Concrete innovation in Norway 2007–2014, COIN Final Seminar, Trondheim, Norway, 2–3 December 2014

COIN project report 82 – 2015
Concrete innovation in Norway 2007–2014, COIN Final Seminar, Trondheim, Norway 2–3 December 2014
Preface

This study has been carried out within COIN - Concrete Innovation Centre - one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfil this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently eight projects in three focus areas:

- Environmentally friendly concrete
- Economically competitive construction
- Aesthetic and technical performance

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %).

For more information, see www.coinweb.no

Tor Arne Hammer
Centre Manager
Summary

COIN was initiated as a Centre for research based innovation (SFI) by The Research Council of Norway. The COIN-programme started in 2007 and lasted for eight years and ended in 2014.

A closure seminar was arranged in Trondheim 2 and 3 of December 2014 to mark the end of this period and to present results from the research, focusing mainly on its usefulness.

This report assembles the presentations from these two days.
# Table of contents

1 **INTRODUCTION** .......................................................................................................................... 6  
   **WELCOME** ............................................................................................................................... 7  
   **INTRODUCTION** ....................................................................................................................... 13  
   **ABOUT COIN** .......................................................................................................................... 18  
2 **TECHNICAL PERFORMANCE** ................................................................................................. 23  
   **CRACKFREE CONCRETE STRUCTURES** .................................................................................. 24  
      **Introduction** .......................................................................................................................... 24  
      **Test rig development** .......................................................................................................... 30  
      **Crack TeSt COIN and education of the industry** ................................................................. 37  
   **RELIABLE DESIGN AND PROLONAGEMENT OF SERVICE LIFE** ...................................... 42  
      **Introduction** ........................................................................................................................ 42  
      **Alkali-silica reactions** ......................................................................................................... 48  
      **Corrosion** ............................................................................................................................ 60  
   **STRUCTURAL PERFORMANCE** ............................................................................................. 67  
      **Ductility of lightweight concrete** ....................................................................................... 67  
      **Ice abrasion** ......................................................................................................................... 82  
3 **COMPETITIVE CONSTRUCTIONS** .......................................................................................... 88  
   **ROBUST AND HIGHLY FLOWABLE CONCRETE WITH CONTROLLED SURFACE QUALITY** .... 89  
      **Introduction** ........................................................................................................................ 89  
      **Surface classification tool** ................................................................................................ 92  
      **Assessment of SCC stability – lab and field** ...................................................................... 100  
   **DUCTILE HIGH TENSILE STRENGTH FIBRE REINFORCED CONCRETE** .............................. 105  
      **Fibre concrete guideline and possibilities with fibre reinforcement** ................................. 105  
   **HIGH QUALITY MANUFACTURED SAND FOR CONCRETE** ............................................... 126  
      **Introduction** ........................................................................................................................ 126  
      **Utilisation of local low grade manufactured sand** .............................................................. 135  
      **Crushed sand, manufactured sand and "engineered sand"** .................................................. 139  
      **Transportation and sustainability** ...................................................................................... 143  
4 **ENVIRONMENTAL FRIENDLY CONCRETE STRUCTURES** .................................................. 151  
   **BINDERS WITH LOW EMISSION AND REDUCED RESOURCE CONSUMPTION** .................. 152  
      **Fly ash - limestone synergy** ................................................................................................ 154  
      **Accelerators for fly ash cement** .......................................................................................... 157  
      **Calcined clay** ..................................................................................................................... 160  
      **Calcined marl** ..................................................................................................................... 161  
      **Plasticizers for SCMs** ......................................................................................................... 165  
   **UTILISATION OF CONCRETE IN LOW ENERGY BUILDING CONCEPTS** ............................. 167  
      **Concrete and Passive House** .............................................................................................. 167  
      **ZEB concrete and LCA** ....................................................................................................... 168  
      **Insulating concrete** ........................................................................................................... 175  
5 **THE ROAD TOWARDS NEW CONCRETE RESEARCH AND INNOVATION** ........................... 176  
   **INTRODUCTION TO THE PANEL DEBATE BY T.A. MARTIUS-HAMMER** ........................... 177  
   **CONCLUDING REMARKS BY T. RØNNING** ........................................................................ 180
1 Introduction

December 2nd 2014

Chairman: Tor Arne Martius-Hammer

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.00 – 12.10</td>
<td>Welcome</td>
<td>Tor Arne Martius-Hammer, COIN's centre manager</td>
</tr>
<tr>
<td>12.10 – 12.20</td>
<td>Introduction</td>
<td>Terje F. Rønning, COIN's chairman of the board</td>
</tr>
<tr>
<td>12.15 – 12.30</td>
<td>About COIN</td>
<td>Einar A. Hansen, COIN's originator</td>
</tr>
</tbody>
</table>
Financing

Total: NOK 250 mill

RCN: NOK 76 mill

Partners: NOK 30 mill in cash
NOK 140 mill in-kind

PhD-students - status Dec 2014

<table>
<thead>
<tr>
<th>Name</th>
<th>FA</th>
<th>Subject</th>
<th>Start</th>
<th>End/ Defence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klaartje de Weerd</td>
<td>1.1</td>
<td>Cements with low CO2 outlet</td>
<td>Jan 2007</td>
<td>Feb 2011</td>
</tr>
<tr>
<td>Ueli Aengst</td>
<td>3.2</td>
<td>Modelling critical chloride content and corrosion proc.</td>
<td>Apr 2007</td>
<td>May 2011</td>
</tr>
<tr>
<td>Sandre Sandbakk</td>
<td>2.2</td>
<td>Fibre reinforced concrete</td>
<td>Aug 2007</td>
<td>Nov 2011</td>
</tr>
<tr>
<td>Havard Nedreid</td>
<td>3.3</td>
<td>LWAC – testing and modelling</td>
<td>Jan 2007</td>
<td>Apr 2012</td>
</tr>
<tr>
<td>Kien Hoang</td>
<td>1.2</td>
<td>Controlling hydration development</td>
<td>Aug 2008</td>
<td>Dec 2012</td>
</tr>
<tr>
<td>Markus Bernhard</td>
<td>3.3</td>
<td>Development of super LWA</td>
<td>Aug 2010</td>
<td>Aug 2012</td>
</tr>
<tr>
<td>Linn Grepstad</td>
<td>3.3</td>
<td>Hybrid structures</td>
<td>Sep 2007</td>
<td>Sep 2010</td>
</tr>
<tr>
<td>Jan Lindgard</td>
<td>3.2</td>
<td>AAR Lab. testing vs field performance</td>
<td>Jan 2007</td>
<td>Oct 2012</td>
</tr>
<tr>
<td>Ya Peng</td>
<td>2.1</td>
<td>Rheology and stability of concrete</td>
<td>Apr 2010</td>
<td>Mar 2014</td>
</tr>
<tr>
<td>Egil Maen</td>
<td>3.3</td>
<td>Ice abrasion</td>
<td>Aug 2007</td>
<td>Mar 2016</td>
</tr>
<tr>
<td>Giedrius Zirgulis</td>
<td>2.2</td>
<td>Fibre</td>
<td>Sep 2010</td>
<td>Mar 2016</td>
</tr>
<tr>
<td>Mahdi Kiumarsi</td>
<td>3.2</td>
<td>Structural effects of reinforcement corrosion</td>
<td>Aug 2011</td>
<td>Mar 2016</td>
</tr>
<tr>
<td>Rolandas Cepuritis</td>
<td>2.3</td>
<td>Industrially produced aggregates</td>
<td>Aug 2011</td>
<td>Nov 2016</td>
</tr>
<tr>
<td>Karlo Hornboestle</td>
<td>3.2</td>
<td>Electrical resistance</td>
<td>Nov 2008</td>
<td>Oct 2016</td>
</tr>
<tr>
<td>Elena V. Sarmiento</td>
<td>2.2</td>
<td>Flowable concrete fibre concrete</td>
<td>Aug 2011</td>
<td>Oct 2016</td>
</tr>
</tbody>
</table>
Did we reach the goals?

The RCN-application:
"The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialised construction, improved work environment, and cost efficiency during the whole service life.

The centre will strive to fulfil this vision by developing advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production".
Did we reach the goals?

**CRI-objectives:**

- stimulate innovation through long-term research
- attract research activities to Norway
- create an active co-operation between industry and research institutions
- promote development of internationally leading research environments
- stimulate education of researchers in important fields for the industry

**Results -**

reported in nearly 150 scientific publications

- Products
- Patent
- Guidelines
- Simulation tools
- Test methods
- Workshops/conferences
"Belite calcium sulfoaluminate ternesite (BCT)" - a new environmentally friendly binder, by HeidelbergCement Technology Center in Germany

"Smart dynamic casting" - robotized casting of complex concrete elements, by ETH Zürich

"ZÜBLIN Earthquake Column" - a novel solution to design earthquake resistant columns, by Ed. Züblin AG, Germany

"Climbing robot for corrosion inspection and monitoring" - a climbing robot for condition control, by ETH Zürich

Focus Areas

1) Environmental friendly concrete structures
   Binders with low emission and reduced resource consumption
   Utilisation of concrete in low energy building concepts

2) Competitive construction
   Stable and robust highly flowable concrete with controlled surfaces
   High tensile ductile strength concrete
   High quality manufactured sand for concrete

3) Technical performance
   Crackfree concrete
   Service life
   Structural performance
More information on www.sintef/coin.no
COIN Seminar: Introduction

COIN ’Assets’

- Research with innovation focus
- Addresses public & sector strategic agenda
- Joint venture Research & Industry:
- Mutual involvement = precondition for success
- Consortium > Value chain >> Σ [single actions]
- External interest / publicity (From whom ..?)
- International levelling of research & Co-op.
- Public funding support
- Volume / Critical mass
- Ability to address flexibility & organisational issues
- Adequate support functions
- AND some challenges, but today we celebrate!
All have their own agenda, but ....?

