study, the corrosion behaviour of steel in chloride exposed AAMs based on fly ash and slag was investigated with and without the addition of red mud. During exposure of AAM to tap water and a 3.5 wt.% NaCl solution, the corrosion process was monitored by corrosion potential and polarisation resistance. AAM mixes containing red mud exhibited better corrosion resistivity and lower current density values compared to mixes without red mud, indicating a possible contribution of the red mud to chloride binding and improving the passivity of the steel.

Chloride profiles with a peak – why and what are the consequences for predictions?

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Chloride ingress profiles do almost always have a peak at some depth but most prediction models are missing this peak. Some prediction models, such as the *fib* model, simply "cut off" a slice of the concrete up to the peak in further predictions. Other prediction models use data only from the profiles beyond the peak but include the concrete up to the peak as if it has the same properties as the rest of the concrete. A physical model has been developed to quantify the local changes because of leaching and the consequences of these changes with time. The model uses Fick's 1st law for chloride diffusion and linear chloride binding. The depth of leaching with time is modelled with a simple square-root equation. The consequences of leaching are assumed to be linear from the surface into the maximum depth of leaching. The consequences of leaching are modelled as depth-dependent changes of porosity, chloride binding and the diffusion coefficient in Fick's first law.

Sustainable reinforced concrete for chloride exposures

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Reinforced concrete is the most used construction material for infrastructure due to its strength and durability. However, under chloride exposure, they often do not achieve the designed service life. Hence, premature repairs or even replacement of components are required, which increases the environmental impacts and costs over the entire service life. This study evaluates the environmental impacts of using high alloy steel as a corrosion prevention measure for different chloride exposure conditions. High alloy steel shows a great potential in reducing the environmental impacts in condition under severe chloride levels.

A comparison between uniform and galvanic corrosion rate in carbonation induced corrosion of reinforced concrete

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Carbonation-induced corrosion is usually considered in uniform or generalized corrosion. This is true for small laboratory samples but not necessary the case for real reinforced concrete structures built with multi-layers reinforcement. Multi-layers reinforcement could lead to a galvanic corrosion between first depassivated layer closed to the concrete surface and deeper layers still passivated. The present paper compares the uniform corrosion density and the galvanic corrosion density for concrete samples made with two different type of cements. CEM III cement despite their higher susceptibility to carbonation show a significant lower galvanic corrosion density, which would lead to a significant increase in the service life of RC structures, exposed to carbonation.

Corrosion-induced concrete cracking - a poromechanical, multiscale approach

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Corrosion of reinforcement bars in concrete plays a significant role in determining a structure's durability and hence, its serviceability lifetime. Ferrous ions released at the steel-concrete interface diffuse through the pores and undergo many chemical reactions leading to the formation of rust (ferrous/ferric precipitates). As the stress-induced in the concrete exceeds the material strength, internal cracking begins. The three corrosion-driven mechanisms: ionic diffusion, chemical reactions and stress development co-occur at the micro-scale (within pores ranging from nanometers to micrometres) and subsequently, influence the load-bearing capacity at the macro-scale.

Chloride threshold and service life of prestressed concrete with various supplementary cementitious systems

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Seven-wire strands in pretensioned concrete (PTC) structures can undergo chloride-induced localized corrosion leading to catastrophic failure. In this case, the corrosion products occupy the space between the seven wires of the strands and do not exert expansive pressure onto the surrounding concrete until advanced stages of corrosion. Hence, unlike the case of conventional reinforced concrete systems, the propagation of corrosion of strands (during the initial stages) cannot be detected by visually observing the possible corrosion stains on the concrete surfaces. Hence, it is important to optimize the corrosion-resistance of PTC systems during the design stage itself such that they can remain corrosion-free throughout the expected service life of 100+ years. This article presents the effect of binder on the critical chloride threshold (Cl_{th}), a key parameter influencing the corrosion initiation period. In this study, pretensioned wire specimens comprising of self-reacting frame and in-built electrochemical cell were prepared to determine the Cl_{th} of prestressed steel embedded in mortar. Wires were stressed to the service-level prestress of 0.76 times the ultimate tensile strength of the prestressing steel. Performance in the three binders, namely ordinary Portland cement (OPC), OPC+30% of Class F fly ash, and OPC+50% ground granulated blast furnace slag were evaluated. The specimens were subjected to wet-dry exposure using simulated concrete pore solution containing NaCl, and the Cl_{th} was determined. It was found that the stress leads to significant reduction in the Cl_{th} and must be considered for service life estimations. Also, the synergistic effects of chloride diffusion coefficient (D_{Cl}) and Cl_{th} on the corrosion-free service life of PTC systems are demonstrated.

3. CONDITION ASSESSMENT OF CONCRETE STRUCTURES

3.1. Degradation and condition assessment

Forensic investigation concerning inspection and diagnosis of condition of water storage systems in the Gulf

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Most of us are fortunate enough to enjoy drinking safe, potable water direct from the tap in our homes and businesses. Most of us give little thought to the challenges and difficulties faced by those operating the water supply system, whose job it is to design, install and operate infrastructure capable of handling, purifying, storing and delivering water safe enough for us to drink. We think little of the design and construction challenges that involves or how designers and contractors ensure that the durability of the installed plant and infrastructure will meet the required service lifetime. In temperate countries that is challenge enough, but when constructing storage towers, reservoirs and piping systems in hot, arid countries it is, perhaps, not surprising that difficulties can occur during construction and operation. This is sometimes further compounded by the fact that designers are often based in Europe in more temperate conditions and may not fully appreciate the difficulties of constructing in a hot, arid climate. Furthermore, Engineers may try to apply the same acceptance standards that they would in more temperate countries, not fully appreciating the difficulties of construction in hot climates. Sandberg were asked to visit and comment on a sizeable project in the Gulf involving water storage towers, ground reservoirs and ancillary buildings in contemplation of legal proceedings. The structures had been built by a contractor but some problems had occurred in construction due to the high temperatures and issues with the concrete placement. The main issue that needed to be resolved was whether the problems that occurred were within acceptable limits for that type of construction and what repair recommendations were appropriate.

Assessment of cantilevered concrete balconies by means of practically oriented evaluation tools

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Facing the aging building stock, challenging times can be expected with a sharp increase of reinforced concrete buildings requiring maintenance, repair and/or replacement. For the condition assessment of existing reinforced concrete structures an in-depth and reliable inspection strategy and evaluation is essential to come to a durable and service-life extending repair strategy. A stepwise protocol to evaluate the condition and remaining bearing capacity of cantilevered reinforced concrete (RC) balconies is presented in this paper. Corrosion causing the reduction of the steel section, incorrect positioning of the reinforcement and/or higher loads are the main reasons service life might not be reached or the failure of the balcony can occur. As mentioned in EN 1504-9 and NEN 8700, an adequate diagnosis prior to repair showing the cause and extent of the damage is important (i) to determine the actual bearing capacity, (ii) to make an estimation of the residual lifespan and (iii) to select a durable repair technique and/or define maintenance requirements. In this paper a newly developed protocol for the assessment of the condition and the bearing capacity of the cantilevered RC balconies of a high-rise residential building is demonstrated. A semi-probabilistic method is used by applying partial safety factors based on Eurocode guidelines and fib Bulletin 80. The condition of the

structure is determined based on NEN2767 regulations. As corrosion is the main contributor to the degradation of existing concrete structures, a chloride contaminated building with damaged reinforced concrete balconies is selected as case study in order to demonstrate the applicability of the developed protocol and tools.

Corrosion monitoring of reinforced concrete structures – actual research results and new guidelines

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The corrosion of reinforcing steel in concrete, caused by de-icing salt or carbonation, represents a considerable repair expense in Germany every year. Electrochemical corrosion monitoring can be a helpful tool to determine the ingress of the depassivation front into a chloride exposed structure. The installation of appropriate sensors in existing structures can make the success of the repair verifiable after the repair work has been completed. To date, however, there is no set of rules for corrosion monitoring. In 2018, a leaflet B12 of the DGZfP [1] was published for the first time, which can serve as a guideline. Furthermore, in the last 3 years a broad-based research project has been carried out in Germany on open questions of corrosion monitoring. The knowledge gained in this way will be incorporated into a DAfStb-Leaflet that is currently being processed. Both the relevant findings of the investigated part at the University of Applied Sciences Munich HM and the content of the leaflet are presented.

Condition assessment of two prestressed concrete slabs after 60 years in service

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Two concrete deck slabs extracted from a Canadian bridge have been evaluated using non-destructive testing (NDT), followed by destructive testing. Throughout its service life, the bridge experienced harsh environmental conditions with frequent freeze-thaw cycles, hot and humid summers, and the use of de-icing salts during winters. This study presents the preliminary results of an exhaustive condition assessment of two prestressed concrete slab panels, where NDT techniques (visual assessments, electrochemical and concrete soundness tests) have been conducted prior to destructive testing. Although visual inspection did not indicate poor concrete quality, the results of the ultrasonic pulse velocity testing showed that both concrete slabs are of poor quality and may be suffering from internal defects. Chlorides may have also been introduced through the strand conduit anchor points. These findings raise concerns regarding the structural integrity of corrosion-affected members.

A case study on concrete testing for accurate assessment and maintenance of concrete structures

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The South African National Road Agency's (SANRAL) Bridge Management System (BMS) identified 5 concrete structures in the Eastern Region for priority assessments and repair. Defects in the structures included spalling and cracking of the concrete with varying degrees of severity recorded across structures and across individual structural elements. Concrete testing was carried out to accurately determine the deterioration causing mechanism, and to select an appropriate repair strategy for the rehabilitation of the defects. Carbonation depth, durability index, chloride content, chloride profile and cover depth tests were carried out on all structures except for the 2 inland structures where chloride tests were omitted due to low chloride exposure conditions. For the remaining 3 structures exposed to airborne salts, chloride-induced corrosion was ruled out following evaluation of the test results. Chloride contents measured were insignificant and good chloride conductivity results were achieved. Crack and spalling defects on all structures were attributed to carbonation-induced corrosion. The variation of carbonation and cover depth test measurements, with due cognisance of the "micro-climate" experienced by various structural elements, correlated well with the variation in the degree of severity of defects recorded across structures and elements. Poor oxygen permeability and water sorptivity measurements also correlated well with carbonation ingress measurements. Test results obtained from the investigation were imperative to accurately assess and determine the appropriate repair methods on this project. The project specifications and repair products were specifically detailed for each structure, ensuring sufficient information was provided for tender and construction purposes.

Evaluation of corrosion damage in reinforced concrete structures in terms of the rebar's residual cross-section

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Corroding reinforced concrete structures are frequently assessed to determine the rate of corrosion propagation and the level of deterioration, which might compromise the structure's reliability. Appropriate measures should be considered in deciding when and how to implement maintenance if safety must be ensured. However, the influential factor that governs or informs such decisions is corrosion damage quantification. Nonetheless, the current non-destructive methods of corrosion damage quantification often lead to ambiguity, and most do not evaluate corrosion damage in terms of the rebar's cross-section loss, which is the primary effect of corrosion. To address these shortcomings, this paper proposes an effective, reliable, and less-complicated model for quantifying corrosion damage in reinforced concrete structures based on the cross-sectional area of the corroding bar. The study was conducted through experimental (laboratory-based) and numerical investigations of the relationship between the level of corrosion and the corrosion-induced crack width. Based on the investigations' findings, appropriate relationships and essential parameters were identified, and the model was derived analytically. The derived model assesses corrosion damage in terms of the corroding bar's residual cross-section and requires only a few input parameters, which can be obtained by non-destructive testing if not known. The model was tested against data obtained from the laboratory experiment and against other experimental and analytical data from the literature, and the results showed a good correlation.

Preliminary evaluation of pier cap from an ASR-affected bridge in Central Canada

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The Bridge, a highway bridge structure, was built using a suspected alkali-silica reactive aggregate in the 1960's in a city in central Canada. Its concrete elements experienced rapid deterioration resulting in the need for costly increased repairs and rehabilitations. Alkali-silica reaction (ASR) is one of several damage mechanisms which might be contributing to damage of concrete elements. Infrastructure in central Canada experiences frequent freeze-thaw cycles, and heavy use of de-icing salts in winter as well as high heat and humidity in summer which might intensify distress. In recent years several concrete elements were selected for further assessment. Among them, five segments of a decommissioned Pier cap were selected for preliminary evaluation through visual inspection (conventional, semi-quantitative and quantitative using the cracking index) and non-destructive techniques (Schmidt hammer, ultrasonic pulse velocity and surface resistivity). Preliminary assessment results will be used to determine the appropriate locations (i.e., demonstrating the lowest/ highest deterioration) to extract cores for further assessment. Future work will be conducted on extracted cores using a multi-level assessment technique consisting of mechanical (compressive testing and stiffness-damage test) and microscopic procedures (the damage rating index and SEM) to assess the condition of the Pier cap.

Approach to the development of a model to quantify the quality of tendon localization in concrete using ultrasound

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Each engineering decision is based on a number of more or less accurate information. In assessment of existing structures, additional relevant information collected with on-site inspections facilitate better decisions. However, observed data basically represents the physical characteristic of interest with an uncertainty. This uncertainty is a measure of the inspection quality and can be quantified by expressing the measurement uncertainty. The internationally accepted rules for calculating measurement uncertainty are well established and can be applied straightforwardly in many practical cases. Nevertheless, the calculations require the occasionally time-consuming development of an individually suitable measurement model. This contribution attempts to emphasize proposals for modelling the non-destructive depth measurement of tendons in concrete using the ultrasonic echo technique. The proposed model can serve as guideline for the determination of the quality of the measured information in future comparable inspection scenarios.