General targets & functions

- Arena for innovation
  - Between Industry & Research & Education
  - Cross-enterprise joint venture
  - Enterprise AND Sector strategic issues
  - Value creation
- Arena for developing ORGANISATIONAL environment
Arena for recruitment & education (PhD) development

—I mitt neste liv skal jeg bli bygningsingeniør

- Ønsker en fælles organisation i byggenæringen
- Langvarigt direktor for bænksortede selskaper

Nos. of researchers per 1,000 employees ....

Globale FoU-investeringer i 2012 eller sist tilgjengelige år.
Forsker* per tusen sysselsette og FoU-utgifter som andel av BNP

HEIDELBERGCEMENT
**COIN Significance**

Norge i forhold til OECD/Norden for øvrig/EU 28 i 2012

- FoU som andel av BNP
- FoU-utgift per 1000 arbeidsplasser
- Andel FoU utført i forvaltningssektoren
- Andel sysselsette med høyere utdanning
- Vekst i FoU-utgifterne 2010-2012
- Andel bedrifter med innovasjonsevne

**Industrialized Construction Sector**

**Can we manage .....

Industriell byggenæring**

Industrialisering må til for å bygge bedre og billigere – ikke bare for økt inntjening, men også for det samfunnsansvar vi som delvis skjermet næring har. Men kan byggenæringen bli industriell? Samlet er vi i dag ingen industri – vi er en næring med håndverkere forsøkt satt i system.

_Oyvind Skarholt_ 30.08.2012 Adm. direktør i Byggevareindustriens forening
Now – what?

New arena for joint strategies discussions?
• Interim group at work.
• Watch – Follow – Attend!

Today

ENJOY & Pose questions

Thank you!
Concrete anno 2004

- Low public image
- The industry talks about technology and volume sales
  - not addressing solutions
- Criticized for a lack of understanding of their customers needs
- "We have made enough research – time to implement"
- No funding from the Research Council

Yet:
- A major concrete research effort in the period 1980 – 2000
- Documented a yield rate of 19 on R&D investments (2002)
- Innovation can release a huge value creation potential (BAE-council, 2002)

  The message: "We have just started – the possibilities are endless"
Winter 2005
The SFI Scheme is launched

Objectives:
1. Promote innovation by supporting long-term research
2. Make it attractive for enterprises that work on the international arena to establish R&D activities in Norway
3. Support close cooperation between R&D intensive companies and prominent research institutions
4. Promote the development of industrially oriented research groups that are on the cutting edge of international research
5. Stimulate researcher training in fields of importance to the business community

The birth of COIN

- Spring 2005: Design of overall objective and topics
- June 2005: Promoting the dream to Norcem and NTNU
- Summer 2005: Discussion with companies; participation and R&D strategies
- October 2005: SINTEF and NTNU Information Day – Final decision
Attractive Concrete Buildings

The birth of COIN

- Spring 2005: Design of overall objective and topics
- June 2005: Promoting the dream to Norcem and NTNU
- Summer 2005: Discussion with companies; participation and R&D strategies
- October 2005: SINTEF and NTNU Information Day – Final decision
- November 2005: Writing the application
- December 1st: Application sent on deadline
Vision of COIN

Attractive Concrete Buildings!

Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life.

The centre will strive to fulfill this vision by developing advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

The birth of COIN

- Spring 2005: Design of overall objective and topics
- June 2005: Promoting the Dream to Norcem and NTNU
- Summer 2005: Discussion with companies; participation and R&D strategies
- October 2005: SINTEF and NTNU Information Day – Final decision
- November 2005: Writing the application in two weeks
- December 1st: Application sent on deadline
- Winter 2006: Promoting COIN in conferences, seminars etc.
- June 16th 2006: COIN announced as SFI
15 januar 2007 - Kick-off

Dag Kavlie, Norwegian Research Council:
“It caused enthusiasms in the international evaluation committee by such a vigorous application from a traditional field like concrete.”

Lessons learned

- Research must be a long-term strategic investment rooted in the company management
- The research groups must be on the cutting edge of international research
- The companies should cooperate and concentrate their research contributions to SINTEF and NTNU
- SINTEF and NTNU need to demonstrate added value from research

The future:
- The competition in the marked will be even tougher
- The industry need to increase their research efforts in order to be in front
2 Technical performance

December 2nd 2014

Chairman: Tor Arne Martius-Hammer

Crackfree concrete structures
12.30 – Introduction Øyvind Bjøntegaard (Norwegian Public Roads Administration)  
Test rig development Anja Estensen Klausen, PhD student (SINTEF/NTNU)  
– 13.15 Crack TeSt COIN and education of the industry Sverre Smeplass (Skanska)

Reliable design and prolongation of service life
13.15 – Introduction Mette Geiker (NTNU)  
Alkali-silica reactions Terje F. Rønning (Norcem) Jan Lindgård (SINTEF)  
– 14.00 Corrosion Karla Hornbostel, PhD student (NTNU)

Chairman: Ya Peng

Structural performance
14.15 – Ductility of lightweight concrete Jan Arve Øverli (NTNU)  
Ice abrasion Stefan Jacobsen (NTNU)  
– 15.00
COIN P3.1 Crackfree Concrete Structures

A) Background / Usefulness
Øyvind Bjøntegaard, NPRA

B) Lab equipment (and tests/calculations)
Ph.D. Candidate Anja E. Klausen, NTNU/SINTEF

C) Implementation and transfer of knowledge
   - New program and course
Sverre Smeplass, Skanska Norge AS

Background
   - Earlier projects

- Earlier genuine Norwegian projects on curing technology / “thermal cracking”
  - NORCON 1993-1996 (NTNU)
  - NOR-IPACS 1996-2000 (Skanska),
  - NOR-CRACK 2001-2005 (NTNU)
    (supported by the Norw. Res. Council)

- Brite-EuRam project IPACS 1997-2001 (Scancem AB)
  - several Norwegian participants

- COIN 3.1, 2007-2014 (Sintef Byggforsk)
Background
- Norwegian Public Roads Administration (NPRA)

- We have participated in all the listed projects – why?

- We own today about 17.000 bridges, including submerged/underground culvert structures. In addition, supporting wall structures, and numerous other structures.

- Our structures are often massive and the exposure is generally severe (XD3, XS3) - meaning:
  - w/c < 0.40
  - high strength
  - high cement contents

- significant heat of hydration and high cracking tendency

---

Background
- Volume changes and stress build-up in the hardening phase

![Diagram showing high restraint effects and temperature changes over time.]

Critical period
Example of crack-pattern in walls due to external restraint from the bottom slab
Background
- what controls stresses and cracking

- **Hydration heat**
- **Coefficient of thermal expansion**

- **Autogenous shrinkage**

- **E-modulus**
- **Creep/relaxation**
- **Tensile strength**

- **Temperature sensitivity**

- **Structural case (L/H-ratio, area of structural parts, etc.)**

---

### For special cases

- **\( \Delta T \)**
  
  (Limits on temperature difference between adjoining structures)

For special cases

- **\( \Delta T \) + Low-heat (LH) concrete**
  
  - The definition of LH set by NPRA in an upcoming revision of Prosesskode-2 is directly taken from work in COIN 3.1

- **Full crack-risk evaluation with advanced curing technology**
Active participants COIN 3.1 (2014)

- K O Kjellsen - NORCEM AS (manager sub-project 3.1)
- E Heimdal - Veidekke
- A Klausen - NTNU/SINTEF
- T Kanstad - NTNU
- G Kjellmark - SINTEF
- S Smeplass - Skanska
- Ø Sæther - Unicon
- N Al-Manasir - Mapei
- Ø Bjøntegaard - NPRA

Reports

- Autogenous deformation and relative humidity – Concrete with Aalborg Portland cement and fly ash.
  - Kjellmark G., COIN report 24 - 2010.

- Basis for and practical approaches to stress calculations and crack risk estimation in hardening concrete structures, state-of-the-art report.
  - Bjøntegaard Ø., COIN report 31 – 2011

- Property development and cracking tendency in hardening concrete: Effect of cement type and fly ash content.
  - Bjøntegaard Ø. and Kjellsen K.O., COIN report 40 – 2012

- Temperature development in on-site curing boxes.
  - Klausen, A.B.E. and Bjøntegaard Ø., COIN report 2014 (In press)

- Crack-risk evaluated with Crack-TeSt COIN
  - Smeplass S., Berget O., COIN-report 2014 (close to press)

- Mechanical properties and calculation of model parameters for concrete with variable fly ash content.
  - Kjellmark G., Klausen A., COIN-report 2014 (close to press)
Conference papers

  Klausen, Anja Birgitta Estensen; Kastad, Terje; Bjøntegaard, Øyvind.