Afrisam Ulco Preheater – digital audit through unmanned technology – a DeltaScan and SpecCon case study

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A visual baseline inspection of the Ulco Preheater Structure was carried out on the 17th of September 2020 using unmanned inspection drones together with proprietary digital inspection software. The objective was to identify, classify and quantify reinforced concrete defects on a 100m high tower and to advise on the required remedial actions. Delta Scan worked with Spec Con to provide a turnkey inspection and repair service where all estimates and guesswork were eliminated. The entire inspection and digitisation were completed in one day on site with no Health and Safety risks, high accuracy in reporting and at a fraction of the cost of conventional inspection techniques.

3.2. Non-destructive measurement and assessment techniques

An artificial intelligence approach to detection and assessment of concrete cracks based on visual inspection photographs

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This paper reports on the development of an artificial intelligence system, based on convolutional neural networks and machine learning algorithms to assess photographic images of concrete surfaces for the presence and characteristics of cracks. CNNs are deep learning techniques that are particularly useful for image categorization. An important challenge in the development of the system was to ensure that real cracks could be distinguished from non-crack features or profiles on the concrete surface. After development, the AI system was trained using 1900 images of cracked and non-cracked concrete surfaces. A further 1100 images were then used for validation and testing of the system. The images were segmented or pixelated in order to simplify the representation of the Image and make it easier to locate objects and boundaries. The system was further developed to estimate the length and average width of cracks in an image. The testing protocols showed that the AI model was 99.6% accurate in classifying cracked and non-cracked images. Furthermore, the average error for calculation of crack length and crack width was 1.5% and 5% respectively. These results show good promise for development of a fully-fledged AI system to support inspection and maintenance of RC structures.

Imaging of results in NDT-CE: strength and limitations in the use of radar vs. ultrasonic echo

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Radar and Ultrasonic Echo are well established NDT-CE methods for the imaging of results of RC structures with tendon ducts. From the physical background both methods are complementary; this becomes obvious looking at the parameter of the reflection coefficient. Whereas Radar is very quick in data acquisition revealing easily metal structures Ultrasonic Echo is slower but goes deeper and gets good results even in highly reinforced areas. For a profound decision what method is most suited for a certain testing task, it is necessary to know the strength and limitations of each method. In this contribution the imaging of results will be presented for both methods. It will be shown up to what depth single rebars, tendon ducts or the backwall can be detected depending on thickness, spacing, reinforcement ratio and bar diameter. Other limiting factors are concrete dampness in case of Radar or compaction quality in case of Ultrasonic that must be taken in account. Knowing these interrelations, it will be possible to distinguish areas that allow a quick data collection with Radar from areas that require the slower Ultrasonic Echo data acquisition but allowing an in-depth sight. This will contribute to a reliable and satisfying solution of ambitious testing tasks using NDT-CE methods.

Recent advances in (ultra)sonic active and passive monitoring of reinforced and prestressed concrete structures

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In addition to already established structural monitoring methods such as deformation, inclination or strain gauges or acoustic emission sensors, sonic or ultrasonic monitoring might provide valuable information about the condition or alteration of a structure. Sensors such as geophones, recording ambient noise in the sonic and subsonic frequency range can provide information beyond modal analysis by using interferometric methods. Wave velocities determined by this method are related to the elastic properties and stiffness of material and structure and can be converted into damage indicators. Embedded active ultrasonic transducer networks can provide more detailed insight about deterioration or damages again, using interferometric technologies. This approach is extremely sensible, detecting relative change in velocity on down to 10^{-5}. These methods, including benefits and remaining challenges, are demonstrated using data from a test structure at BAM's test site demonstrating the case of prestress loss, and data from an actual bridge still under traffic.

Testing methods for concrete-to-concrete interfaces as pathways for corrosive attack

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Concrete-to-concrete interfaces, commonly described as joints, are inevitable when casting an additional layer of concrete onto an existing structure as part of a repair or retrofitting measure. Due to the wall-effect, segregation and temporal effects, the interfacial bond is a structural weakness, resulting in reduced tensile strength and durability. As interfaces present a quasi-two-dimensional problem, many experimental methods for the determination of concrete properties, which focus on a three-dimensional isotropic bulk material, are not applicable. The key parameter for assessing the mechanical and durability properties of a concrete-to-concrete interface is the adhesive bond strength. Since the determination of concrete tensile strength is generally complex due to concrete brittleness, the focus lies on indirect testing methods such as flexural or splitting tests, where a compressive load evokes crack inducing tensile stresses.

Microscopic assessment of ASR-affected columns after 20 years in service

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Deterioration signs were observed on the concrete surface of the exterior columns of the SITE building located at the University of Ottawa, Ottawa (Ontario, Canada) which demonstrated the potential presence of a concrete damage mechanism, suspected to be alkali-silica reaction (ASR). To investigate the root cause of this deterioration, a visual inspection was conducted to select concrete members for coring. Damage development in the extracted cores was then evaluated through various microscopic techniques to identify the cause and extent of deterioration. First, the petrographic examination was carried out with the aim of detecting the cause of damage in the extracted core specimens through the analysis of damage features; confirming the presence of ASR in the selected elements. Afterwards, the Damage Rating Index (DRI), a semi-quantitative microscopic procedure, was used to evaluate the extent of the damage. Data collected during the visual inspection and petrographic examination will be presented and analyzed. Moreover, based upon the analysis of DRI results, the induced expansion levels in affected columns will be discussed, along with potential implications on their structural performance.

A framework for non-destructive assessment and monitoring of 3D printed steel fibre reinforced concrete (SFRC) tunnel segments

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3D Concrete Printing (3DCP) has been gaining in the very last years great potential due to the necessity of enhancing the innovation uptake of concrete construction industry and make it aligned with the evolving needs of the society, mostly in terms of sustainability. The start-up company Hinfra has developed and is currently implementing in the market a new slip-forming methodology for the refurbishment of existing tunnels, using 3D printable steel fibre reinforced concrete (SFRC). This method provides an innovative framework for the strongly needed maintenance interventions of (often obsolete) highways and railways, whose network ranks among the top positions worldwide. Along with the description of the Hinfra slip-forming process, the purpose of this paper is to provide a framework for non-destructive assessment and monitoring of the “as-built” full-scale 3D printed SFRC tunnel segments. The methodology consists of a non-destructive ultrasound tomography and magnetic fibre-dispersion monitoring, further validated by means of destructive tests performed on cores extracted from the same segments. On cores, besides compression strength tests, the fracture behaviour of the SFRC will be measured by means of Double Edge Wedge Splitting tests, together with the resistance to water penetration under pressure. Thus, on the one hand the homogeneity of the concrete and the fibre dispersion has been monitored through the non-destructive tests with tomograph and magnetic sensor respectively, providing broad information about the quality of the slip-forming process, whereas, on the other hand, the destructive tests on cores, will validate in detail the same information, in an overall attempt to define a framework for on-site non-destructive assessment and monitoring of the performance of retrofitting interventions in concrete tunnel linings.

Practical procedure for the precise measurement of geometrical tendon positions in concrete with ultrasonic echo

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Existing concrete structures were usually designed for lifetimes of several decades. The current and urgently required efforts to increase sustainability and protect the environment will likely result in extended service lives up to 100 years. To achieve such objectives, it is required to assess structures over their entire lifecycles. Non-destructive testing (NDT) methods can reliably support the assessment of existing structures during the construction, operational, and decommissioning phases. One of the most important and safety-relevant components of a prestressed concrete structure are the tendons. NDT methods such as the ultrasonic echo method are suitable for both the detection and the localization of the tendons, i.e., the measurement of their geometrical position inside the component. The uniqueness of structures, concrete heterogeneity, and varying amounts of secondary components such as the reinforcement represent obstacles in the application of these methods in practice. The aim of this contribution is to demonstrate a practicable procedure, that can be used in the field to determine the parameters required for the measuring data analysis without extensive knowledge about the investigated components. For this purpose, a polyamide reference specimen is used to show which steps are required to obtain reliable imaging information on the position of tendons from the measurement data. The procedure is then demonstrated on a concrete test specimen that covers various relevant and practice-oriented test scenarios, such as varying tendon depths and component thicknesses.

Sewer concrete subjected to biogenic acid corrosion: analysis of concrete deterioration phases using QEMSCAN

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QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy) was used to analyse the evolution of cementitious phases of sewer concrete after biogenic acid attack. Two concrete mixes; a blend of Sulphate Resisting Portland Cement and Fly Ash (SRPC+FA) and Calcium Sulpho-Aluminate (CSA) cement, with calcite and siliceous aggregates, were subjected to a field sewer environment, with a maximum H_2S gas concentration of 100 ppm, for about two years. After exposure, both concretes experienced thickness losses, with CSA indicating mass gain and SRPC+FA mass loss. QEMSCAN analysis results indicated that SRPC+FA was rich in calcium silicate hydrates in the intact zone, Mg-silicate in the transition zone, and Al-silicate, gypsum, and quartz in the deterioration layer. CSA contained ettringite and portlandite in the intact zone, gypsum and aluminate phases in the deterioration zone, while the transition zone was challenging to observe due to the superimposition of ettringite before and after the attack. It was concluded that, despite CSA showing a lower corrosion rate than SRPC+FA, it exhibited severe deterioration under QEMSCAN. Therefore, QEMSCAN is a potential tool for preliminary analysing of concrete microstructural phases under biogenic acid attack. However, it should be incorporated with other microstructural analysis tools.

Laser induced breakdown spectroscopy – a tool for imaging the chemical composition of concrete

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One of the most common causes of damage is the ingress of harmful ions into the concrete, which can lead to deterioration processes and affect structural performance. Therefore, the increasingly aging infrastructure is regularly inspected to assess durability. Regular chemical analysis can be useful to determine the extent and evolution of ion ingress and to intervene in a timely manner. This could prove more economical than extensive repairs for major damage, particularly for critical infrastructure. In addition to already established elemental analysis techniques in civil engineering such as potentiometric titration or X-ray fluorescence analysis, laser-induced breakdown spectroscopy (LIBS) can provide further important complementary information and benefits. The possibilities of LIBS are demonstrated using the example of a drill core taken from a parking garage.

Determination of surface properties of treated cement pastes by acoustic methods and scratch test - pilot experiments

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The concrete has been and at the same time will be the most used construction material worldwide. It is exposed to various physical and chemical degradation processes that deteriorate its properties and shorten its service life in most applications. As most of the detrimental effects on concrete come from the ambient environment, the quality of concrete surface plays a key role in the overall concrete performance. It should be resistant to abrasion, free of microcracks and open pores to prevent ingress of water, aggressive solutions, and gases. To enhance the properties of the concrete surface, various approaches can be used. The treatment via silicate-based sealers is becoming increasingly popular in concrete technology, especially in preventing deterioration when exposed to highly aggressive environments. This contribution focuses on applying unconventional test methods (e.g. combined scratch/acoustic emission method) to detect the fundamental properties of the treated cementitious surfaces will also provide a new perspective approach of material testing, which may be in the future advantageously used in technical practice. The present combined scratch/acoustic emission test evaluation will provide an excellent insight into lithium silicate sealers' physical behaviour on fine-grained cement-based materials during this test.

The effect of curing, specimen thickness, and saturation on surface resistivity of concrete

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Electrical resistivity measurements are used to assess the potential durability of concrete. The surface resistivity method is a popular method because of the ease of testing, non-destructive nature, and time efficiency. The moisture state of concrete has a significant influence on the resistivity results. Laboratory specimens cured using practical curing methods should be saturated before testing to eliminate this effect and avoid incorrect interpretation of the results. However, the available standard test methods for surface resistivity do not deal with this issue. Consequently, an experimental study has been conducted on the effect of drying on concrete resistivity values, as reported in this paper. The results show that a reduction in the specimen thickness can improve the ability of the surface resistivity method to be used for assessing curing effectiveness.

Mortar resistivity as a parameter for monitoring steel corrosion in alkali-activated materials

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The development of novel binders with a longer service life than ordinary Portland cement (OPC) is a cost-effective and environmentally friendly option. Alkali-activated material (AAM), one of the available alternative binders, offers a lot of potential for development and is widely regarded as a viable alternative to OPC due to its low carbon emissions and promising performance. However, existing understanding is insufficient to assure long-term reliability due to discrepancies in the reaction processes of AAM and OPC, as well as a wide range of unique AAM compositions. In this study, the long-term corrosion behaviour of reinforcing steel embedded in three different alkali-activated mortars was monitored in chloride rich environments throughout the test period. The half-cell potential and corrosion rate were determined by linear polarisation (LP) and the individual resistance of the mortar was determined by electrochemical impedance spectroscopy (EIS). The objective of this study is to determine an indirect method for evaluating the corrosion conditions of steel embedded in AAM. The mortar resistance (R_{mortar}), determined by fitting the EIS data, can roughly determine the condition of the steel and is a suitable tool for indirect measurements as an alternative to monitoring the corrosion potential (E_{corr}), which is very sensitive to the composition of the pore solution and the availability of oxygen.

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4. CONCRETE REPAIR, REHABILITATION AND RETROFITTING

4.1. Repair methods, materials and techniques

Application of RFID corrosion environment sensing system to repair work and results of 10-year study

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To perform preventive maintenance for reinforcing steel corrosion in reinforced concrete, an RFID corrosion environment detection system is developed that can monitor wirelessly iron sensors that simulate reinforcing bars. This system can be embedded in concrete for a long period of time according to the life cycle of the target structure, and semiconductor parts can be used for the passive RFID used in the communication interface. Therefore, it is necessary to confirm long-term durability. In this study, an RFID corrosion environment detection system was used to the repair work of bridge piers in addition to the conventional method of diagnosing rebar corrosion. Accordingly, this study reports the results of our research conducted over a period of 10 years. The performance of the RFID corrosion environment detection system was compared with that of the expansion ring sensor system and rebar self-potential measurement results. In addition, electron probe microanalyzer (EPMA) was used to analyze the chloride ion permeation of cores sampled from 5- and 10-year-old structures. The reaction results of the RFID corrosion environment sensor were compared with the permeation of chloride ions inside the structure.

Investigating the effects of anti-corrosive coatings on the bond between corrosion-damaged rebar and concrete repair materials

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Reinforcement corrosion causes destruction to the steel by a loss in cross section and rib height, which can affect the bond between steel and concrete. During repair of corrosion-damaged reinforced concrete members, a protective coating is usually applied to the cleaned corroded steel. There is, however, little information available on the bond performance of repair coatings. Furthermore, the effect of their coating thickness and other parameters like rebar diameter, corrosion degree and repair material properties are not well understood when considered in parallel with repair coatings. This paper seeks to contribute towards understanding the use of anti-corrosive coatings and the influence of their thickness on the bond between cleaned steel reinforcement and repair materials, when used in combination with different bar geometries at varying degrees of corrosion damage. In this investigation, two high tensile steel bars, Y12 and Y16, were considered. Rebar corrosion damage levels of 0%, 10% and 20% (of steel mass loss) were simulated by mechanical grinding of sound rebar samples to represent the condition of cleaned corroded rebar. A commercially available epoxy-modified, cementitious coating material was applied to the steel in one or two coats, with each coat being 0.6 mm thick. Three repair materials with CEM I 52.5N were considered in this study, which included one concrete with a w/b ratio of 0.45 and two mortars with w/b ratios of 0.47 and 0.65. Pull-out testing was conducted on 108 specimens, and the results analysed by means of the one-way ANOVA test to assess the effect of mainly coatings and other parameters on the bond. The results indicate applying coatings to 10% and 20% corroded steel does not significantly reduce the bond for the M65 and C45 mixes. Furthermore, the difference between one and two coats had little influence on the bond of corroded steel for all rebar geometries and repair mixes.

Re-using existing prefabricated prestressed concrete girders

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The construction industry will have to undergo a transition from a linear to a circular construction industry. In the Netherlands an agreement is made where goals are set to reduce the CO_2 emissions with 49% in view to 1990, to recycle all concrete waste in new concrete and all tenders should be circular by 2030. One of the first steps is to change the current linear approach in the construction industry. Therefore, Royal HaskoningDHV started an innovative approach of reusing prefabricated concrete girders for new overpasses. Structural assessments have shown that the existing girders are still able to perform for another 100 years in a new structure. To put the theory into practice, a pilot project was started in which a viaduct with 40-year-old girders was dismantled. The girders were transported to a storage location where they were inspected, adjusted and repaired for application in the new overpass. Structural assessments, ecological footprint and costs calculations were documented. Instead of making new girders, re-using prefabricated girders saves approximately 90% of CO_2 emissions and abiotic depletion. The main obstacle to the transition to a circular building economy is the awareness of stakeholders that the reuse of these high-quality elements is possible. Royal HaskoningDHV believes that re-using prefabricated prestressed concrete girders is technically possible, economically feasible and environmentally sustainable.

Repair of a hydraulic structure with different strain-hardening cement-based composites

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The transport infrastructure in many countries has been increasingly ageing. Both space limitations and narrow time frames for construction significantly restrict the possibilities for replacement or new construction. In addition, the need to use resources as efficiently as possible makes maintenance and repair to sustainable measures. Particularly in the case of superficial repairs, solutions are required with low demands to the existing substrate, the thinnest possible overlays, high crack-width controlling properties and fast application times. These requirements can be met by thin, strain-hardening material layers as shown in different studies, but often fail due to existing regulations and standards, which is why practical demonstrators are urgently needed. In the following, a hydraulic engineering demonstrator, a water lock, with the objective of restoring the impermeability of the structure, is presented and its rehabilitation by means of strain-hardening cement-based composite (SHCC) and textile reinforced concrete (TRC) is examined in detail.

Crack control for repair and strengthening of reinforced concrete structures using the multi-cracking behaviour of ultra-high performance fibre reinforced shotcrete (UHPFRSC)

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Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is an innovative material for the repair and/or strengthening of reinforced concrete structures. In the field of traffic infrastructure, the outstanding mechanical properties are used as a protective surface layer and to increase the load capacity of the structure. UHPFRC is characterised by a dense granular structure and correspondingly high resistance against chloride attack. The material is typically applied as cast in-situ concrete. To optimise implementation of the strengthening and repair method, the UHPFRC is applied as sprayed concrete, so-called Ultra-High Performance Fibre Reinforced Shotcrete (UHPFRSC). The research aims to increase the service life of damaged and/or overloaded structures. Crack widths in the UHPFRSC layer must be limited to avoid migration of chlorides. The thin UHPFRSC layer provides crack distribution and control of localised macro cracks in the existing reinforced concrete structure. The fibres in the Ultra-High Performance Shotcrete (UHPSC) allows for limiting the crack width to 50 µm. When the UHPFRSC is applied on cracked reinforced concrete, it can be assumed that multi-cracking in the UHPFRSC surface layer will provide a chloride-dense layer equivalent to a coating. Under load, the two layers - UHPFRC and RC - act as a composite. For structural analysis, a particular focus must be placed on the interaction between cementitious materials. In addition, the pre-damage and pre-loading of the existing structure will influence the structural behaviour and crack formation. The paper presents the results of bending tests of UHPFRC - RC composite elements. The investigation shows the outstanding crack control behaviour

of UHPFRSC. Based on this investigation, an analytical model will be provided, and a calculation of the crack widths will be derived. The research presents a central aspect of a large interdisciplinary research project at Munich University of Applied Science, called i-SCUP.

Concrete substrate moisture requirements for durable concrete repairs – a field study

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In concrete repair specifications, the required moisture condition of the substrate, which can play an important role for bond development, and, ultimately, on the long-term repair / overlay durability, is generally ill-defined and addressed without due consideration to the given substrate characteristics. The standard specification, if any, is to require saturated surface dry (SSD) condition of the substrate prior to application of cementitious repair materials, which is theoretically achieved after saturating the substrate and then letting the surface just start to dry out. This does provide an intuitive solution founded on rational considerations, but it has never really been precisely defined, measured, nor validated. The influence of substrate surface moisture on the bond between the existing concrete and the new repair material is an issue of significant importance. This paper revisits the question, in light of results from a project designed to develop guidelines for moisture conditioning of a concrete substrate prior to a cementitious repair, which was part of a larger effort to develop guidelines for surface preparation of concrete prior to repair. Over the course of the project, multiple series of test slabs were repaired after being subjected to different surface moisture conditioning and then tested for bond strength tests at different ages. The findings are discussed, together with those from previous studies, and recommendations are issued.

History, diagnosis and repair of the Corniche Kennedy in Marseilles

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The Corniche Kennedy is an emblematic road of the city of Marseilles in France. Located on the seafront, it was built in the 19th century and widened in the 1960s to create a corbelled pedestrian promenade. Its widening structure, made of slabs resting on corbels anchored in a retaining wall or on crossing structures, has been subjected for more than 60 years to a very aggressive marine environment and presents many damages. After having carried out the diagnosis of the structure, the Infrastructure Department of the Metropole of Aix-Marseille-Provence selected the engineers of the Setec Group to carry out the complete project management for the rehabilitation of the Corniche Kennedy. Between 2018 and 2022, the Corniche Kennedy underwent major rehabilitation work, using modern techniques to prevent and treat the main pathology of the structure, the corrosion. This article presents all the steps of the rehabilitation of the Corniche Kennedy from diagnosis to maintenance of the structure after renovation.

Sustainable concrete repair & protection products – the impact on renovation works

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Repair and protection systems can have a positive impact on sustainability by prolonging the life of a structure and reducing the amount of new construction works. Over recent years, new products and technologies for use as concrete repair mortars and protective coatings, have been developed and launched on the market with lower environmental footprints than their traditional counterparts. To help visualise the environmental impact of these new technologies and products with improved environmental footprints, this paper will use a Life Cycle Analysis (LCA) of a repair project in Johannesburg, South Africa, which was completed in 2021. Two different scenarios will be compared and assessed – the first, is an existing product range for concrete repair and protection works that was used on the

project, and the second is an alternative solution using the new and more sustainable technologies-based product range. This paper will provide an example of the positive environmental impact for such asset owners, by using more sustainable concrete repair and protection materials, by focusing on the Global Warming Potential (GWP) and Abiotic Depletion Potential fossil (ADP fossil) indicators.

A long-term study on the effect of a hydrophobic treatment on the moisture balance and durability of a reinforced concrete structure in a road tunnel

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Concrete structures in the vicinity of seawater or deicing salts on roads in regions with cold climatic conditions, are exposed to chlorides. Transport of chlorides in concrete due to capillary suction during drying and wetting cycles as well as diffusion in combination with carbonation tends to result in corrosion of the rebar and loss of structural integrity. This damage mechanism mainly applies to directly weathered components. After a longer service life, however, components that are not directly exposed, such as concrete surfaces outside the spraying water area of a tunnel, are also affected. A long-term study over 12 years was performed to investigate the effect of hydrophobic treatment on the moisture balance and durability of a suspended tunnel ceiling compared to an untreated surface with the same exposure. Embedded sensors installed in the concrete structure and an online monitoring system were used to measure the electrical resistivity of the concrete and the corrosion rate of the steel reinforcement over time. Furthermore, the data obtained were combined with climate measurements in the tunnel to gain new insights on the effect of tunnel climate on the damage mechanism. The measurements allowed to prove the long-term effect and correct application of hydrophobic treatment. With these results it is possible to make a more precise estimation of the condition and the deterioration process of the tunnel ceiling and to optimize the rehabilitation schedule.

Emergency rehabilitation of Selby interchange on M2, in Johannesburg, South Africa

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In this paper, the retrofitting and rehabilitation of the M2 Selby interchange, on the M2 in Johannesburg, Gauteng, South Africa, is presented. After noting large shear cracks on the pier columns, the highway had to be closed down, for 10 months. The client for the project was the Johannesburg Roads Agency (JRA), the contractor was Stefanutti Stocks Civils, and the consultant was WSP. The project commenced with the design of jacking towers which were used to jack up and support the drop-in slabs. The support system was designed to be used as a kit that can be reused in future. The demolition of the piers posed some difficulties due to the small working area within the constraints of the jacked slabs, which remained in the jacked position. The piers were designed in accordance with TMH7. A key design focus was the creep calculation, due to the unique geometry of the mushroom heads. Granite aggregates were chosen to reduce the creep and the cantilever ends were precambered. The jacked slabs were lowered and aligned only at the end of the project timeline just in time for the Thorma joints and asphalt to be added before opening the bridge to the public.

Product data templates of repair products for Building Information Modeling (BIM)

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Building Information Modeling (BIM) describes the digital and collaborative planning, construction and management of buildings by all stakeholders by means of a digital 3D building (data) model. This enables complex analyses, simulations and optimizations of cost, time and quality. For these reasons, BIM is becoming increasingly important in the construction industry and brings changes along the entire “construction value chain”. Such changing and unclear (data) requirements are major challenges for the manufacturers of construction chemicals, e.g. for products for ”Concrete Repair and Protection”. As harmonized standards are still lacking and a wide variety of concepts are available on the market today. Therefore, demand-oriented BIM product data templates for two pilot groups of construction chemicals products were developed by the German association of manufacturers of construction chemical products

(Deutsche Bauchemie e. V.). With all parties involved in the process, from planning to construction, the information requirements were recorded. Furthermore, characteristics were defined using existing standards and structured in an extensive list of characteristics. In addition, software templates were created in native but also in open file formats. The development of further lists of characteristics is currently in preparation, in addition to other product groups, also for repair mortars and other repair products.

Use of fibres in improving the mechanical properties of a multifunctional cement for structural repair purposes

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Calcium phosphate cement (CPC) is a multifunctional cement whose potential application depends on the reactants used to synthesise it. Just like many inorganic cements, the pure CPCs synthesised in all cases are very brittle and have low toughness values under loading. In this research, the CPC material is formed from the exothermic reaction between phosphoric acid and calcium silicate at controlled room temperature. Three fibre types, namely; macro polypropylene fibres, amorphous metallic fibres and recycled carbon fibres were chosen due to their corrosion resistance in acid to enhance the mechanical performance of this cement as a repair material. 1.5% by volume of each of these fibres were added to the CPC material and autogenously cured for 14 days at room temperature. Mechanical destructive and non-destructive tests were carried out on the resulting composites. The experimental results revealed that each type of fibre contributes to increase flexural strength, compressive strength, fracture energy and dynamic elastic modulus of CPC material. However, for this purpose the recycled carbon fibres have proven to be more efficient.

The use of hydrophobic treatments to extend the service life of deteriorated marine RC structures

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Although concrete has for many decades been thought to be a durable material, evidence shows that concrete in aggressive environmental conditions such as the marine environment is susceptible to premature deterioration. Various methods including hydrophobic impregnation have been implemented in practice for addressing concrete durability problems, both for new and existing reinforced concrete (RC) structures. The use of hydrophobic impregnation as a proactive maintenance strategy for marine RC structures should be based on quantitative engineering models for predicting the course of corrosion damage after treatment. However, these are currently lacking in the literature. This on-going project aims to investigate the use of hydrophobic impregnation to extend the service life of existing marine structures that have already been contaminated with sufficient chlorides to initiate corrosion. The experimental variables chosen for the study are cover depth, surface crack width, corrosion rate at the time of application of the silane and water/binder (w/b) ratio. This work will provide insight into the mechanisms by which silane impregnations limit steel corrosion in marine RC structures, and the appropriate timing of application of the product. The results of the study will be used in the development of an empirical model for the propagation of corrosion in silane treated marine RC structures, and eventually, practical recommendations on using hydrophobic treatments for corrosion control and service life extension of deteriorating structures.

4.2. Concrete patch repairs and bonded overlays

Journey through time - concrete repair mortar

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Time. Various issues can occur when dealing with concrete and concrete repair, as the concept of time can have very different meanings in terms of cause and effect. Let's first consider simply the fabrication of a building from reinforced concrete. It can be simplified to its three dimensions, namely, length, width and height. This three-dimensional building is constructed with the latest technology according to corresponding structural calculations and the execution itself, and is then handed over for its intended use. However, the key factor for any building is time. In this context there are many perspectives that need to be considered. For example, at the time of constructing a reinforced concrete building, its use is stipulated in the statement of work, which then influences the design and dimensioning of the concrete. Or else exposure of the concrete to aggressive media that may damage the concrete or its reinforcement.