  Dirk Schlicke, Nguyen Viet Tue, Anja Klausen, Terje Kastad, Øyvind Bjøntegaard.

  Bjøntegaard, Øyvind; Klausen, Anja Birgitta Estensen; Kastad, Terje.

  Kastad, Terje; Kjellmark, Gunrid; Klausen, Anja Birgitta Estensen; Bjøntegaard, Øyvind.

Memos

- User-manual for the TSTM-system
  Klausen, A B E (2014)

- Autogenous shrinkage measured during different test series and projects 1996-2006
  Bjøntegaard, Ø (2013)

- TSTM: Description of mode of action and algorithm for the new control system
  Bjøntegaard, Ø (2009)
COIN P3.1 Crackfree Concrete Structures - Lab Equipment

The Free Deformation System
The Temperature-Stress Testing Machine

Ph.D. Candidate Anja E. Klausen, NTNU/SINTEF
Supervisor: Terje Kastad, NTNU
Co-Supervisor: Øyvind Bjantegaard, NFRA

Content

- Background
- Lab Equipment
  - Free Deformation (FD) - System
  - Temperature-Stress Testing Machine (TSTM) - System
- Performed Tests and Calculation Approaches
- Results
- Conclusion
Background

- Early age concrete
  - Volum changes
  - Crack development

Problems:
- Functionality
- Durability
- Aesthetics
- Economical

How can we control/reduce crack development?:
- Material properties + Pre-calculations

The Free Deformation System (FD-System)

- Measures free deformation
  - Thermal dilation
  - Autogenous deformation
- 7 Rigs
- Temperature controlled

[Diagram of the Free Deformation System]
The Temperature-Stress Testing Machine (TSTM) - System

Built in 1995, updated in 2009 - 2013

Temperature-Stress Testing Machine (TSTM)

The TSTM
Perfomed Tests and Calculation Approaches

- Isothermal 20 °C, R = 100 %
- Realistic temperature development, R = 50 %
- Concrete:
  - Portland Cement
  - Water-to-binder (w/b) ratio 0.4
  - Varying amount of fly ash
- Calculations
  - Excel
  - CrackTeSt COIN
  - DIANA
Results

- Measured free deformation – Dilation Rig
- Measured stress development – TSTM
- Calculated stress development
Measured free deformation
Realistic temperature development

Free deformation
Thermal dilation
Autogenous deformation

Measured stress development, R = 50 %
Realistic temperature development

Temperature
Tensile strength

Stress [N/mm²]
Temperature [°C]

Time [h]

Measured
Excel
CrackTest COIN
DIANA
Measured stress development, $R = 50\%$

Effect of fly ash

---

Measured stress development, $R = 50\%$

Effect of fly ash

---

COIN: Seminar, December 2014: P3.1 Crackfree Concrete Structures
Conclusion

- The TSTM-System shows good reproducibility

- Measured stress development in the TSTM offer good agreement with corresponding calculated stress development

- Solid material knowledge based on materials testing in the laboratory, combined with reliable calculations (CrackTeSt COIN) makes us able to predict, and thus control, the crack risk in concrete structures caused by early age volume changes.

One of the deliveries of COIN FA 3.1:

**Crack TeSt COIN**

2D tool for assessment of crack risk in massive structures subject to thermal restraint
Crack TeSt COIN can be used to:

1. Improve structural design to avoid or limit thermal restraint effects
2. Detail contract specifications in order to avoid harmful cracking
3. Select the most suitable concrete mix design
4. Plan and select curing and protection measures, including insulation, heating and cooling
5. Documentation of obtained crack risk

Implementation and transfer of knowledge?
- The Crack Test COIN course!

Target group for the CrackTeSt COIN course
1. Consulting engineers
2. Developers / Clients
3. Contractors
4. Material suppliers
Contents - CrackTeSt COIN course

1. Basic curing technology
   - Maturity principle
   - Material models
   - Thermal and autogenous restraint
   - Recognition of restraint cases
2. Introduction to software and data base
3. Training through case study - individual analysis and report
4. Discussion of results
**Status**

- 1 course conducted, 2014 (Multiconsult and Veidekke)
- 1-2 courses planned, winter/spring 2015

**Course committee:**
Sverre Smeplas, Skanska  
Terje Konstad, NTNU  
Øyvind Bjøntegaard, SVV/NPRA

**Further development**

- More material data should be provided
- Mandatory use in SVV / NPRA projects?
- Other types of massive structures?
  - Railroad structures
  - Concrete dams
  - Harbour structures
COIN Seminar
2nd and 3rd December 2014

Focus area 3.2
Reliable design and prolongation of service life (of concrete structures)

Mette R. Geiker

NTNU

Focus Area 3.2
Activities

1. Modelling (see also 7)
2. Critical chloride content
3. Electrical resistivity
4. Alkali-silica reaction – Performance testing
5. Preventive measures
6. Residual Service life
7. Improved service life modelling of reinforced concrete structures
8. Impact of corrosion on structural performance
COIN FA 3.2 – Activities

<table>
<thead>
<tr>
<th>Topics</th>
<th>PhD / Post Doc</th>
<th>Main partners</th>
<th>Visitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Modelling</td>
<td></td>
<td>SKANSKA, SINTEF, DTU, Stanford</td>
<td>Alexander Michel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Madeleine Flint</td>
</tr>
<tr>
<td>2 Critical chloride content</td>
<td>Ueli Angst</td>
<td>ETH</td>
<td></td>
</tr>
<tr>
<td>3 Electrical resistivity</td>
<td>Karla Hornbostel</td>
<td>SVV, ETH</td>
<td></td>
</tr>
<tr>
<td>4 Alkali-silica reaction – Performance testing</td>
<td>Jan Lindgård</td>
<td>NORCEM New Brunswick</td>
<td></td>
</tr>
<tr>
<td>5 Preventive measures</td>
<td></td>
<td>SINTEF</td>
<td></td>
</tr>
<tr>
<td>6 Residual Service life</td>
<td></td>
<td>SKANSKA SINTEF</td>
<td></td>
</tr>
<tr>
<td>7 Improved service life modelling of reinforced concrete structures</td>
<td>Klaartje De Weerdt</td>
<td>SVV, DTU, DTI</td>
<td>Denisa Orsakova Arnaud Müller Ulla H. Jakobsen</td>
</tr>
<tr>
<td>8 Impact of corrosion on structural performance</td>
<td>Mahdi Kiourmarsi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

COIN FA 3.2

Publications and presentations

<table>
<thead>
<tr>
<th>Topics</th>
<th>Journal</th>
<th>Conference</th>
<th>Reports</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Modelling &amp; general</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2 Critical chloride content</td>
<td>9</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>3 Electrical resistivity</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>4 Alkali-silica reaction – Performance testing</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>5 Preventive measures</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6 Residual Service life</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>7 Improved service life modelling of reinforced concrete structures</td>
<td>4</td>
<td>8</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>8 Impact of corrosion on structural performance</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Total 27 29 8 27
Research on reinforcement corrosion within COIN FA 3.2

- Structural performance
- Corrosion initiation
- Ingress and phase changes
- Corrosion rate

Chloride ingress and phase changes

Post Doc Project
Klaartje De Weerdt

Summary
- Phase changes affect chloride binding and are part of the explanation for D(t) and Cs(t)
- Pore solution chemistry should be considered when quantifying the impact of binder composition on chloride ingress
Initiation of chloride induced reinforcement corrosion

**PhD Project**
Ueli Angst

**Supervisors**
Øystein Vennesland
Claus K. Larsen, SVV/NTNU
Bernhard Elsener, ETH

**Summary**
The “characteristic structural length” should be taken into account when determining the critical chloride content for a given structural element.

---

Impact of concrete resistivity on corrosion rate

**PHD Project**
Karla Hornbostel

**Supervisors**
Mette R. Geiker
Claus K. Larsen, SVV/NTNU
Bernhard Elsener, ETH
Ueli Angst, ETH
Impact of corrosion on structural performance

PHD Project
Mahdi Kioumarsi

Supervisors
Mette R. Geiker
Max Hendriks
Terje Kanstad

Summary
- A 3D numerical model was established to investigate the possible impact on carrying capacity of localized corrosion on adjacent rebars
- Interference of localized corrosion within a critical distance

Alkali-silica reaction (ASR) – Performance testing

PhD Project
Jan Lindgård

Supervisors
Harald Justnes, NTNU
Erik J. Sellevold, NTNU
Michael D.A. Thomas, UNB, Canada

Summary
- The test procedure (i.e. specimen "pre-treatment", "exposure conditions" and prism cross-section) dramatically influences the outcome of an ASR performance test
- Alkali leaching is the main source of error during accelerated ASR performance testing
Presentations - Selected findings

Alkali silica reactions
Terje Rønning (NORCEM)
Jan Lindgård (SINTEF)

Reinforcement corrosion
Karla Hornbostel (NTNU)
Claus Larsen (SVV)

Acknowledgements

Funding
• COIN
• SVV
• NRC
• NTNU

Collaboration
• Colleagues in COIN
• Colleagues at DTU, ETH, New Brunswick University and Stanford University
ASR vs. Heidelberg Cement NE innovation
What & How

List of content

- Specification vs. Performance based requirements
  - and industrial needs
- Role of NB 21
- Role of RILEM TC
- Spin-offs to other markets
- DRAFT CONCEPT
- TEST RESULTS EXTRACT
  - Overview of research activities
    - PhD study
    - Follow-up study
  - Main results and conclusions
  - Main recommendations - future research
ASR Specifications vs. Performance Approach

How they differ ....

Specs :
- Normative
- Simple (normally)
- Sometimes “copied” from abroad
- Non-transparent wrt risk / safety margins
- Often discriminate certain construction materials, i.e.;
- Do not provide equal playing field leverage
- Prohibits product and marketing development, i.e.;
- Prevent innovation

Performance approach
- Must be NORMATIVE
- May be combined with Specs ...
- Allow assessment of construction products in combination, i.e.;
- Address functional properties & inter-dependency
- Provides product value leverage
- Sometimes disturbs established market shares ...
- i.e. Provides FLEXIBILITY
- Requires assessment criteria
- Assumes lab/field alignment
- Need mtrl. (constituent) characterisation & Concrete Performance Testing
- Representative Accelerated Testing
- Penetration assumes intl. accepted principles
HC NE – ASR Targets & Tasks Differentiation

NOR & Stakeholders
- Basic research & support for sustainable concepts & concept development
- International state-of-the-art alignment & key thresholds addressing
- CEN & NRI interface
- HTC co-ordination & alignment
- National stakeholder
- NB 21 regulations dialogue

SWE Business development
- Boundary conditions investigations
- Organisational environment development
- National regulations subject to differential approach
- Aggregate marketing development potential
- CEM II marketing concept potential

Baltic market development
- Stakeholder liaison development
- National stakeholder education
- National regulations design (dialogue / up-date)

National & cross boarder market access / development

HEIDELBERGCEMENT

NB 21
- Spec with «Performance extension»
- PT used for product application rules
- Fits product declaration needs
- Norw. CPT amongst «the best» but test application rules & formal interface in need of up-date
- Technical issues (probably) due for update, following RILEM & new KPN project

HEIDELBERGCEMENT
**TC AAR Subject matter**

Develop/promote performance based testing concept for preventing ASR

- Finalize and validate testing methods (Alkali boosting, Pessimium, Binder/Aggregate kinetics (T), RRT & Lab/Field)
- Potential aggregate alkalis release assessment and alkali household implications (Finalizing testing method and developing application procedure, Alkali “re-cycling”?)
- Flow chart proposal ....
- Standardisation input NO, SE, CAN, ASTM, Balt, CEN
Previous “WP 1 related” Deliveries

- “Information mapping” lab/field studies (no success)
- Attempt to quickly address key issues and proceed with draft procedure (failed) – Need to step back and;
- Identified critical issues & Research issues
  - Leaching/Threshold: Substantial support from JL PhD
  - Substantial general research information exchange
  - Boosting of alkalis (draft programme & sampling) / Limitations; Boosting trial procedure developed. Weimar-HC-Sintef issue. Test samples for trial.
  - Improved focus on lab/field relation investigations
  - Pre-curing (C-type); JL, F(C/Aggr)? < Coin WP2
  - Remaining issues must be solved by “convention” / “lack of precision”

Draft procedure

<table>
<thead>
<tr>
<th>Concrete prism testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate fraction(s)</td>
</tr>
<tr>
<td>Potential reactivity</td>
</tr>
<tr>
<td>Alkali threshold level</td>
</tr>
<tr>
<td>Aggregate combinations with pessimum</td>
</tr>
</tbody>
</table>

Potential objectives:
- Detection of reactive or potentially reactive aggregates, following initial characterisation by petrography and possible other tests, including...
- Characterisation of specific aggregate(s) product combined with specific/generic cement/binder, including modified alkali threshold levels, with such binder (e.g.alkali aggregate reaction declaration II)
- Characterisation of specific cement/binder product combined with reference binder

Characterisation ≠ Performance
Testing method ≠ Assessment
Assessment = Char. + Performance T. + T. Criteria (locally or mineral dependant testing limits)

- Input to guidelines / NAD1's of aggregates classification and application
- Construction project, but at a fixed w/c-ratio to avoid artefacts, and formal handling of constituents’ quality variations
- Input to guidelines / NAD1's of aggregates, cement/binder

1 National Application Document, i.e. regulations valid in place of use
ASR - Performance testing

Extract from research within COIN

Jan Lindgård

“Alkali-silica worms” (ASR gel) escaping from a test sample....

ASR performance testing (principle)

Alkali reactive aggregate

Assumption:
Expansion in lab. reflects long term performance in field structures

Example: Is addition of fly ash able to reduce the effective alkali content (pH) sufficiently?

High moisture content
Overview of research activities

- PhD study (WP1)
  - Main question:
    - Are national and international ASR test methods developed for assessment of alkali-silica reactivity of aggregates suitable for general ASR performance testing of concrete?
  - Extensive lab. program
    - Modified various test procedures – detect any sources of errors
  - Recommendations for performance testing
    - Papers in journals and at conferences
    - Input to RILEM TC 219-ACS on ASR

Important technical questions

1. Are the alkalis kept in the system? (pH?)

Questions:
1a. Rate and extent of alkali leaching for various test procedures? (no alkali leaching in field)
1b. Influence on the ASR expansion?
2. Sufficient moisture?

![Graph showing the relation between RH and damage due to ASR](image)

**Questions:**
- 2a. Internal RH when testing concrete with low w/cm?
- 2b. Internal RH when adding Supplementary Cementing Materials (SCMs)?
- 2c. Influence on the ASR expansion?

---

3. Any influence of the exposure temperature?

![Triangle with temperatures](image)

**Questions:**
- 3a. Influence on rate and extent of alkali leaching?
- 3b. Influence on internal moisture state?
- 3c. Influence on the ASR expansion?
**Follow-up study** (WP2, 2010-2014)

- Focus on the lab./field correlation
- Extensive test program
  - Selection of the most promising test procedures from WP1
  - Selected aggregate/binder combinations (115 test series)
  - Two field exposure sites established

**Main results**

- Summary results for different concrete recipes?
  - NO!

- WP1: Identical concrete composition (CEM I, w/c 0.45). Result of modifying:
  - Prism size (70 or 100 mm)
  - Specimen “pre-treatment” (incl. pre-curing)
  - “ASR storage conditions” (356°C, wrapping or not, ...)

In general, for concretes with w/b ≥ 0.45:

Rate and extent of alkali leaching is controlling the ASR expansion
Main conclusions

- Specimen "pre-treatment", "exposure conditions" and prism cross-section dramatically influences the outcome of an ASR performance test.

- Alkali leaching the most important source of "error"
  - Early age alkali leaching of particular importance - totally controls expansion at 60°C
  - Urgent: Limit, compensate for, or preferably eliminate alkali leaching

- Internal moisture state becomes of importance for more dense binders (low w/b)

Main recommendations to RILEM

- Remove the wrapping procedure from the RILEM ASR aggregate test methods
  - Wrapping leads to high extent of alkali leaching in the early age
  - Immediately adopted by RILEM TC 219-ACS (two of the three RILEM test procedures withdrawn in 2010)

- Adopt the "Norwegian concept" for performance testing (NB21)
  - Several applications (reactivity of aggregates, alkali threshold for aggregates, etc.)
  - Focus on testing at 38°C (lack of correlation for testing at 60°C)
  - Increase the prism cross section (reduces the extent of alkali leaching)
  - Adopted in the draft RILEM performance test procedure (2012)

- Avoid testing of low w/b concretes
  - Must secure access to sufficient water supply during testing (avoid "false negative" test results)
  - Adopted in the draft RILEM performance test procedure (2012)

- New RILEM TC "AAA" on ASR (2014-2019)
  - Norway have taken the leadership (chair, etc.) led performance task group, ....)
Future research on ASR (based on COIN)

• ASR – Reliable concept for performance testing (BIA/KPN, 2014-2019, 18.5 MNOK)
  • Focus on the lab./field correlation (structures, field exposure sites)
  • Lead by SINTEF
  • Partners: Norcem, NTNU, owners, aggregates producers, international collaborators
  • Input to future regulations (NE21, RILEM TC “AAA”)
  • Also basis for research on repair actions

Summary

• ASR based innovation is feasible
• Norwegian (COIN+) based research is well reputed and contributes to the development of a sustainable performance concept on international level
• Research needs still exist, but we believe that:
  • Threshold items have been identified and are adequately dealt with / are in the pipeline
  • NB 21 main principles are sound (but modifications due)
COIN Seminar
2\textsuperscript{nd} and 3\textsuperscript{rd} December 2014

Focus area 3.2
Reliable design and prolongation of service life
Impact of concrete resistivity on corrosion rate

Karla Hornbostel
\textsuperscript{\small NTNU}

PhD project Participants

Supervisors
Mette Geiker (NTNU - main)
Claus K. Larsen (SVV)
Bernhard Elsener (ETH)
Ueli Angst (ETH)
PhD project
Background