Rehabilitation and repair of concrete overlays

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Concrete overlays are a growing solution in the United States for pavement rehabilitation and preservation. Many different overlay types and designs can be used based on existing conditions and to achieve a variety of design goals. Recent performance studies have indicated that concrete overlays are capable of providing an extended service life of 35 years or more. However, the intended design life of an overlay may be shorter, and in some cases, overlays experience early distresses and failures. Because many agencies are new to concrete overlays, there is a growing need to identify best practices for rehabilitation and repair of these pavements. This paper presents a survey of typical short- and long-term distresses that have been observed on US concrete overlay projects. Common failure modes vary based on overlay type and design details, and distresses frequently depend on local materials and climate conditions. Best practices and case studies for rehabilitation and repair of concrete overlays are identified, offering options both for extension of concrete overlay service life as well as rehabilitation or reconstruction with a new pavement surface.

UHPC overlay as sustainable solution to preserve old concrete structures

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Concrete structures exposed to harsh environments, especially including bridges, harbor structures are often suffered from durability problems. Typical external signs include surface deterioration, cracking caused by for example sulphate attack, frost action or reinforcement corrosion. All are strongly linked to the porous microstructure of the binder matrix and chemical decomposition of certain phases. Full replacement of deteriorated concrete structures is costly and can be troublesome for their users. The increasing demand to reduce the carbon footprint and to prolong the service life of concrete structures adds yet another argument to restore the existing structures. One alternative is to use very dense Ultra-High-Performance concrete (UHPC) as an external protective coating. The goal of this study was to determine the interfacial bonding characteristics between a damaged normal concrete (NC) and the applied thin layer of the UHPC. To curb the CO_2 emission, UHPC is produced by substituting 50 wt% of Portland cement with a fine limestone powder. Fresh and hardened properties, shrinkage and frost durability have been evaluated. Mechanical properties were determined on a full-scale hybrid element using ultrasonic pulse velocity (UPV) and bond test (pull-off test). The results showed a significant increase of mechanical properties. Despite the applied thin layer of UHPC and volumetric restrain from the substrate normal concrete (NC) only limited surface shrinkage cracks were observed. The bond test and UPV showed good excellent values.

Volume change behavior of cement-based repair materials labelled as shrinkage-compensating, shrinkage-compensated or nonshrink

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The labels *shrinkage-compensating, shrinkage-compensated* and *nonshrink* found in the technical documentation of many proprietary repair materials are all intended in principle to describe systems that exhibit no or little net contraction as a result of shrinkage. In practice, however, these terms are of limited significance in the selection of repair materials without appropriate test data on time-dependent volume changes. This paper provides clarifications on the dimensional behavior of shrinkage-compensating materials and uses experimental findings to emphasize the shortcomings in the information provided in the data sheets of many repair materials labelled as such. In view of a more effective and reliable use of cementitious shrinkage-compensating repair materials, recommendations are made to improve and uniformize the content of the technical data sheets.

Strain-hardening limestone calcined clay cement-based (SHLC3) composites for strengthening concrete elements against impact loadings

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The mitigation of the consequences of exceptional events is a compelling challenge, as their sudden occurrence might bring into play dramatic societal impact. To enhance the impact safety of the built environment, high-performance limestone calcined clay cement (LC^3) based binders have been developed as the basis for sustainable strain-hardening fibre-reinforced composites, intended as thin protective layers for concrete members, like beams, girders and slabs. In combination with LC^3 matrices, synthetic fibres endow the LC^3 matrix with enhanced dissipation capability, thus providing a successful confinement degree for the concrete substrate. In this contribution, we present the most recent advancements in the development of $SHLC^3$ composite materials with optimised composition, suitable for shotcreting and automated construction.

Investigating the structural contribution of patch repairs to reinforced concrete elements

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The repair and rehabilitation of RC structures has become a common requirement in modern construction. A common method used by engineers for repairing RC structures is the patch repair technique. Concrete patch repairs are broadly categorised into structural and cosmetic repairs. Structural patch repairs are expected to carry loads or stresses and contribute to load sharing in the repaired concrete element. The properties of the repair material can have a significant effect in this regard, the most significant of which are the elastic modulus, shrinkage, and creep. An analytical model used to determine the distribution of stress in a repaired element over-time is presented. The elastic modulus, shrinkage, and creep was determined for three high strength cement-based repair materials and used as inputs to the model. The model results suggest that high strength materials do not structurally contribute in the long term, for patch repaired concrete elements under axial compression.

Thin bonded overlays with carbon reinforcement for concrete pavements

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Here a possible alternative joint design in plain concrete pavements was investigated. The basis for this is to cover the concrete pavement with a thin jointless carbon reinforced concrete layer (CRC layer) of 50 to 70 mm as the top concrete. In the process, the classic joints already present in the lower concrete layer are also covered. The carbon reinforcement with a very high load capacity is intended to generate a finely distributed crack pattern in the upper concrete layer, thus preventing the penetration of moisture and other fluids into the joint area. This method thus represents an alternative to conventional joint sealing. Such a construction method is applicable both in the context of repair and new construction measures. In addition to tests on the cracking behaviour of CRC for concrete

pavements, the main focus was on tests on large scale composite beams (classic jointed lower concrete + CRC layer). The focus was on the effects of static and cyclic bending on the material behaviour of the CRC over the moving joints in the lower concrete and the bond behaviour of lower and carbon reinforced concrete. The influence of differently designed bond breakers on the crack formation in the joint area was also considered.

Carbonation and chloride penetration of repair mortars with water treatment plant sludge and sugarcane bagasse ash sand

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Water treatment plant sludge (WTPS) and sugarcane bagasse ash sand (SBAS) (wastes from water treatment and sugar/ethanol industries) can be used as replacements of natural sand in concrete. Thus, this paper aims to evaluate carbonation depth and chloride penetration of cementitious repair mortars produced with WTPS and SBAS. Three mortars compositions were analysed: plain reference sample (REF); sample with 3% of WTPS (3WTPS); and sample with 30% of SBAS (30SBAS). They were subjected to tests of accelerated carbonation and immersion in NaCl solution up to 84 days (12 weeks). The results showed that SBAS mortars had the best performance in relation to carbonation and chloride penetration tests. 3WTPS mortars had similar results to the reference sample. This is due to refinement of pores given by incorporation of fine waste materials making it difficult for aggressive agents to penetrate cement matrices. Therefore, 3WTPS and 30SBAS composites can be satisfactorily used in buildings repair services for more sustainable and durable construction.

4.3. Structural repairs and strengthening

Actual achievements and future challenges of HPFRC for structural rehabilitation of bridges

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The state of road infrastructures in many advanced countries is rapidly changing under the impulse of massive funding from governments, eager to have more efficient and safer transportation systems. The use of well-known materials such as fibre-reinforced concrete (FRC) is finding a growing space for structural rehabilitation of bridges; the adopted material is often defined as High performance fibre reinforced concrete (HPFRC) due to its enhanced performance. The paper presents the principal findings of an EU-funded project that involved the repair of two road bridges in Italy using HPFRC. The project has successfully carried out the jacketing of bridge piers and cap-beams, heavily damaged by corrosion, with a new HPFRC layer of reduced thickness (40-60 mm) and limited use of steel reinforcements. Experimental tests carried out in the laboratory of the University of Brescia on 1:2 scaled specimens have shown the possibility to increase the load bearing capacity of the cap beams (with respect to vertical loading) up to 73%, with moderate effects on the change in stiffness and ductility of the existing structure. Based on field and laboratory experience, the article eventually presents some new challenges for the use of HPFRC in the reduction of environmental impact of construction industry.

Shear strengthening of concrete T-beams with lateral layers of UHPC

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Concrete T-beams are commonly used in building slab systems and bridge decks. They may require strengthening in shear when they are deteriorated or when loading requirements increased. This research project studied the shear behaviour of concrete T-beams using cast-in-place Ultra High-Performance Concrete (UHPC) layers as a lateral strengthening method avoiding beam depth modification. Three UHPC strengthened beams together with one reference reinforced concrete beam were tested in monotonic three-point bending. Parameters investigated include the thickness of UHPC layers and the presence of steel anchors at the UHPC-concrete interface. A digital image correlation (DIC) technique was used to investigate the strain distribution of T-beams during the testing. Strain distribution, failure modes and strengthening effects provided by the UHPC lateral strengthening were analyzed. Results show that UHPC strengthening can substantially improve the stiffness and shear capacity of concrete T-beams, 25 and 50 mm lateral layers increased by 102% and 113% the T-beam shear capacity, respectively. Typical bending-shear behaviour were observed on each strengthened beam with UHPC layers. A final shear failure was observed in the T-beam with 25 mm UHPC layers and 50 mm UHPC layers without anchors, while a combination of shear and bending failure was noted in the T-beam with 50 mm UHPC layers and steel anchors. The steel anchors at the UHPC-concrete interface can further increase the ultimate shear capacity and beam stiffness, but at a limited extent. Therefore, experimental results confirmed that cast-in-place UHPC lateral layers are an effective way to strengthen existing concrete T-beams with inadequate shear capacity.

Numerical modeling of deep beams strengthened in shear with fabric-reinforced matrix composites

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Numerical models were developed to simulate the behavior of reinforced concrete (RC) deep beams strengthened in shear with carbon fabric-reinforced matrix (C-FRM) composites. The matrix of the C-FRM composite reinforcement was cementitious or geopolymeric. External strengthening with C-FRM composites resulted in a two-fold increase in the shear capacity in the absence of internal steel stirrups. The models with internal steel stirrups exhibited a maximum shear strength gain of 20%. The shear capacity of the models with a geopolymeric matrix was, on average, 5% lower than those with a cementitious mortar. A comparison with experimental results verified accuracy and validity of the numerical models.

Study on the application of inorganic resin-based micro-FRP bars in strengthening marine concrete structures

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Aiming at the technical problem of rapid reinforcement of corroded concrete structures in harsh marine environment, a new method of strengthening marine concrete structures with micro-FRP bars based on inorganic resin is proposed. The dry-wet cyclic corrosion test and flexural capacity test are carried out for RC beams reinforced with inorganic resin CFRP bars, and the change rule and evolution mode of the durability of RC beams reinforced with inorganic resin CFRP bars are obtained. Furthermore, based on the reinforcement project of a high-piled wharf in South China, the feasibility, effectiveness and advancement of strengthening Marine concrete structures with inorganic resin FRP bars are fully verified.

Experimental testing on the structural capacity of coupling beams with non-anchored longitudinal rebars

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Coupling beams are structural elements which connect shear walls to improve the lateral stiffness and allow to transfer shear forces, while possessing sufficient ductility to dissipate the energy produced due to the lateral displacement. An error in the construction of a 16-story buildings resulted in that only the bottom layer of the longitudinal reinforcement bars in all coupled beams are anchored into the lateral walls, the upper longitudinal bars are cut before anchored to the lateral walls. The reconstruction of all coupled beams in the building is technical and economically non-feasible therefore, to propose a more efficient and less costly retrofit procedure, an experimental study is undertaken to analyze the real structural capacity of these coupling beams. Carbon fiber reinforced polymer (CFRP) is chosen as the reinforcement material for the upper part of the beams. A total of three specimens are tested, two of them under cyclic quasi-static load to determine the flexural capacity of the cross section in the interface wall-coupling beam, and one of them under monotonic loading to determine the shear capacity of the cracked cross section. The results of the cyclic test showed a very limited contribution of the CFRP in the flexural capacity when the fiber is in tension. However, the flexural behavior of the section with the lower reinforcement in tension is not affected by the upper non-anchored bars and showed a flexural capacity and energy dissipation according to the existing rate of the steel reinforcement. The experimental results are used to develop a finite element model which reproduce the structural behavior of the beams with the construction error.

Flexural behaviour of RC beams strengthened using hybrid combination of CFRP laminates and UHPC overlay

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There is an urgent need for practical and durable rehabilitation solutions for deteriorated concrete elements. Various reasons for the deterioration of reinforced concrete beams include vehicular loading, cracking, delamination of cover concrete, and corrosion of internal reinforcement. The overlay using ultra-high-performance concrete (UHPC) is an effective strengthening technique for deteriorated beams for service life extension. UHPC offers advantages like superior mechanical properties, higher durability and lower permeability. In some situations, concrete beams are strengthened to accommodate the additional loading. Combining UHPC overlay with FRP strengthening can effectively improve durability and increase the strength of RC beams. In this study, four large-scale reinforced concrete (RC) beams of 300 x 300 x 3500 mm are tested to evaluate the flexural performance of control and strengthened beam specimens. The test matrix consists of a control RC beam (RC), a beam strengthened using UHPC overlay (UO), a beam strengthened with a hybrid combination of CFRP fabric and UHPC overlay (HB_UO+F), and a beam with a hybrid combination of CFRP laminates and UHPC overlay (HB_UO+L). All the strengthened specimens had higher strength and stiffness. However, the hybrid combination improves the flexural capacity and ductility compared to the UO specimen. Due to the addition of overlay and the additional tension reinforcement in the form of CFRP laminates, the increased lever arm led to good strength improvement of the hybrid strengthened RC beams.

Partial reconstruction and lengthening of a continuous post-tensioned concrete bridge deck: case study of emergency rehabilitation of the Seaward Road Bridge after partial collapse

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This case study demonstrates the surprising extent to which a large, continuous, prestressed concrete bridge can be taken apart, modified from the original design and rebuilt. Elements may in some cases be re-used after a structure is damaged, or when major modifications are required. The option of re-using structural elements is much more environmentally sustainable and creates opportunities for large cost-savings and time-savings. The case study also demonstrates how modification of existing structures is fraught with risks and technical challenges, many of which may be difficult to anticipate. Major challenges in this case included: (1) supporting a structure with an unusually high global instability through extreme and ongoing variations in loading and displacement, (2) demolishing deck spans of a concrete bridge suspended over a sensitive waterway through ongoing flood events, (3) meticulously quarrying out and exposing prestress couplers buried deep in existing reinforced concrete, so they could be safely reused, (4) custom modifying and testing bespoke prestress components, (5) applying a precisely limited prestress force to the new deck spans, to account for the age-related differences in concrete behaviour, and increase in length, of the reconfigured bridge. It is also a case study for how environmental sustainability concerns can be addressed in multiple different ways in any project. In this case: (1) salvaging and reusing undamaged portions of a concrete bridge instead of wastefully demolishing and rebuilding from scratch, (2) avoiding disturbance of a sensitive natural environment by keeping demolition and its associated pollution and physical damage footprint, to a minimum, (3) recycling all material from components that were irredeemably damaged, and (4) addressing existing issues that were negatively effecting the environment in the vicinity of the site. The project emphasises how close coordination between the client, technical design team and contractor are critical to effectively managing complex risks and challenges.

CFCM for strengthening potentials

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FRP (Fibre Reinforced Polymer) composite materials are possessing many advantageous properties (e.g., high tensile strength), however the matrix has relatively low resistance to high temperature. To mitigate the decrease of mechanical properties, a new carbon fibre reinforcement has been developed (patented: PCT/HU2017/050010) where the matrix is cement based. The patent owner calls it CFCM that is Carbon Fibre reinforced Cementitious Matrix. This new material shares some similarities with the FRCM (Fibre Reinforced Cementitious Matrix) technique. This extended abstract provides introductory information about the possibility to use this new material in strengthening application, by focusing on the most important material properties based on a national research project. In particular, the initial steps of the development of this new composite material.Properties of the CFCM reinforcement are very much dependent on the fibre ratio that is limited by the grain size of the cement. If high enough fibre volume ratio is reached, the high strength and modulus of elasticity of carbon fibres provide exceptional material properties both as strengthening application and internal reinforcement for structural concrete, while having better fire and corrosion resistance than traditional steel or FRP reinforcement.

4.4. Service life extension: methods and materials

Numerical study of galvanic anode systems used for patch repair of reinforced concrete structures

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Cathodic protection (CP) is a common electrochemical repair technique for reinforced concrete (RC) structures. Due to the comparably high resistivity of the concrete, serving as electrolyte, impressed current cathodic protection (ICCP) is predominant today. Nevertheless, the market provides a wide range of galvanic anode systems for RC structures. Their most common use is the application within the framework of partial concrete replacement due to chloride-induced corrosion. This patch repair is often accompanied by the so-called anode ring effect, causing accelerated corrosion of the rebar in the substrate concrete in the vicinity of repair patches. This is caused by the cathodic capabilities of the repassivated rebar. Galvanic anodes are reported to prevent this effect. In the course of this work, laboratory investigations regarding the polarization properties of different galvanic anode systems have been conducted. Furthermore, a numerical model is proposed, which is capable of predicting the effectiveness of the investigated anode systems for different on-site situations. The method is presented for a specific set of input parameters and the applicability is discussed against the background of different protection criteria, such as the compliance with the 100mV decay criterion, the suppression of macrocell activity or an electrochemical cloaking of the repair patch.

Current distribution and throwing power of galvanic cathodic protection with discrete anodes in reinforced concrete beam or column elements

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Galvanic cathodic protection (GCP) of steel in concrete by means embedded discrete anodes is a commonly used repair method to reduce or prevent steel reinforcement corrosion. The design and efficiency of the system depends greatly on the corrosion activity of the steel reinforcement and electrical resistivity of the concrete. In this research, the influence of chloride concentration and cement type in the concrete on the current distribution and throwing power of GCP with discrete anodes is investigated for linear concrete elements such as beams or columns. Results show a high throwing power (> 500 mm) of the GCP system for concrete with a CEM I cement (low resistivity) and limited chloride contamination. For concrete with a severe contamination of chlorides (2 m% by mass of cement) or high electrical resistivity (e.g. by the use of CEM III/A cement), the throwing power is greatly reduced to values of 60 mm and 110 mm, respectively. Consequently, based on the 100 mV depolarization criterium (EN ISO 12696:2016), GCP with discrete anodes was found to be most efficient for concrete with relatively low resistivity and limited corrosion activity of the steel reinforcement (related to chloride concentration in the concrete).

Field performance of hybrid and galvanic anodes in reinforced lime concrete heritage structure using electrochemical studies

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Sacrificial Anode Cathodic Protection (SACP) system or galvanic anode is a proven method to control corrosion in reinforced concrete structures. Upon installation, they shift the potential of reinforcing steel by catholically polarizing it and prevents further corrosion. Hybrid anodes are a recent advancement to this system. Initially it provides an impressed current which aids the repassivation of steel, after this phase it functions as a galvanic anode. Less field studies are performed to assess the long-term performance of anodes and to identify the changes that occur at steel concrete interface with cathodic protection. This paper focuses on a pilot study conducted on a 100-year-old reinforced lime concrete structure which has undergone frequent repair in the past due to low pH corrosion. In the study, two types of anodes (galvanic and hybrid anodes) were installed and their performance was monitored for 3 years. The electrochemical data obtained over the period was analysed to assess the performance of anodes and to compare their performance for a heavily corroded system. Microstructural studies were also performed at the steel concrete interface to validate the results obtained from the electrochemical studies.

A rapid test to screen the functionality of galvanic anodes for cathodic protection of reinforced concrete

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Galvanic anodes are increasingly popular in the repair, rehabilitation, and maintenance of reinforced concrete structures suffering from chloride-induced corrosion for the added durability benefits. There is a consensus among engineers that demand will increase due to ageing infrastructure stock, climate change, and the option to reuse structures which is a logical solution to help reduce carbon emissions. New manufacturers will likely emerge to meet the needs of a growing market. However, there is no standard for galvanic anodes for use in concrete. In theory, products may come to market that fails to work as anodes, and hence corrosion may not be arrested, and repeated intervention could be required. This paper presents a methodology that has been developed for demonstrating anodes function as intended in a short-term test. Anodes were cast into concrete, and drive voltage, resistivity, and resultant current were measured when connected to an external cathode. The test setup was applied to several commercially available galvanic anodes. All anodes achieved a current output of 0.35 mA in this experimental setup. This could provide a rapid test to screen anodes new to the market. The analyses show inherent anode behaviour varied with different manufacturers, and there were also performance differences among replicate anodes. Such behavioural characteristics may affect the long-term performance of the anodes. These results provide new data on galvanic anodes and demonstrate the potential need for standardisation in the industry.

Ion distribution in concrete overlay, mapped by laser induced breakdown spectroscopy (LIBS), modified by an embedded zinc anode

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Galvanic corrosion protection by embedded zinc anodes is an accepted technique for the corrosion protection of reinforcing steel in concrete. Galvanic currents flow between the zinc anode and the steel reinforcement due to the potential difference that is in the range of a few hundred mV. The ion distribution was studied on two steel reinforced concrete specimens admixed with 3 wt.% chloride/wt. cement and galvanically protected by a surface applied EZ-anode. On both specimens, a zinc anode was embedded and glued to the concrete surface by a geo-polymer-based chloride-free binder. At one specimen, the EZ-anode was operated for 2,5 years, the EZ-anode at the other specimen was not electrically connected to the reinforcement, this specimen serves as a reference. Both specimens have been stored under identical conditions. The ion distribution between the anode (EZ-ANODE) and cathode (steel reinforcement) was studied by laser-induced breakdown spectroscopy (LIBS) after 7 months, 12 months, and 2,5 years. Results of the LIBS studies on the specimen with activated EZ-anode after 7 months, 12 months, and 2,5 years and of the reference specimen after 2,5 years are reported. Results show that diffusion of ions contributes to the changes in the ion distribution but migration, especially of chlorides towards the EZ-anode is significant despite the weak electric field – several hundred millivolts - generated by the galvanic current. Results show that chloride ions accumulate near the zinc-anode as in water-insoluble zinc-hydroxy chlorides - Simonkolleit.

The performance of cement-based coatings for drinking water reservoirs: a case study

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Drinking water reservoirs are often made of cementitious materials. The inorganic mineral phases exhibit a similar chemical composition as the natural rocks. This enables the concrete in contact with drinking water to be a safe material with respect to the human health. The carbonate or the free-CO^2 content of the water control the extent of the concrete deterioration. To increase the durability, cement-based mortars are applied as a coating. In this work, the damage on site and in laboratory, such as bubbles, cracks and microcracks formation, leaching effects and detachments of three cement-based coatings were investigated. The coating systems exhibited conventional mechanical parameters, such as the compressive and flexural strength, but a different behavior with respect to the cracks formation. This fact was dependent from the coating thickness, application features, water content, superplasticizer dosage, environment parameters and mortar quality. The damage was less related to the mechanical properties, in

particular the compression strength. The coatings generally exhibited a dense compact microstructure. The addition of superplasticizers promoted the segregation of the aggregates. The fine particles were concentrated along the surface layers, which in turn, were more susceptible to the environmental changes. The coatings adhesion strength was always above 2 N/mm^2 for the coatings tested in laboratory. A reliable and acceptable adhesion that increased the durability.

Practical service life assessment and rehabilitation strategy development for hyperbolic shell natural draft cooling towers

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Years of service in industrial plant operating environments can cause varying types and degrees of concrete deterioration on reinforced concrete hyperbolic shell natural draft cooling towers. Exposure to plant operating cooling water can potentially result in concrete material erosion and corrosion of embedded reinforcing steel and associated concrete delamination and spalling over time. Such deterioration can affect the integrity of the structure to the degree that repair programs are required to reliably maintain the towers for their required service life. Condition assessment of natural draft cooling towers is challenging due to their massive size, hyperbolic geometry, and plant operational considerations (i.e. schedule, risk and cost). A case history is presented illustrating a rational and targeted investigation approach that included a combination of field condition survey, laboratory materials testing, consideration of operational constraints, probabilistic-based concrete deterioration service life modeling, and structural analysis. Existing degradation as well as predicted conditions from service life modeling informed structural analyses that were performed to identify risk-based limit states over time. The multi-faceted approach provided information critical to understand degradation mechanisms, characterize structural health, and develop prioritized repair strategies to obtain the desired service life extension.

The environmental impact of service life-extending repair for corrosion damaged reinforced concrete balconies: a case study in a coastal context

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Nowadays a vast number of concrete structures are approaching the end of their expected service life. The need for sustainable rehabilitation (maintenance and repair) is urgent and due to the expected deterioration of buildings and civil structures, there will be a great need for preventive and/or curative interventions in the near future. More than 2/3 of the damage to reinforced concrete structures is linked to reinforcement corrosion, which can affect the durability of the structure and the residual load-bearing capacity. With the necessary transition towards a circular economy and the Sustainable Development Goals in mind, it is important to deviate from considering only the technical requirements and initial costs during the design of concrete structures. Hence, the environmental impact over the entire life cycle and the intended service life extension need to be considered as well. A typical residential building in a Belgian coastal environment with damaged reinforced concrete balconies is selected as case study to evaluate different frequently used repair techniques (i.e. patch repair, conventional repair, galvanic cathodic protection, impressed current cathodic protection and total replacement) by means of a life cycle assessment. Several sensitivities are mapped by analysing the influence of the intended service life extension, the volume and configuration of the construction, the repair mortar composition and the application of coating/waterproofing. It was stressed that these uncertainties could have a substantial effect on the environmental impact and highlight the domains where further research is needed (e.g. assumed life span and composition of repairs). Due to this manner, it is not possible to identify one environmental optimal repair method. However, for a short service life extension (e.g. 5y) small interventions like patch repair seem to be more sustainable while methods like cathodic protection and conventional repair are preferable for longer service life extensions (e.g. 40y).

Extending the service life of existing concrete structures to last beyond 100 years

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New bridges and other concrete structures are being built using the design concepts presented in SHRP2 R19A (Bridges for Service Life Beyond 100 Years: Innovative Systems, Subsystems, and Components) and FIB Bulletin 34 (Model Code for Service Life Design) to achieve 100+ year service life. Existing concrete structures may not have been built with a specific design service life in mind but the principles of SHRP2 R19A can be used to maintain and extend the service life of existing concrete structures. Application of these principles and methods can extend service life by mitigating corrosion of embedded reinforcing steel by over 80%. Extending the service life of existing reinforced concrete structures provides many benefits to structure owners and society. Direct benefits include cost savings for owners and a general reduction in disruption to the public caused by repair and replacement. Extending service life also provides many indirect benefits including; reduction in the use of materials, reduction in the generation of demolition waste, reduction of environmental emissions, and the protection of sensitive habitat and existing ecosystems. This paper presents case studies which illustrate how the SHRP2 R19A protocol was used to design durable repairs to extend service life of existing concrete structures and the direct and indirect benefits which were achieved. Service life extension of existing reinforced concrete structures is a sustainable practice and should be encouraged.

Galvanic corrosion of prestressed strands in re-grouted post-tensioned concrete systems

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Grouted post-tensioned (PT) concrete systems are widely used to construct long-span segmental bridges with a target service life of 100+ years. However, the usage of poor-quality grout materials and improper construction practices have resulted in the formation of unwanted voids in the duct, which in turn led to premature corrosion (say, within about 20 years) of strands and failure of PT systems. Also, the regrouting/repairing of void regions have led to localized corrosion of strands at the interface between the dissimilar base and repair grout. This study aims to quantify the possible corrosion mechanisms at the void region in a PT system re-grouted with a dissimilar grout. The formation of bleed water and soft grout and the carbonation resistance of the Site-Batched-Grout (SBG) was evaluated. Prestressing steel wire test specimens simulating the re-grouted tendons with interfaces comprising the base and repair grouts were made. The base grouts were carbonated at a 3% CO_2 environment, and the depassivation of the prestressing steel wire was quantified using Electrochemical Impedance Spectroscopy (EIS). The macro-cell current (galvanic current) was determined between the portion of steel in the base grout and the repair grout at various humidity conditions. The findings imply that there can be possible corrosion due to the galvanic coupling of the metals embedded in the base grout and the repair grout due to the variations in pH, porosity, and chemical composition, which initiates the macro-cell formation.