COIN - Concrete innovation in Norway 2007-2014
Closure seminar - Trondheim 2 and 3 of December 2014

PhD project
Background

Electrical resistivity

... characterizes ion transport in concrete

PhD project
Objectives and approach

*Identify and quantify parameters affecting the relationship between corrosion rate and concrete resistivity*

**Approach**
- Literature review $\rightarrow$ hypotheses
- Laboratory testing
- Conclusions
Literature Review

Hypotheses

Improved parameter determination
- Corrosion rate
- Electrical resistivity

Improved understanding
- Rate limiting step
Experimental setup

Simulating macrocell corrosion
Artificial anodes in a large network of cathodes

Results 1

No direct correlation between cell resistance and concrete resistivity
Results 1

Results 2 + 3

- Corrosion process not under resistance control

- Corrosion process is under anodic control

Preliminary conclusion

Chloride induced reinforcement corrosion is under anodic control

Corrosion rate not only dependent on bulk resistivity

... Improves Service Life prediction

Acknowledgements

Funding
• COIN
• SVV
• NTNU

Collaboration
• Colleagues in ETH, COIN
Ductility of Lightweight Aggregate Concrete

Confinement Effects of Fibres

Jan Arve Øverli
Norwegian University of Science and Technology

FA 3 Technical performance

FA 3.3 Structural Performance

- High performance LWAC
- Ice abrasion
- Hybrid structures
- Ductility of LWAC structures
  - A project initiated and in cooperation with KVERNER
People:
- Tore Myrland Jensen, SINTEF
- Helge Brå, SINTEF
- Gunrid Kjellmark, SINTEF
- Tore Arne Martius-Hammer, SINTEF
- Knut Lervik, SINTEF
- Jan Arve Øverli, NTNU
- Ove Loraas, NTNU
- Steinar Seehuus, NTNU
- Gøran Loraas, NTNU

Lightweight aggregate concrete

Advantages
- Reduced dead load
- Reduced inertia forces
- Easier handling and transportation
- Improved durability properties and fire resistance
- Low thermal conductivity

Disadvantages
- Brittness in compression
- Price
Lightweight aggregate concrete

\[ \sigma_c [N/mm^2] = \begin{cases} 
20 & \text{for } C30/37 \\
15 & \text{for } LC30/33 
\end{cases} 
\]

\[ \varepsilon_c [10^{-3}] \]

Construction of GBS

Photos: Norsk Oljemuseum
Construction of GBS

Photos: Norsk Oljemuseum

Construction of GBS

Photos: Norsk Oljemuseum
Construction of GBS

Photos: Norsk Oljemuseum

Ductility

- Ductility is defined as individual structural members or entire structures ability to sustain significant inelastic deformations after peak load without a significant loss in the capacity prior to failure.

- Of great importance in redistribution of forces and a major consideration in design of structures subjected to dynamic loading.
## Confinement

- **Confinement Types:**
  - **Material (axial) ductility**
  - **Cross-section (curvature) ductility**
  - **Member (rotation) ductility**
  - **Structure (displacement) ductility**

  ![Ductility Types](image)

  *Gioncu, 2000*

## Confinement Methods:

- **Circular hoops or spiral**
- **Rectangular hoops with cross ties**
- **Overlapping rectangular hoops**
- **Confinement by transverse bars**
- **Confinement by longitudinal bars**

*Mander et al., 1996*  
*Dowrick, 2003*
Motivation for project

- Increase ductility in lightweight aggregate structures
- Focus on large structures, GBS offshore structures, LNG terminals
- Flexural ductility in heavily reinforced cross-sections
- Effect of fibres and stirrups on the ductility

Experimental program

- Four point bending of beams
- Configurations of confinement, two beams each

**Test series 1**
- Only LWAC
- Steel fibre
- Stirrups with spacing 100mm
- Stirrups + steel fibre

**Test series 2**
- Only LWAC
- Steel fibre 60mm
- Steel fibre 35mm
- Basaltic fibre
**Fibre-Reinforced Lightweight Concrete**

- Density ~1800 kg/m³
- Maximum size of lightweight aggregate 8mm (LECA)
- Compressive strength 30-40 MPa
- 1% fibre
Fibre-Reinforced Lightweight Concrete

![Stress vs. Strain Graph]

Load-displacement, program 1

![Load-displacement Graph]
Load-displacement, program 1

Load-displacement, program 2
**Failure mode**

**LWAC only**

At peak load  
At end of loading

---

**Failure mode**

Steel-fibre

At peak load  
At 90% of spalling load

---
Failure mode

Stirrups

At peak load

At 90% of spalling load

Steel fibre + Stirrups

At peak load

At 90% of spalling load
Strain measurements

Strain distribution

Moment, $M$ [kN.m]

Strain, $\varepsilon$ [%]

LWAC only
Strain distribution

Fibre + stirrup

Ductility

Load steps (LS1-LS10)

Load, P

Continuous loading

Load steps

Ppeak

Ppeak

0.9Pspall

P_spall

Displacement

\[\Delta \text{LS}0\]
## Ductility

<table>
<thead>
<tr>
<th>Beam Configuration</th>
<th>$f_c$ (MPa)</th>
<th>$\Delta_{\text{spall}}$ (mm)</th>
<th>$\Delta_{\text{peak}}$ (mm)</th>
<th>$\Delta_{0.9 \text{spall}}$ (mm)</th>
<th>$\Delta_{0.9 \text{spall}}/\Delta_{\text{spall}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A: Only LWAC</td>
<td>36.9</td>
<td>24.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1B: Only LWAC</td>
<td>39.7</td>
<td>25.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2A: Steel fibre</td>
<td>34.9</td>
<td>23.9</td>
<td>30.5</td>
<td>37.2</td>
<td>1.55</td>
</tr>
<tr>
<td>2B: Steel fibre</td>
<td>39.6</td>
<td>23.1</td>
<td>29.5</td>
<td>52.1</td>
<td>2.25</td>
</tr>
<tr>
<td>3A: Shear links</td>
<td>34.5</td>
<td>24.5</td>
<td>26.0</td>
<td>36.3</td>
<td>1.48</td>
</tr>
<tr>
<td>3B: Shear links</td>
<td>33.5</td>
<td>23.9</td>
<td>28.8</td>
<td>39.5</td>
<td>1.66</td>
</tr>
<tr>
<td>4A: Shear links +</td>
<td>27.7</td>
<td>22.0</td>
<td>34.2</td>
<td>100.7</td>
<td>4.57</td>
</tr>
<tr>
<td>steel fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4B: Shear links +</td>
<td>40.4</td>
<td>22.6</td>
<td>31.4</td>
<td>79.9</td>
<td>3.54</td>
</tr>
<tr>
<td>steel fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Conclusions

- Considerably increased flexural ductility of the beams when applying steel fibres and/or confinement reinforcement. Especially the combination of fibre and confinement reinforcement experienced a continuous response and the beams were able to maintain a high load level after reaching the maximum load.
- No significant influence of the different confinement configurations on the response before initiation of spalling.
- The fibres introduce a softer transformation at spalling. There is no drop in the load response.
Research with COIN & new initiatives 2015 onwards:

- Fresh concrete
  - PhD 2014:89 - Ya Peng on Stability
  - PhD ongoing - Rolands Cepuritis on Crushed aggregates and rheology

- Concrete exposed to ice and frost
  - Review, Kverner in Russia's Far East/Sea of Okhotsk
  - NTNU concrete ice abrasion lab

- New project proposals sent Research Council of Norway
  - Kvaerner et al BIA Innovation DaCS – Durable advanced Concrete Solutions (stage 2 sent 15Oct14)
  - NTNU et al BIA Kompetanse FLOC – FLOWing stable and sustainable Concrete (stage 1 sent 19Nov14)
Stability: the ability to retain a uniform distribution

Hydrostatic Pressure Measurements to study Sedimentation of cement paste

\[ p_0 = \rho_{\text{sus}}gh = \left( \rho_p \cdot \Phi + \rho_i (1 - \Phi) \right) \cdot gh \]

Particles supported by liquid at terminal velocity: \( \rho = p/gh \Rightarrow m/A = p/g \). So at a depth \( h \) with pressure \( p(t) \), initial particle flow \( J \) (kg/m²s) = d/dt (m³/A) = 1/g (dp/dt) and in sediment \( p = \rho gh \) (hydrostatic pressure of water).
HYSPT experimental setup in NTNU's lab

PhD by YP: sedimentation in various powder/admixture combinations

Ongoing YP: further development of method by studies of:
• bleeding (combined with light scanning in turbid media)
• aggregate particles sinking – higher plateau pressure than that of water detected
Rolands Cepuritis PhD characterizing fine crushed aggregate particles and their relation to rheology of fresh concrete:

- «ground truth» vs industrial application of controlled particle size distributions, specific surface, shape, mineralogy etc in crushed fines
- a little «pre-taste» of his work at NIST on μCT:

Figure 9: 3-D VRML images of selected crushed fine particles of basalt studied with μCT scanning and spherical harmonic analysis

DaCS DP3 Concrete-Ice Abrasion

how can a soft material (ice) abrade a hard material (concrete)?