Long-term performance parameters influencing the service life of galvanic anodes in reinforced concrete systems

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Galvanic anode cathodic protection is a promising electrochemical repair technique to control corrosion of embedded steel in reinforced concrete systems. However, laboratory tests have proven that poor-quality anodes that may stop functioning after about 3 to 5 years are being used in many projects – leading to repeated repairs. This work focuses on assessing the long-term performance and understanding the degradation/failure mechanisms of galvanic anodes in cementitious systems. Three commercially available galvanic anodes with different encapsulating mortars and different surface area and mass of anode metal were subjected to a recently developed Galvanic Anode Performance (GAP) test. The minimum service life, SL_{min}, of the galvanic anodes was estimated based on Faraday's law and the total charge supplied. Physico-chemical characteristics such as pH and the pore size distribution of the encapsulating mortar of the virgin galvanic anodes were determined. The long-term performances of the galvanic anodes were correlated to the physico-chemical characteristics of the virgin galvanic anodes. In addition, an attempt was made to understand the Physico-chemical modifications at/near the interface between the anode metal and encapsulating mortar. For this, special profiles of the physico-chemical characteristics of the encapsulating mortar of the aged galvanic anodes were determined. The degradation/failure mechanisms of the galvanic anodes in cementitious systems have been conceptualized.

Performance assessment of galvanic anodes in cathodic protection systems in reinforced concrete structures

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Cathodic protection (CP) using galvanic anodes is a proven electrochemical technique that can enhance the service life and reduce the life cycle cost of reinforced concrete (RC) structures. Over the past decade, there has been a significant increase in the usage of galvanic anodes for various repair projects. However, this increased demand led to the circulation of poor-quality galvanic anodes in the market. Presently, the performance of galvanic anodes in RC systems is assessed using certain criteria specified in the EN ISO 12696. However, there are contradicting arguments on using these criteria for concrete systems, as they are derived from experiments conducted in the 1940s on metals in low resistive electrolyte systems, such as seawater or soil. Hence, there is a need to understand the suitability of EN ISO 12696 in assessing the performance of galvanic anode CP systems. Therefore, this study considered galvanic anode CP systems installed in two RC structures and investigated the polarisation shift induced by the anodes to steel rebars. The instantaneous performance of the CP system was assessed by conducting frequent depolarization tests for 2.5 years. It was observed that 100 mV polarisation shift was not always achieved, especially when the corrosion rate of steel is less than 2 mA/m^2 – indicating that the criterion is not suitable if the rebars attained passivity.

5. DEVELOPMENTS IN CONCRETE TECHNOLOGY, ASSESSMENT AND PROCESSING

Feasibility of using clays from Southeast European deposits in limestone calcined clay cements

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Recently, the cement industry has faced new challenges in addition to the environmental constraints of the last decade. The decline in availability and current inconsistent prices of common supplementary cementitious materials (SCMs), such as by-products from the iron industry or coal-fired power plants, have opened the search for more reliable materials. Research on cements containing calcined clays now serve as a possible solution to the forementioned problems. Clays containing the mineral kaolinite in sufficient quantities, when calcined and mixed with limestone powder, produce hydration products that can improve the strength and durability of concrete. In addition, the production of limestone calcined clay is reported to be less CO_2 intensive, but this eco-efficient solution is viable only if the materials are locally available. For this reason, this study investigates the possibility of using natural clays from the Southeast European region (SEE) as cement replacements. A systematic experimental study was conducted on 18 different clays from 13 different deposits to determine the physical and mineralogical composition of the raw clays, their reactivity and mortar strength. The results were then related to the environmental contributions they might have in comparison with ordinary Portland cement in concrete.

The investigations on properties of self-healing concrete with crystalline admixture and recycled concrete waste

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The concept of self-healing concrete is becoming more necessary as sustainability in construction is more desirable. Amongst the current solutions in this technology are autogenous, chemical, and bacterial self-healing. It is paramount that secondary raw materials be used in the production of self-healing concrete as a form of a sustainable solution. Therefore, in this paper, the admixture “Betocrete-CP360-WP”, which is a crystallizing waterproofing admixture with hydrophobic effect and is 100% recyclable, has been used and its effect on the physical, chemical, and mechanical properties of concrete, as well as self-healing capabilities of concrete, have been determined. According to the obtained results, the crystalline additive “Betocrete-CP-360-WP” has no effect on density and slightly increases the amount of entrained air in the concrete mix. However, it does decrease the workability of the concrete mixture which could prove problematic in transportation to the construction site or in concreting in general. Also, with the crystalline admixture in the concrete mix, a 60% reduction in concrete compressive strength after one day of hardening has been estimated, but after 7 and 28 days, the strength attained is within the ranges of the control samples. In addition, concrete containing Betocrete-CP360-WP was 30% less water permeable as compared to control samples. The self-healing efficiency of the concrete was determined by a water flow test through a formed crack (approximately 0.35 mm wide). This was done by gluing a plastic pipe to the top of the cracked concrete specimens and maintaining a constant pressure of the water in the pipe. The experiment was continued for 28 days, and the crack self-healing efficiency of the concrete was calculated from the differences in the amount of water passed through the crack before healing and after 7, 14, 21 and 28 days of the healing process. After 28 days of the water flow test, the cracks in the concrete with the crystalline admixture and recycled concrete dust were completely healed, while the control specimens were not.

Interactions between hydrated cement pastes and aggressive ammonium: experimental batches characterization

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Agricultural and food industries concrete facilities face chemically aggressive conditions that can damage their microstructure and reduce their lifespan. They are particularly exposed to ammonium-rich environments from natural microbial activity. The poorly crystalline mineralogy of hydrated cement pastes, the compositional variability of the phases and their reactivity make the geochemical behaviour of such materials difficult to investigate and predict over both large periods of time and wide variety of chemical compositions. This work aims (i) to assess the stability of the cement phases involved in ammonium-rich conditions as well as to identify the alteration products, and (ii) to understand the mechanisms and intensity of alteration. To do this, experiments were carried out both on OPC paste powder and on monolithic OPC pastes, degraded by an ammonium nitrate solution in semi-batch conditions. The powder was gradually added to the aggressive solution while the monoliths were immersed for 16 weeks in regularly renewed solution. The pH and the concentration of the chemical elements in solution were monitored over the experiments. The microstructural, chemical and mineralogical changes of the samples were analysed by scanning electron microscopy, electron probe micro-analysis and X-Ray diffraction and showed phenomena of dissolution, leaching and carbonation.

Stability of synthetic calcium silicates hydrates in chemically aggressive conditions

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Concrete strategic structures, such as dams, water pipes, and effluent management facilities, are often subject to conditions that can be chemically degrading (leaching, organic compounds, acid attacks, etc.). A good understanding of the degradation mechanisms of concrete is therefore necessary to improve the durability of these facilities. In recent years, numerous degradation phenomena have been characterized according to the chemical and/or biochemical systems to which cementitious pastes can be subjected. Decalcification, among other, plays a central role in the mechanisms that have been identified. Due to their composition, Calcium Silicate Hydrates (C-S-H), which can constitute up to 70% by mass of a hydrated cement paste and which are largely responsible for their mechanical resistance, are very sensitive to decalcification.

Influence of alkali content and silica modulus on the carbonation kinetics of alkali-activated slag concrete

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Carbonation is inevitable process during the service life of concrete structures, where CO_2 causes decalcification of the calcium-bearing phases. These changes affect the durability of concrete and accelerate the corrosion of reinforcement. Alkali-activated materials (AAMs) are alternative, cement-free binders based on aluminosilicate rich precursor and alkaline activator. The interest in AAMs increased during the last century, due to the production process with low CO_2 footprint comparing to Portland cement (PC) concrete, the possibility to use wide range of industrial by-products as precursors and comparable performance to PC concrete. Despite the extensive research in this field, the carbonation resistance of AAMs needs to be better understood, due to the differences and complexity of binder chemistry compared to PC concrete. The propagation of carbonation process will depend on chemical composition of the precursors and the type and dosage of activators. This paper presents the results of microstructural changes of three alkali-activated concrete mixes after exposure to accelerated carbonation. Ground granulated blast furnace slag was used as a precursor and sodium hydroxide and sodium silicate as activators. Three mixes have constant water to binder ratio and slag content, while alkali content and silica modulus were varied. The carbonation resistance was evaluated by testing carbonation depth after 7 and 28 days of exposure in carbonation chamber. Microstructural changes during carbonation were investigated by thermogravimetric analysis and mercury intrusion porosimetry.

High-performance reactive magnesium cement incorporating hollow natural fiber and silica sand

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Global warming caused by CO^2 emissions makes reactive magnesium cement (RMC) increasingly attractive due to its ability to sequester CO^2, however, the diffusion of CO^2 in RMC is severely limited by the dense hydrated magnesium carbonates (HMCs) formed on the outer layer. This work utilizes hollow natural fiber (e.g., sisal fiber) to facilitate the diffusion of CO^2 into the deep part of the RMC specimen. Combining with adding silica sand as a filling agent, the mechanical strength can be enhanced from 42.4 MPa of the control group to 92.6 MPa of the specimen with 2 vol.% sisal fiber, this is attributed to that the addition of sisal fiber significantly enhances the carbonation depth. FTIR and XPS results further prove that the addition of 2 vol.% or more sisal fiber can improve the carbonation degree by over 200%, leading to a sharp reduction of CO^2 emission from 37 kg/(m^3 MPa) of the control group to 12.1 kg/(m^3 MPa) of the specimen with 2 vol.% sisal fiber. Therefore, adding hollow natural fiber and silica sand to RMC can be a promising approach to make RMC stronger and more sustainable.

Quantified point clouds and enriched BIM-models for digitalised maintenance planning

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Digitisation in the construction industry continues to advance and, together with the increasing dissemination and further development of hardware and software, is steadily opening up further opportunities for innovative ways of working. Building Information Modelling (BIM) is currently becoming the standard for new construction but has not yet been optimised for use in existing buildings. Therefore, the Institute of Building Materials Research (ibac) is researching new methods and possibilities for BIM-based building preservation. In this paper, the automated creation and analysis of point clouds as well as the implementation of further information from in situ diagnosis and monitoring systems in BIM-Models are presented. On a practical example, the different steps of a subsequent digitisation of an existing building are demonstrated considering new possibilities as autonomous robots and the intelligent utilisation of sensors and diagnostics tools. The goal is a decision support tool, which is independent from proprietary software, adaptive to different types of buildings and open for various interfaces. Current results show that quantifying point clouds and making BIM-models usable beyond the planning and execution phase for new buildings are essential steps for the digitisation of building maintenance. The proposed digital workflow holds great potential for effective building diagnoses and efficient service life management.

Case Study: implementation of photoluminescent polymer concrete elements on bridge and infrastructure projects

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Phosphorescent particles are excited to a higher energy state during exposure to light which is released over time by decaying to a lower energy state. This form of Photoluminescence has been achieved in various materials by incorporating phosphorescent particles that store and slowly releases the light energy, that passes through it. Due to its opacity, implementation of photoluminescence in concrete has been constrained to architectural and decorative applications such as exposed aggregated concrete finishes. By incorporating phosphorescent particles into polymer concrete and through the development of photoluminescent polymer concrete, various other applications are possible in concrete infrastructure projects. This study presents the development of a photoluminescent polymer concrete used to improve pedestrian safety on a concrete pedestrian bridge. The luminance and decay time were used to determine the optimal dosage of phosphorescent particles. Mesopic vision, and standard photoluminescent safety signage parameters, were used to evaluate the luminance performance as it reduces with time. The luminance performance, and decay time, of the photoluminescent polymer concrete elements, significantly exceeded the standardized requirements for photoluminescent safety signage. Through this case study further applications for incorporating photoluminescent polymer concrete elements into concrete structures are realised, to improve pedestrian and user safety, especially where electrical lighting is not feasible or when a more sustainable and less invasive lighting solution is required.

Design of smart cementitious composites based on multi-walled carbon nanotubes (MWCNTs) using probe ultrasonicator for dispersion

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The purpose of this study is to develop smart cementitious material by incorporating multi-walled carbon nanotubes (MWCNTs). Two different types of carbon nanotubes (CNT) were dispersed using probe ultrasonicator; (i) Pristine CNT (P-CNT), and (ii) Functionalized CNT through annealing (A-CNT). Percolation threshold and optimum content of CNTs were determined by measuring electrical resistivity, porosity, compressive and flexural strengths at various contents of CNTs (0, 0.5%, 0.75%, and 1% with respect to mass of cement). Self-sensing study was also carried out on smart material by relating the electrical properties with cyclic compressive loading. For this purpose, the electrical response was recorded with Wheatstone Bridge (WSB) circuit. The effect of curing and saturation degree of specimens on the resistivity pattern was also discussed. The results of electrical resistivity and mechanical properties showed that the content of CNTs should be at least 0.75% to develop smart cementitious materials with a significant sensitivity and without detrimental effect on the mechanical properties. Moreover, smart material incorporating pristine CNT provides better sensitivity of self-sensing response as compared to the annealed CNT. Self-sensing test results also showed that with the increase in the content of CNT, sensitivity and repeatability of the sensing response were improved.

Early age properties of high-performance concrete

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High Performance Concrete is used to not only minimize the environmental footprint of the cement and concrete industry, but also to enable the design and rapid construction of taller and more slender structures. Despite the significant change in concrete property requirements, the properties of concrete as used during design of concrete structures are mostly still based on 28-day water cured compressive strength, stiffness, long term drying shrinkage and creep. The relevance of these measured properties on the actual behaviour of the structure should be questioned as high strength concrete is known to have low water/cement ratios resulting in significant early age shrinkage, which is currently not taken into account by designers. This paper is based on a study where the early age properties of concrete was investigated, with specific focus on the first 24 hours after casting. The effect of factors such as low water/cement ratio, admixtures, ambient and material temperatures, shutter type and cast volume on properties such as setting time, early age shrinkage, strength development and stiffness was studied and observed trends discussed in this paper.

The tensile deformation and capillary pressure build up in fresh concrete

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During the plastic state of concrete, any hindrance or resistance of the free volume change in plastic concrete induce tensile stresses and or strains in the concrete element. Crack formation is expected to occur if the tensile stress and strain is greater than the capacity of the concrete. Investigation into the tensile properties and relaxation behaviour of plastic concrete was carried out using a direct tensile testing machine. The capillary pressure was measured during the tensile tests in low evaporation conditions, as well as in a climate controlled chamber where the concrete was exposed to high evaporation conditions. Most of the measured strength gain (tensile capacity) of the concrete is due to the capillary pressure in the pores of the fresh concrete which keeps the particles together by means of free water in the concrete during the early stiffening phase of the concrete. Later the hydration products bridge the pores which provides strength to the concrete. The capillary pressure results indicate how the rate of hydration influence the interconnectivity of the pores, and the contribution to the measured strength gain of the fresh concrete. The capillary pressure measurements during tensile tests revealed that the mechanism behind relaxation is the negative capillary pressure build-up induced by the mechanical tensile strain. The results also showed a correlation between the build-up of the capillary pressure in the concrete and the tensile deformation of the fresh concrete where the capillary pressure increased as the tensile load increased.

Effects of high and very temperatures on blast furnace slag concrete

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The performed research work focused on concretes containing different proportion of cement and blast furnace slag (Merit) (90/10, 50/50, 10/90). Test samples were exposed to temperature ranging 400°C and 800°C. The result of the study shows residual compressive strength, weight loose, residual colour change and morphology in a concrete structure exposed to high temperature. Results can give an idea about the effect of high temperatures on the properties.

Using simple soil water content sensors to measure water availability in fresh concrete

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Preventing plastic shrinkage cracks improves the durability of concrete. This is because plastic shrinkage cracks serve as pathways by which corroding agents can penetrate concrete. Freshly cast concrete is a saturated mixture of reactive and non-reactive materials. As water moves out of the concrete mass and as water is used in the hydration process, the free water in the mixture reduces. Eventually, the mixture can be considered to be unsaturated. In this research project, the viability of using soil water content sensors to measure the change in water availability in concrete from fresh state to early-age was explored. The soil water content sensors measured dielectric permittivity. The dielectric permittivity, cumulative evaporation and setting time of mortars with varying water/cement ratios were tested. It was found that the dielectric constant was influenced by changes in fresh mortar and that the sensors have the potential to qualitatively monitor cement content, bleeding, hydration and evaporation. Further work is required in this field.

Effectiveness of concrete curing compounds in extreme windy and dry conditions

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Curing is one of the most crucial phases of concrete conditioning as it determines not only the long-term strength, but also influences the durability. Curing compounds are useful for reducing the evaporation rate of water from the concrete surface. They are typically sprayed on concrete as soon as possible after consolidation, especially for concrete members that have large areas exposed to the environment. These compounds have been proven to work well, however, how effective are different curing compounds in a variety of high wind and high temperature with low relative humidity conditions? The focus of this work is the effectiveness of different types of curing compounds at windy and dry conditions. The tests were done in a state-of-the-art Mobile Climate Chamber (MCC) where the weight of all samples was measured constantly to determine the water loss. It was concluded that the resin-emulsion based curing compound performed best at all environmentally tested conditions. The acrylic-based curing compound performed worse than the control, where nothing was applied to the top surface.

Preventing plastic shrinkage cracking by monitoring the capillary pressure build-up in self-compacting concrete

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Plastic shrinkage cracking is a problem for the service life, aesthetics and durability of concrete members. It occurs when tensile stresses are induced in fresh concrete, through plastic shrinkage that is restrained. Plastic shrinkage is caused by negative capillary pressure build-up, but the capillary pressure of fresh concrete can be controlled to prevent plastic shrinkage. In this paper, the control of capillary pressure to prevent plastic shrinkage cracking using high-capacity capillary pressure sensors is explored. The capillary pressure behaviour of a self-compacting concrete mix design in various evaporation rates was determined. Capillary pressure boundaries for concrete wetting to relieve tensile stresses were identified. The effectiveness of wetting fresh concrete at a predefined capillary pressure boundary was investigated.

Investigation of the influence of fine recycled sand on the setting behaviour of cement when used as supplementary cementitious material (SCM)

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The building materials industry makes a major contribution to greenhouse gases emitted each year, particularly by the cement clinker production. Therefore, the aim should be to maintain an increased part of building material from demolition sites in the material cycle. The use of the fine material (< 2mm) from demolition waste in concrete has so far proved to be problematic due to the increased water demand and loss of compressive strength. One approach is the use of recycled concrete powder (RCP) as supplementary cementitious material (SCM). Demolition material used in this study has been obtained from discarded railroad sleepers and pre-crushed as sand (< 4 mm). The recycled sand was subjected to a mechanical and thermal activation process before use, then was ground to a particle size <63 µm and then fired at 4 different temperatures (750°C, 800°C, 850°C, 900°C). The aim was to convert parts of the hydrated C-S-H structure back into reactive silicate phases through firing process. They can contribute again to the hydration process when used as supplementary cementitious material. The ground and thermally treated material - called SCM - was examined for their physical and chemical properties. Subsequently, 10 and 20 Vol.-% were replaced by the SCM in a binder mixture, respectively. In a first step, the different water demand of the binders was documented. Ultrasonic methods were used to investigate the stiffening and setting behaviour of the binders. The decisive factor here was the proportion of chemically bound water in the binder mixtures. Finally, the mechanical properties of the binders were investigated in mortar tests. Acceptable compressive strengths were achieved compared to the reference mortar (mortar mixture without cement substitution). At first glance, it seems possible to use it as an SCM.

Application of mine tailings sand as construction material – a review

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Tailings are found during the exploration and processing of mineral ores. They contain a mixture of grounded rocks, processed effluent, and some trace elements that have the potential to damage the environment. Recent urbanisation has led to a large stockpile of tailings in many mining environment constituting health hazard. It becomes very important to develop disposal techniques that will reduce the huge mountain of tailings in mining environment. One of such method is the application of tailings in sustainable concrete production. It is shown that physical and chemical characteristics of tailings are comparable to crusher sand used in engineering construction and therefore, tailings can be used to partially replace sand in bituminous and concrete mixtures. In this review, specific interest has been given to iron, copper, and gold tailings, this is due to their dominance in mining areas of Kwa-Zulu Natal province of South Africa.

A novel approach for the consolidation of sand by MICP single treatment

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Saving natural resources has become increasingly important. In construction, research has been done on alternative methods to replace conventional building materials. One of those novel methods is MICP (microbial induced calcium carbonate precipitation). In this process, calcium carbonate crystals are precipitated with the help of ureolytic bacteria. A cementation solution consisting of urea and calcium salt is used. This precipitation can be used for solidification. In the field of MICP research, there exist multiple publications with several kinds of tests, but no verifiable compressive strength test. However, most researchers are concerned with soil improvement or self-healing methods, to fill cracks in concrete. Similarly, column tests are mainly conducted to investigate the strength. This study presents, a new method of strength assay that uses hardened sand samples of 3 cm edge length. This allows for an accurate compressive strength verification and thus the effect of the biocementation treatment. In addition, this method applies a single treatment method with a novel type of formulation of the MICP components. The results show that a single MICP treatment is sufficient for the consolidation of various sands. Compressive strength of up to 1.8 N/mm^2 was achieved in the process tests in the uniaxial strength test.

Towards sustainable building materials through lithium silicate densifiers

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Nowadays, the building industry entering an era where durability and sustainability of materials are considered more important than high early strength and high speed of construction. From this point of view, surface treatment technology has become an integral part of concrete structures preventing their damage in aggressive environments, which leads to a significant extension of service life. One of the usual inorganic treatment methods is realized with silicate solutions known as waterglasses. It has been proven that their action mechanism lies in the initiation of new C-S-H gel formation that blocks capillary pores in concrete surfaces resulting in increased hardness and impermeability. In most cases, sodium and potassium silicates are referred to as cheap and widely used densifiers. In addition to those already mentioned, the popularity of lithium silicates has been growing in market share. The beneficial effect of lithium-based compounds lies in preventing alkali silica reaction as well as a potentially lower tendency to efflorescence. However, the efficiency of lithium based densifiers is affected by many factors. The aim of this study is to summarize and evaluate the main chemical and physical characteristics, which should be taken into account in their application that will allow unlocking a more effective way for concrete treatment.

5.1. Fibre reinforced cementitious materials

A textile reinforcement method for 3D printed concrete

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The reinforcement of 3D printed concrete elements has proven to be a significant challenge that needs to be addressed. However, before reinforcement can be applied, the behaviour of the consequent composite materials must first be studied. This study, therefore, investigates the macro-mechanical behaviour of AR glass fibre textile material as reinforcement in terms of its flexural performance, to determine whether it is a feasible solution. During this study, elements, consisting of four layers, are printed flat on the surface bed of the printer and are reinforced by a textile mesh in between subsequently printed layers. The specimens are reinforced at different locations, with different geometrical orientations as well as different filament orientations, and are then compared. The flexural performance is quantified by conducting four-point bending tests 28 days after printing. The results of the tests show that by adding this specific mesh, the average flexural strength of the elements increases significantly. Furthermore, elements with the warp yarns aligned with the printed filament have increased flexural strength. During the testing, it is also discovered that voids form underneath the textile mesh when applied between the layers and that these voids influence on the performance of the elements.

Textile reinforced concrete for free-form concrete elements: influence of the binding type of textile reinforcements on the drapability for manufacturing double-curved concrete elements

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Textile reinforced concrete (TRC) is a sustainable composite material consisting of a cementitious based matrix in combination with an open meshed technical textile reinforcement made of carbon or glass fibres. In the future, TRC could be increasingly used in the form of double-curved concrete elements with the aim of producing filigree yet load-bearing concrete shell structures. To assess whether a textile is suitable as a reinforcement structure in double-curved textile concrete elements, numerous properties need to be investigated and evaluated. The most important of these include good handling properties, bending stiffness tailored to the application, sufficiently pronounced mesh openings, and defect-free drapability. In the course of this work, biaxially reinforced knitted fabrics with five different stitch types (pillar open, pillar closed, tricot counterlaid, tricot closed and plain) were investigated to evaluate the above properties. The draping tests were conducted on a robot-controlled draping test apparatus and evaluated with the aid of an optical measuring system. In addition, the geometric relationship between surface curvature of the double curved elements and the shear angle of different textiles was used to classify the influence of the stitch type on the drapability. Finally, for a given double curved geometry, based on the results the selection of an appropriate textile reinforcement which fulfils the component requirements is carried out and a double curved TRC demonstrator element is prefabricated. Thus, using the drapability analysis proposed in this paper, a component specific selection of textile reinforcement for freeform concrete panels is now possible. This enables the selection of the textile reinforcement with appropriate textile parameters, thereby ensuring not only textile positioning but also good concrete penetration and good handling of the textile during precasting.

Study on fundamental properties of the spraying ultra high strength fiber reinforced concrete cured at normal temperature

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In this study, the hardened properties and spraying characteristics of ultra high strength fiber-reinforced mortar mixed with copper fibers along with nylon fibers and polypropylene fibers are examined. The chemical fibers are added in the expectation that they will prevent cracking during initial curing. It is confirmed that, even with the addition of chemical fibers, the fresh properties of the mortar are similar to those of formulations containing only copper fibers. It is also found spray-application of this formulation achieves sufficient application thickness and that on-site application would be possible.

Performance of high-strength strain-hardening cement-based composites (HS-SHCC) under cyclic loading

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Buildings and objects of infrastructure are exposed to a variety of quasi-static and dynamic/cyclic loads. For a safe, material-minimized structural design, a broad knowledge of the mechanical behaviour of construction materials under various loading conditions is required. Previous studies showed that Strain-Hardening Cement-based Composites (SHCC) are a promising class of materials that exhibit an outstanding resistance under both quasi-static and cyclic loading regimes. However, a deep comprehension of the mechanisms leading to the specific behaviours of SHCC, especially that under cyclic loads, is still missing. The contribution at hand presents the experimental results from uniaxial cyclic loading tests performed on notched dogbone-shaped specimens made of high-strength SHCC with a polyethylene fibre content of 2% by volume. The samples were exposed to harmonic loads with different frequencies and predefined force levels for a certain number of load cycles. In addition, morphological analysis of the fracture surfaces and crack patterns were performed by means of microscopy in order to determine the degradation condition of each phase, i.e., fibre and matrix. The results are finally discussed referring to the physical phenomena causing the observed behaviour.

Flexural strength of fibre reinforced concrete in relation to the angle of magnetically orientated fibres

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This paper focuses on high-performance fibre-reinforced concrete and its flexural strength concerning fibre orientation. The orientation is provided by a fully controlled special device. This device can align the fibres in fresh concrete using a magnetic field. The specimens are inserted into the device at different angles to ensure different fibre orientations concerning the longer side of the sample, which corresponds to the direction of the main tensile stresses. Specifically, angles of 0°, 30°, 60° and 90° are tested and compared with each other and with reference specimens that are not exposed to a magnetic field. All samples are measured by a non-destructive method. This method was developed in our previous research and is based on measuring the quality factor Q of a measuring coil using an impedance meter. The samples are inserted into a measuring coil connected to an impedance meter. Flexural strength is obtained from the results of a three-point bending test. All samples are tested until complete failure.