Canadian Confederation bridge (McGuinn et al 2007)
NTNU Concrete Ice Abrasion lab (Kirkhaug 2013, Grenker 2014 etc)

Concrete-Ice Abrasion Mechanics (Jacobsen, Scherer, Schlulson 2014)
# DaCS DP3 Concrete Ice Abrasion

<table>
<thead>
<tr>
<th>No.</th>
<th>Main activity, objectives and deliverables</th>
<th>Participating partners</th>
</tr>
</thead>
</table>
| 3   | Main activity: Concrete ice abrasion resistance  
Objectives/deliverables: To develop a test and calculation model for the wear of concrete due to abrading ice, investigate the effect of basic parameters (material, exposure, roughness etc), combined effect of abrasion and freeze/thaw damage and the effect of repair systems on new and damaged concrete. | Kvæner, Mapei, NTNU, Sintef |

---

# DaCS DP2 Air entrained sustainable concrete

- From AEA to foam to protective air voids
- L-stoff + SP +vann + pulver
- adsorpsjon/stabiliserings/skum
- Paste+aggregate =betong luftpore (hvitt)
- Frostbestandig betong?
<table>
<thead>
<tr>
<th>DP No.</th>
<th>Main activity, objectives and deliverables</th>
<th>Participating partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Main activity: Frost resistant concrete for various purposes</td>
<td>Kvaerner, Norbetong, Mapei, Statens Vegvesen, NTNU, SINTEF</td>
</tr>
<tr>
<td></td>
<td>Objectives deliverables: Identify requirements for frost durability for various purposes including air entrainment mechanisms and the reciprocal effects of cracking and scaling in freeze/thaw performance testing</td>
<td></td>
</tr>
</tbody>
</table>

New BIA KMB proposal – FLOC – 3p stage 1 sent BIA-RCN 19nov14

Outline for Knowledge-building Project for Industry (the BIA programme)

<table>
<thead>
<tr>
<th>Working title of project</th>
<th>FLO:ing stable and sustainable Concrete (FLOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applicant institution</td>
<td>NTNU</td>
</tr>
<tr>
<td>Website of applicant institution</td>
<td><a href="http://www.ntnu.no">www.ntnu.no</a></td>
</tr>
<tr>
<td>Email address of contact person</td>
<td><a href="mailto:stefan.jacobson@ntnu.no">stefan.jacobson@ntnu.no</a></td>
</tr>
<tr>
<td>Telephone number of contact person</td>
<td>+4791180997</td>
</tr>
</tbody>
</table>

1. Is the project of relevance for Research Council programmes other than the BIA programme?
   - If: We have looked for other relevant programmes, but did not find any.
   - No: We are uncertain whether the BIA programme is the correct programme and would like an assessment. Relevant programme(s) may be...

2. Have you submitted an outline to the BIA programme previously?
   - Yes, with BIA outline number: [ ]
   - No: [ ]
   - Don’t know: [ ]

3. What is the objective of the Knowledge-building Project for Industry and what new expertise is the project expected to lead to within Norwegian research groups? How will the project be incorporated into the strategic plans of the applicant institution?
   The goal of this project is to increase knowledge and competence in the fields of particle packing and chemical admixtures to control the stability and rheology of fresh cement-based materials, such as Self-Compacting Concrete (SCC) and Fiber Reinforced Self-Compacting Concrete (FRSCC).
   The research aims to solve the scientific problems of optimizing particle size distribution, dispersion, stability and rheology, with the goal of reaching the quality problem which are often encountered with SCC. This will fulfill the needs of Norwegian concrete industry and society by allowing industrial use of SCC made with sustainable manufactured mineral powders and non-spherical (more irregularly shaped) particles, such as crushed aggregate and steel fibers. Use of crushed aggregate and fibers in concrete production will also conserve natural sand and gravel resources and reduce cost of a significant part of the fine fraction work. SCC is one of the most innovative developments of the concrete industry due to its potential to reduce concrete costs, facilitate placement, improve working environment and enhance surface quality. Moreover, the amount of SCC cast in-situ in Norway has stagnated at a very low level due to factors such as...
3 Competitive constructions

December 2nd 2014

Chairman: Ya Peng

Robust and highly flowable concrete with controlled surface quality

| 15.00 – | Introduction | Klaartje De Weerdt (SINTEF/NTNU) |
| – 15.45 | Surface classification tool | Tone Østnor (SINTEF) |
|         | Assessment of SCC stability – lab and field | Tor Arne Martius-Hammer (SINTEF) Sverre Smeplass (Skanska) |

Chairman: Gunrid Kjellmark

Ductile high tensile strength fibre reinforced concrete

| 16.00 – | Fibre concrete guideline | Terje Kanstad (NTNU) |
| 16.45   | "Pros and cons" and possibilities with fibre reinforcement |

High quality manufactured sand for concrete

| 16.45 – | Introduction | Børge J. Wigum (Norcem) |
|         | Utilisation of Local Low Grade Manufactured Sand | Sverre Smeplass (Skanska) |
|         | Crushed sand, Manufactured sand and "Engineered sand" | Rolands Cepuritis, PhD student (Norcem/NTNU) |
| – 17.30 | Tranportation and Sustainability | Svein Willy Danielsen (SINTEF) |
COIN FA 2.1
Robust and highly flowable concrete with controlled surface quality
Klaartje De Weerdt, NTNU/SINTEF

Members of COIN FA 2.1

SINTEF
- Tone Østnor
- Tor Arne Martius-Hammer
- Kari Aarstad
- Kristin Kaspersen
- Klaartje De Weerdt
- Knut Lervik
- Stig
- Erik
- Roger
- Chris
- Hedda Vikan
- Mari Behnadsale Eide
- Mapei
- Espen Rudberg

NTNU
- Stefan Jacobsen
- Ya Peng
- Ove Loraas
- Albertas Klovas

Norbetong
- Britt Marstander
- Ernst Mørtsell

Norcem
- Knut Kjellisen
- Rolands Cepuritis

Skanska
- Sverre Smeplass

Veidekke
- Lise Bårhen

Statens Vegvesen
- Eva Rodum

ICI
- Jon Vallevik

External advisor
- Olafur Vallevik
Content

1. Surface classification tool
   Tone Østnor

2. Assessment of SCC stability – lab and field
   Tor Arne Martius Hammer and Sverre Smeplass
Classification of Exposed Concrete Surfaces

Kari Aarstad
Kristin Kaspersen*
Klaartje De Weerdt
Tone Østnor

SINTEF Building and Infrastructure
*SINTEF Information and Communication Technology

Motivation

What happens if you end up with a concrete surface with an unacceptable number and size of pores?

- Result in extra finishing costs and man hours
- Result in disagreements between the various parties
- In the worst case: Start all over again
Bygg Uten Grenser

- Their main focus is description of concrete surfaces and how to obtain them
- Our aim is to supplement this work by offering an objective classification tool and system.

The need for a classification tool

- Be able to coordinate expectations on concrete surfaces in advance
  - A tool both for architects and contractors
- Get an objective measure of the amount and size of pores
  - Be an help in discussions between contractors, ready-mixed concrete producers, architects and building owners
- In future, make it easier to study how parameters affect the in-situ cast concrete surface
**Proposed classification system**

<table>
<thead>
<tr>
<th>Pore diameter [mm]</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
<th>Class D</th>
<th>Class E</th>
<th>Class 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>250</td>
<td>800</td>
<td>2500</td>
<td>5000</td>
<td>Project specific</td>
<td>No requirements</td>
</tr>
<tr>
<td>5-10</td>
<td>5</td>
<td>20</td>
<td>50</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-15</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


**Examples of classified surfaces**

200x200 mm

A

B

C

D
BetongGUI

- Objective and quantitative tool
- Image analysis programme based on Matlab for analysing smooth concrete surfaces with regards to pores
- For the photographic procedure normal commercially available photo equipment is used
- The test area is about 60 x 60 cm and the scale is set with a ruler
- User friendly

Set up

- Images are taken with flash from left and right angle (approx. 45°)
- The images are combined by choosing the darkest pixel for each position. This highlights the pores and evens out the background lighting.
Comparison of results

- Compared manual measurement on wall, manual measurement on paper and results from BetongGUI
- Overall good correspondence between all three measurement methods

Demo of BetongGUI
Results after analysis BetongGUI
Future

We now have a tool which allows objective quantification of pores on the concrete surfaces

- It gives a basis to establish the classification system
- It can be used in the description and evaluation of surfaces

We depend on you!

- A beta-version of BetongGUI is available on request
- We wish to test BetongGUI on a wider range of concrete surface qualities.
**SCC - Stability assessment**

**Goal:** To find a method to assess stability of SCC which is practical, reliable and representative for in situ stability problems.

1. Requirements
2. Survey of test methods to find those with potential to fit the requirements
3. Gain experience with them in lab
4. Test them against stability assessed in situ:
   - Stone content along a 10 m long wall, at the top and bottom
   - One "stable" concrete; SF = 700 mm and one "unstable" concrete, SF = 740 mm
**The methods**

0/0.1 Stable and homogeneous concrete. Aggregates and paste flow towards the rim of the sample.

0.2/0.3 Stable and homogeneous concrete that flows well, but has become a shiny surface with possible black spots.

0.4/0.5 Has additionally a hint of a paste rim at the outer edge of the spread, but the aggregates follow the flow towards the edge. Still solid.

0.6/0.7 Clear rim of paste at the outer edge of the spread. Coarse aggregates tend not to flow towards the edge of the spread (are left in the middle of the spread).

0.8/0.9 Additional separation of water paste at the outer rim of the spread.

1 Complete separation.

---

**Settlement Pipe**

**Segregation, SPSI**

**Rheological Segregation, RSI**

**T-Box - penetration index, PDI, and volumetric index, VI**

---

**In field**
In field
Results

Casting of wall element - Mix A

Casting of wall element - Mix B

Results

Part of stone [kg/m]

Part of stone [kg/m]

SINTEF
Results

<table>
<thead>
<tr>
<th>Concrete</th>
<th>VSI&lt;sup&gt;b&lt;/sup&gt;</th>
<th>RSI</th>
<th>SPSI</th>
<th>T-Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, SU=700, ( t_{500} = 0.8 )</td>
<td>0.5/0.6</td>
<td>0.5</td>
<td>0.88</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>B, SU=740, ( t_{500} = 0.4 )</td>
<td>0.7/0.8</td>
<td>0.9</td>
<td>0.68</td>
<td>-6 mm</td>
</tr>
</tbody>
</table>

Conclusion

Three methods seem to reflect segregation in a wall in a good way.

The VSI-test is obviously the easiest and fastest one, also because slumpflow is measured in most cases anyway. Person dependency?

The RSI-test is relatively easy and fast, but power supply is needed and data has to be processed in a separate computer.

The SPSI-test is the slowest and less easy one of the three, also because it includes flushing, drying and weighing of the coarse aggregates. But, fairly directly to the point; the difference in coarse aggregate content.

Note: Limited investigation; more concretes (with higher viscosity?) must be tested.

Nevertheless, the results show that these methods may be used to specify and control stability, and thus form a basis for revision of NB29.
COIN FA 2.2: Ductile high tensile strength fibre reinforced concrete
Terje Kanstad - Department of structural engineering, NTNU

Fibre concrete guideline - "Pros and cons" and possibilities with fibre reinforcement

+Project overview:

(1) Fibres and concrete qualities with high tensile stress after cracking
(2) Development of regulations for design and execution of FRC
(3) Tests of load carrying structural elements within or related to COIN

Overall objective: To do R&D work which stimulates and makes use of fibres possible in load carrying structures.

Project Overview

• Industrial partners:
  • Veidekke, Unicon, Mapei, Norwegian public roads admin, Reforcetech
  • Outside COIN: Spenncon/Consolis, Thilt AS and Bekaert
  • FA 3.3: Kvaerner and Weber St Gobain

• NTNU researchers: Giedrius Zirgulis, Elena Vidal Sarmiento, Håvard Nedrelid, Mette Geiker, Stefan Jacobsen, Max Hendriks, Jan Arve Øverli and Terje Kanstad

• Lab-engineers: Ove Lorås, Steinar Seehuus and Gøran Lorås

• SINTEF researchers: Gunrid Kjellmark, Tor Arne Hammer, Helge Brå

• Ex SINTEF-researchers: Sindre Sandbakk, Hedda Vikan, Bjørn Erik Jakobsen

• + 6 MSc students this spring (typical number for all years)

• Thanks to all who have contributed, and to those who funded the project
Time schedule COIN FA 2.2:

- It’s not over until it’s over !!

Giedrius Zirgulis Ph.D defence March 1st 2015
Elena Vidal Sarmiento Ph.D defence Oct 2015

1 jan. 2007
31.des. 2014

Ongoing PhD-studies: Giedrius Zirgulis

Main topics
- Quantification of fibre orientation in structural elements by CT and image analysis of sawn and polished sections.
- Influence of geometry, casting method, mould surface structure, and reinforcement on fibre orientation
- Investigation of relations between fibre orientation and post-cracking tensile strength

Main contribution
Basis for avoiding the most unfavourable situation and utilizing the favourable effects of fibre orientation in practice
**Ongoing PhD-studies: Elena Vidal Sarmiento**

**Main Topics**
- Quantification of fibre orientation and fibre volume variations
- Structural analysis (Nonlinear finite element analysis) including the effects of fibre orientation and fibre volume variations due to flow and segregation.
- Further utilization of the 15MPa concrete
- Uniaxial tensile strength testing

**Main contribution**
- Will contribute a more thorough basis for design of structures made of flowable FRC

The fibre efficiency parameter:

\[ \mu = w_1(\cos \theta) + w_2 \left( \frac{\sigma_f}{f_f} \right) \]

---

**Fibre types:**

- Steel fibres with hooked ends, ordinary / high strength quality – L=35-60mm several suppliers
- Alternative steelfibres
  - Alternative geometry
  - Alternative steelquality
  - Short fibres
- Polymer-fibres (typically Barchip)
- Basalt-fibres (=Reforcetech’s Minibars)
Traditional fibre concrete for slabs on grade and sprayed concrete:

- Until 40 kg steel fibres per m³ concrete (0.5 volum%)*
- Until 10 kg polymer fibres per m³ concrete (1.0 volum%)*
- Until 12 kg Minibars per m³ concrete (0.6 volum%)*

- Concrete composition as for ordinary concrete
- Suitable for floors, sprayed concrete for rock stabilization and for solutions combined with traditional longitudinal reinforcement

*Based on the speakers personal experience and overview

What is fibre concrete and how does the fibres work?

Together with longitudinal reinforcement can fibres contribute to:
- Closer crack spacing and smaller crackwidths (invisible)
- Less deformations (increased stiffness)
- Increased moment and shear capacity

Traditional reinforcement can therefore partly be replaced by fibres
The fibre concretes materials properties can be characterized by various test methods:

- **Uniaxial residual tensile strength**
  \[ \sigma = \sigma (w) \]

- **Slab test according to NB7**

- **Residual-flexural tensile strength**

- **Pullout of single fibres**

  Ph.D. Sindre Sandbakk (2011)

---

**NS-EN 14651**

---

109
The design-parametres are taken from the beam test

Restbøyestrekkestabilitet ved 2,5 mm rissvidde: \( f_{R3} = \frac{3P1}{2bh^2} \)

One step towards the vision of a 15MPa tensile strength concrete

- Concrete delivered by Unicon with 1 vol% 60mm steel fibres (80kg/m³)
  The concrete recipe is modified by removing parts of the course aggregate (økt finstoffmengde) (PhD-candidate Giedrius Zirgulis)

Characteristic value
Characteristic uni-axial residual tensile strength
Best so far .... \( w/b = 0.35, 2\text{vol\% Steel fibres} \)

**Characteristic value**

**Characteristic uni-axial residual tensile strength**

---

**Development of national and international regulations**

**Norsk betongforeningspublikasjoner relatert til fiberarmert betong:**

- **NB 15** Betonggulv, gulv på grunn og påstøp (ferdig i løpet av 2014)

- **NB 38** Use of fibre reinforcement in load carrying concrete structures: Guidelines for design, execution and control (høringsversjon ferdig i løpet av 2014)
NB 38 Use of fibre reinforcement in load carrying concrete structures: Guidelines for design, execution and control

Committee:

Øivind Bjøntegaard, Statens Vegvesen, Vegdirektoratet
Alf Egil Mathisen, Jernbaneverket (tidlig Veidekke)
Arne Vatnar, Skanska (tidlig Unicon)
Åse Lyslo Døssland, Multiconsult, Bergen
Nils Leirud, Bekaert
Dan Arve Juvik, Mapei
Thor Sandaker, Norconsult
Jorun-Marie Hisdal, Sintef
Helge Brå, Sintef
Terje Kanstad NTNU

Steinar Leivestad (NB representant og "godfather" for the committee)

Overview over standardization work

Norwegian arena

COIN-rapporten Forøg til retningslinjer for dimensjonering, utførelse og kontroll av fiberarmerte betongkonstruksjoner ble gitt ut og oversendt Norsk Betongforening i 2011.
Komite for Norsk betongforenings-publikasjon etablert i 2012
Rapporten planlegges ferdigstilt i 2014

Praktisk erfaring med retningslinjene og videre verifikasjon og utvikling
Flere referanseprosjekt er ønsket !!

International arena

Fib Model Code ble ferdigstilt i 2011. Endelig trykt utgave i 2013.:

Etablering av Eurocode 2 komite CEN/TC 250/SC 2 TG 2 "Fibre reinforced concrete" høsten 2012 (Norsk initiativ)

Tysk regelverk iht EC2: Steel fibre reinforced concrete. «Komplett» iht EN 206 og 13670.
2013: Forslag til Svensk Standard, SS 812310 Dimensionering av Fiberbetongkonstruktioner
2014: Forslag til Dansk regelverk (DTI), Spesielt tilpasset SCC

Nytt annex til EC2 om Fiberbetong planlegges ferdig i 2015, og endelig utgave i 2020.
Committee work organized within NB

- Based on a COIN-report (2011) but is rewritten to be similar to NB’s sprayed concrete publication (NB7)
  - Specification (Spesifikasjon)
  - Test methods (Prøvingsmetoder)
  - Calculation methods (Dimensjoneringsregler)
  - Guidelines (Veiledning)
- To be finished in 2014
- Today:
  - Validity range (Gyldighetsområde)
  - Design-parameters & strength-classes
  - Test program for concrete producers
  - Control and documentation of execution

Validity range: Structures with hardening...