Behaviour of steel fibre reinforced concrete pavements on a single fibre level

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Concrete is a popular construction material used all around the globe. It is strong in compression and weak in tension. To mitigate this tensile weakness, various reinforcement methods have been used over the years, of these, fibre reinforced concrete (FRC) has gained popularity. Fibres not only improve the tensile strength of the concrete matrix, but also control crack propagation through crack bridging action. The goal of this study is to investigate the long-term behaviour of FRC pavements through conduction of static and fatigue meso-scale level tests using different steel fibres. To achieve this goal, the influence of different fibre geometries and embedment angles on the pull-out behaviour of fibres in FRC was investigated first. This was carried out by examining 60mm Dramix 3D steel and 5D steel fibres at single fibre level. The embedment depth was kept constant at half the fibre length, and the fibre embedment angles were tested at 0°, 15° and 30°. The average maximum pull-out load, A_{max}, was determined first through static tests then fatigue tests were carried out using 85% of the A_{max} value on pre-damaged samples. These tests indicated that an increase in fibre embedment angle and number of hooks leads to additional anchorage of the fibre. Fibre pull-out was found to be the dominant fibre failure mechanism for the static single fibre pull-out tests (SFPTs).

6. Alkali-aggregate reaction migration (RILEM TC 300-ARM)

Actions to mitigate alkali-aggregate reaction in affected structures

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One of the aims of the new RILEM TC 300-ARM is to help bridge the gap between the important advances in procedures for the diagnosis, prognosis and mitigation of alkali-aggregate reaction (AAR), and their application in real structures. This paper presents the ongoing work of this TC to develop a state-of-the-art report on current strategies to mitigate alkali-aggregate reaction (AAR) in affected concrete infrastructures, including a critical review of those strategies and a set of criteria to consider before choosing the best solution.

Non-traditional alkali-silica reaction mitigation products in new and affected concrete

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Alkali-Silica Reaction (ASR) is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide. ASR damage degree and features depend upon the type (i.e., fine and coarse aggregate) and reactivity of the aggregates used, the amount of alkalis of the concrete, the temperature and relative humidity of the environment. Over the years, several approaches and recommendations, including a comprehensive variety of laboratory test procedures, have been developed around the world to assess the potential alkali-reactivity of concrete aggregates and the efficiency of preventive measures (i.e. control of the cement & concrete alkali content, use of supplementary cementing materials - SCMs, etc.). Although SCM have been used with a high level of success to reduce expansion due to ASR to a very low level, it is of interest to find alternatives or additional ways to mitigate the expansion due to the following reasons: (i) the scarcity of SCM in some locations worldwide, (ii) the recently reported uncertainties associated with the long-term expansion of concrete with SCM, and (iii) the need for materials to combat ASR in affected structures.

Test procedures and strategies to evaluate non-traditional mitigation products in concrete

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[1]Department of Civil Engineering, University of Ottawa, Ottawa, Canada

Alkali-Silica Reaction (ASR) is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide. ASR damage degree and features depend upon the type (i.e., fine and coarse aggregate) and reactivity of the aggregates used, the amount of alkalis of the concrete, the temperature and relative humidity of the environment. Over the years, several approaches and recommendations, including a comprehensive variety of laboratory test procedures, have been developed around the world to assess the potential alkali-reactivity of concrete aggregates and the efficiency of preventive measures (i.e. control of the cement & concrete alkali content, use of supplementary cementing materials - SCMs, etc.). Although numerous studies have found that ASR-induced expansion and distress may be prevented by the appropriate use of SCMs, recent studies are now finding that the deterioration is actually ”only” delayed and not entirely suppressed. Moreover, once ASR starts in the field, onerous (and often inefficient) human intervention becomes necessary.

Mitigation of the alkali-aggregate reaction

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The alkali-aggregate reaction (AAR), and more specifically the alkali-silica reaction (ASR), is generally a slow rate reaction. Especially when there are large volumes of concrete, the symptoms of the reaction can take between 20 and 30 years to manifest. This means that more and more cases of concrete structures damaged by this expansive reaction are currently being found, due to the time that has elapsed since their construction. Therefore, there is an increasing number of structures with a significant degree of alteration, since when they were built this phenomenon was not considered. On the other hand, since the ASR is a massive phenomenon in concrete, the potential treatments to mitigate the reaction do not act adequately in general. The objective of the TC-ARM is to make a critical analysis of the existing methods for the mitigation of the ASR; as well as to identify potential products for the self-healing of concrete when the alteration process is progressing. Finally, it is also planned to evaluate new test methods that allow evaluating the efficiency of self-repairing products. In the present work, the evolution of the ASR over time is analyzed, from the construction of the structure, the appearance of the first symptoms, the evolution of the reaction and mitigation, to achieve the extension of the useful life.

Author Index

Abou-Chakra; A., 45
Aboulela; A., 11
Achenbach; R., 29
Adeyeye; R., 62
Agapitos; K., 43
Ahmed; H., 26, 38
Ajayan; A., 52
Ajoku; C.A., 45
Alexander; M.G., 20, 39, 40
Almeida; F.C.R., 48
Alsallamin; A., 24
Amadi; I.G., 20
Angst; U., 3, 25, 28, 30, 31
Atkins; C., 53
Audenaert; A., 54
Augonis; A., 57
Ayer; K., 34

Büchler; M., 44
Bílý; P., 40, 63
Bílek; V., 63
Bašić; A.-D., 27
Babafemi; A.J., 23, 64
Bakera; A.T., 39
Balayssac; J.-P., 23, 60
Balla; T.M.R., 50
Ballim; Y., 37
Balázs; G. L., 51
Baptist; S., 62
Basheer; M., 26
Beigh; M.A.B., 47
Bertron; A., 11, 58
Beushausen; H., 20, 27, 40, 41, 45, 47
Bhat; S., 64
Bissonnette; B., 43, 47
Bista; M., 58
Bonin; K., 46
Boshoff; W.P., 26, 61
Bouillard; T., 23
Bourbon; X., 23
Breitenbücher; R., 47
Brem; M., 44
Brueckner; R., 53
Bukvic; O., 58
Butler; M., 47
Buvigner; A., 11
Buyle; M., 54

Carcasses; M., 31
Carrera; K., 65
Caspeele; R., 33
Cassiani; D., 31
Certain; P.-V., 47
Charron; J.-P., 49
Cibelli; A., 26
Cobbs; R., 53
Collis; V., 15
Combrinck; R., 25, 26, 60, 64, 65
Courard; L., 43
Craeye; B., 33, 54
Csurgai; F., 51
Cwirzen; A., 46, 61

da Silva; J., 44
Daniel; T., 50
Dauberschmidt; C., 25, 30, 34
De Belie; N., 5
De Folleville; T., 43
De Souza; D.J., 66
Dehn; F., 38
Dennis; A., 54
Deysel; R., 61
di Luzio; G., 26
Donadio; M., 43

Ebell; G., 53
El-Dieb; A., 24
El-Hassan; H., 24, 49
El-Maaddawy; T., 49
El-Mir; A., 24
Elias; N., 27
Epple; N., 37
Epstein; D., 36
Eriguchi; A., 41

Fadele; O.A., 22
Fataar; H., 65
Felicetti; R., 38
Fenton; P., 51
Ferrara; L., 26, 38
Fládr; J., 40, 63
Flegar; M., 57
Flohr; A., 21
Fornůsek; J., 65
François; R., 31
Fraundorfer; A., 25, 30, 34
Fujiwara; H., 22, 23, 41, 64
Furcas; F.E., 28

Gagné; R., 47
Gamieldien; A., 20
Garbacz; A., 43
Gehlen; C., 30
Geiker; M.R., 9
Gilayeneh; V.S., 24, 35
Giroudon; M., 58
Gomera; M., 37
Goyal; A., 53
Grantham; M., 33
Gries; M.B., 54; T., 64
Griffa; M., 28
Guanziroli; S., 38
Gunasekara; C., 22

Höffgen; J.P., 38
Harrell; S.J., 43
Harripershad; J., 51
Hayashi; K., 22
Hedlund; H., 61
Heilmayer; T., 30
Helm; C., 52
Helson; O., 23
Hemkemeier; T.A., 48

Ideker; J.H., 21, 24
Ikotun; J., 62
Iliushchenko; V., 40
Isaka; Y., 41
Isgor; O.B., 21, 28
Ishiduka; H., 23
Ivanauskas; E., 57

Jabbour; S., 29
Janse van Rensburg; J.J., 64
Jarratt; N., 41, 47
Jilissen; D., 42
Joel; A., 50
Jolin; M., 47
Jornet; A., 53
Joseline; D., 32
Junger; D., 65
Jungwirth; J., 42

Künzel; K., 65
Küttenbaum; S., 35, 39
Kai; K., 26
Kalina; L., 40, 63
Kalthoff; M., 64
Kamde; D.K., 55
Kammer; D., 31
Kancir; I.V., 30
Kanjee; J.P., 20
Kapteina; G., 29
Katsumi; N., 53
Kearsley; E., 13, 60
Keerthi; V.T., 56
Keßler; S., 31
Kgatle; K., 54
Khan; Y., 60
Kheml; P., 65
Khir Allah; N., 49
King; D., 46
Klemm; A.J., 48
Klewe; T., 39
Kobayashi; A., 22
Kocáb; D., 40
Kongolo; O., 44
Konrád; P., 65
Kothari; A., 46
Krishnan; N., 56
Kristufek; L., 34, 35
Kruschwitz; S., 39
Kunz; D., 28
Kustermann; A., 62

Lacarrière; L., 58
Lamothe; C., 47
Lamparter; S., 38
Langer; C., 29
Law; D.W., 22
Lawler; J.S., 54
Leconte; R., 43
Liao; C.-M., 37
Linden; C., 25
Liu; Me., 50; Mi., 29; T., 49
Lohner; J., 43, 44
Londono-Zuluaga; D., 21, 57
Long; A., 26
Lothenbach; B., 28
Ludwig; H., 27

Müller; S., 42
Mára; M., 65
Maack; S., 35, 37, 39
Maes; M., 52
Makara; N., 65
Malárics-Pfaff; V., 38
Malumbela; G., 24
Manhanga; F.C., 57
Manickam; K., 55
Marcucci; A., 38
Martín-Pérez; B., 29, 34, 35
Maruoka; M., 22, 23, 64
Matschei; T., 64
Mechtcherine; V., 42, 47, 65
Menéndez; E., 67
Meyer; M., 25, 26, 60
Michols; K.A., 54
Mikanovic; I., 27
Minne; P., 33
Mohs; M., 38
Molez; L., 47
Morbi; A., 49
Morgenstern; H., 59
Morthala; R.R., 50
Mosca; C., 53
Mostert; D., 60
Mueller; M., 27
Muhammad Ameen; M., 41

Mundra; S., 28
Muscolino; F., 38

Nüsslein; J., 43
Nagy; B., 62
Naraghi; V., 47
Ndawula; J., 45
Negrini; A., 38
Neumann; J., 47
Nguyen; T.T., 31
Niederleithinger; E., 37, 39
Nilsson; L.-O., 31
Noël; M., 34, 35
Noor; L., 21, 24
Nulliah; N., 59
Nwaubani; S.O., 35

Osburg; A., 21
Otieno; M., 7, 22, 45, 62
Owada; M., 22

Pace; L., 43
Padayachee; J., 59
Paglia; C., 53
Papež; V., 65
Patapy; C., 11
Patrisia; Y., 22
Paule; J., 62
Peyre Lavigne; M., 11, 58
Pfändler; P., 30
Pillai; R.G., 32, 52, 55, 56
Plizzari; G.A., 49
Polder; R., 33; R.B., 18
Pourbehi; M.S., 23
Prakash; S.S., 50
Pretorius; M., 54
Prinsloo; G., 23
Provis; J.L., 61
Pundir; M., 31

Qiu; J., 59

Radoš; V., 30
Rajczakowska; M., 46
Ram; K., 21
Raupach; M., 29, 52, 59
Reggia; A., 49
Reichardt; M., 42
Reid; L., 51
Renne; N., 33, 54
Ripa; F., 25
Roosz; C., 58
Rudžionis; Ž., 57
Ruffray; N., 28
Runci; A., 40

Sales; A., 48
Sanchez; L.F.M., 34, 35, 38, 66
Sannoh; A.V.J., 24
Santos; L.O., 66
Santos Silva; A., 67
Schmid; T., 28, 30
Schröter; N., 44
Schwarz; W., 53
Scrivener; K., 1, 21, 57
Serdar; M., 21, 27, 30, 40, 57, 58
Shahzad; S., 60
Shehat; M.H., 66
Shroeder; P., 64
Signorini; C., 47
Sikhakhane; T., 20
Smilek; J., 63
Smit; M.S., 61
Smithers; W., 43
Soetens; T., 52
Solyom; S., 51
Soukal; F., 63
Sovják; R., 65
Spijkerman; Z., 61
Strotmann; A., 42
Strydom; J., 44
Su; L., 50
Surana; S., 20, 40

Taffe; A., 35, 37
Tanaka; S., 23
Tawil; D., 34, 35
Taylor; P., 46
Tejane; O., 20
Tits; J., 28
Topolář; L., 40, 63
Toumi; A., 23, 60
Trabucchi; I., 49
Tuinukuafe; A., 21
Turatsinze; A., 23, 45, 60

Völker; T., 39, 53
Van Belleghem; B., 52
van den Hondel; A.W.M., 18
van der Merwe; A., 34
van Eck; G.-J., 42
van Zyl; J., 25
Vaysburd; A.M., 43
Vergoossen; R., 42
ViRooszljoen; C., 58
Volmink; K., 34, 59
von Fay; K.F., 43
Vu; T.N., 31

Wünsch; J., 31
Wagner; E.I., 54
Walenta; G., 27
Wang; T., 23
Wardhono; A., 22
Warren; L.G., 61
Whitmore; D., 55
Wieland; E., 28
Wilsch; G., 39, 53
Wittocx; L., 33
Wolf; B., 62
Wu; B., 59

Yang; S., 50
Ying; Z., 50
Yoshikawa; J., 64; K., 64
Zahedi; A., 35, 38
Zhang; Z., 28
Zintel; M., 25
Zyzak; M., 61