Crackwidth control according to EC2 7.3.4 when required for durability

Can be achieved by:
- Fibres and reinforcing bars
- Fibres & other load bearing systems
- Fibres alone
- Taken care of by modified minimum reinforcement rules (Chapter 9 in EC2)
Experience with structural elements

- Moment capacity of beams with fibres+bars
- Moment capacity, beams with only fibres

Minimum reinforcement (Chap 9 i EC2)

Bjelker skal ha en minste armeringsmengde på strekksiden:

$$A_{x,\text{min}} = 0.26 \cdot \frac{f_{ctm}-f_{Fstm}}{f_{yk}} \cdot b_t d \geq 0.0013 \cdot (1 - \frac{f_{Fstm}}{f_{ctm}}) \cdot b_t d$$

For armerte betongbjelker er kravet til minimum skjærarmering [mm²/mm²]:

$$\rho_{w,\text{min}} = \left(0.1 \sqrt{f_{ck}} - 0.2 f_{Fstm}\right) / f_{yk}$$

About 0.7 volume % (50kg/m³) eliminates the need for minimum reinforcement according to these formulas.
Minimum reinforcement (Chapter 9 i EC2)

Minimumsarmeringkravet for plater er i prinsippet de samme som for bjelker, men gjelder begge retningene. Hovedarmeringen og en gjennomgående minimumsarmering på tvers av denne skal derfor begge ha et tverrsnittsareal som svarer til:

$$A_{x,min} = 0.26 \cdot \frac{f_{ctm} - f_{Ft,m}}{f_{yk}} \cdot A_c \geq 0.0013 \cdot (1 - \frac{f_{Ft,m}}{f_{ctm}}) \cdot A_c$$

About 0.7 volume % (50kg/m3) eliminates the need for minimum reinforcement according to this formula.

Moment capacity

Figur 6.2: Spennings- og tyngdfordelings for rektangulært tverrsnitt av armert fiberbetong utsatt for ren boyning. Betongens bruddtyngning for trykk, $\varepsilon_{u,0}$, er gitt i tabell 3.1 i Eurocode 2.

$$M_{Rd} = S_f(0,5h + 0,1x) + S_a(d-0,4x)$$
Addition rule for bending and axial forces:

For structural members exposed to moments and/or axial forces where a structural collapse can lead to loss of human life, or is of major social or economic importance shall it in addition be verified that bending moments and the axial tensile forces can be carried by the cross section without contribution from the fibre reinforcement.

In this control all load and material coefficients shall be set equal to 1.0, and the combination factors $\psi_{0,i}$ (Table A1.1 EN 1990) be used for the accompanying variable actions.

From the specification part:

The specification to the concrete producer shall at least include:
- Strength class (Fasthetsklaasse)
- Durability class (Bestandighetsklasser)
- Residual strength class (Restkrekkfasthetsklaasse)
- Max aggregate class (Maksimal tilslagsstørrelse) $D_{max}$

The fibres shall be declared according to the following materials standards:
- NS-EN 14889 – 1 Fiber for betong Del 1: Stålfibre. Definisjonskrav, krav og samsvar, eller
- Teknisk Godkjenning/ ETA (European technical approval)

Longtime-load and temperature stability
Uncertaintly due to polymer fibers properties under longtime load and high temperatures
For situations where this might be critical, these properties must be particularly verified
Pre-documentation of the residual flexural strength

In addition to ordinary testing, the concrete producer shall document the residual flexural tensile strength (restbøyestrekkfastheten) using standard beams cast with the current concrete, mixing and transport equipment, and fibre addition method.

If the fibres are added directly in the automixer shall the mixing volume be at least 50% of the automixers total volume. Requirements for amount of fibres and distribution (minus- and plus tolerances) shall also be controlled for the same volume.

Scope and procedures are described

Test program for concrete producers

- The concrete producers shall verify the residual flexural tensile strength. Scope and procedures are proposed:

![Graph showing the relationship between residual flexural strength and steel fibre content.](image)
Control and dokumentation of execution:

- A risk evaluation regarding stability for the concrete deliveries and the casting works shall be carried out by the contractor.
- It is for safety reasons extremely important that fibre-continuity between different casting batches is secured.
- Casting breaks which might give (separate) layers shall not occur. This is the contractor’s responsibility.
- It is very important that hindrances do not create weakness zones with low amounts of fibres.

Design-parameters & methods

Uniaxial residual tensile strength $= 0.37 \times$ Residual flexural strength

$$f_{\text{fr},\text{res},2.5} = 0.37 f_{R,2.5}$$

Expressions for moment capacity
Moment and axial force
Shear force capacity
Torsion
Crackwidth calculations
Minimum reinforcement rules
Typical applications:

- Foundations
- Walls
- Beams
- Load carrying slabs and ground slabs on piles
- Pipes and culverts
- Design for concentrated loads on slabs on grade and design of sprayed concrete in special cases
- Others? For sure

Design, testing and evaluation of a fullscale post-tensioned steelfibre reinforced flat slab

Ordinary reinforcement replaced by steel fibres (0.4% /30kg/m3)

Dr. Steinar Trygstad
THILT Engineering AS, Ålesund

Prof. Terje Kanstad
Department of structural engineering, NTNU

Funded by Spennteknikk construction AS, Betong Øst, Dyrøy betong, Mapei, Innovation Norway, NTNU mfl)
Objectives

- Stimulate use of fibres in load carrying structures
- Verify Norwegian proposal for fibre concrete guidelines
- Moment capacity
- Moment (re)distribution – Elastic analysis vs yield line analyses
- Shear capacity around central column
- EN14651 strength vs in-situ residual strength
- Ductility & robustness as input to future Eurocode 2 annex for steel fibres

Tendon layout and slab geometry

150 mm² tendons

Figure 50: Tendon layout in x-direction.
Test results: Deflections in both slabs

Summary and conclusions

- The results are considerably at the safe side if characteristic strength values and elastic theory for calculation of moment and shear forces are used – This holds independently of which guidelines are used
- If yield line analysis and redistribution of forces is accounted for – nice agreement between theory and experiment is achieved
- The ductility seems to be sufficient
- The current approach with a relatively low degree of prestressing and low amount of fibres can be recommended for further use in practice
- A reference project has been carried out (Munkvold – Trondheim)
- A technical approval is in progress at Sintef
Structural fibre-reinforced concrete - Tests and design methods for RC beams with dapped ends and RC beams with openings Carried out in cooperation with Spenncon

Also:
I-shaped cross sections
Post-tensioned beams
LWAC beams
Anchorage of steel details
Post-tensioned flat slab
Conclusions

- The proposed calculation model agrees well with experimental behaviour.
- Dapped end beam reinforcement can be considerably reduced if fibres are used.
- Only main tensile bars is possible, but not recommended.

One hanger should be included for practical and economical reasons.
And nib tensile reinforcement for robustness and uptake of horizontal forces.
Summary beams with openings

- It has been shown that the shear reinforcement in the region of the openings can be replaced by 1.0 vol% hooked-end steel fibres
- Simple shear design formulas for RC beams with openings based on the EC2 expressions for solid beams have been proposed
Final comment

- The use of fibres in load carrying structures will increase ...
- And COIN has contributed to this ...

- And thank you for listening ..
COIN – Concrete Innovation Center
Concrete innovation in Norway 2007-2014

December 2nd & 3rd, 2014
Realfagsbygget, Auditorium R9, NTNU Høgskolen i Trondheim

COIN FA 2.3
High quality manufactured sand for concrete

Børge J Wigum – Norcem/NTNU

The outcome; 2008 - 2014

COIN FA 2.3
High quality manufactured sand for concrete:

New aggregate processing methods (crushing and classification) - along with new sophisticated ways of concrete mix design - have enabled the production of various types of concrete containing 100% crushed aggregates.

These innovative new processes and products provide a better utilization of natural resources; reducing transportation and environmental impacts, and lead to improved sustainability in the building sector.
Why manufactured sand?

Natural resources are depleting
Transportation of aggregates in Norway (2012); 110,000 tonn CO₂

- 1.1% of all transport
- 10% of cement

Increased transportation

Manufactured sand
Utilisation and Innovation – both by low- and high quality
This session

16:45-17:00  Introduction & Background  - Berge Johannes Wigum

17:00-17:10  Utilisation of Local Low Grade Manufactured Sand  - Sverre Smeplass

17:10-17:30  Crushed sand, Manufactured sand & «Engineered sand»  - Rolands Capuritis

17:30-17:30  Transportation and Sustainability  - Svein Willy Danielsen

Manufactured sand – Workshop; Stavanger, Norway, October 30th and 31st 2008
Trade journals - newspapers

New type of crushed sand to replace natural sand in concrete production

Korteist stein løser knipe

Theses

Effects of Concrete Aggregate Crushing on Rheological Properties of Concrete and Matrix

Phd. thesis 2015
Rolands Cepuritis

NTNU
Manufactured Sand in Concrete
Sustainable & Durable Structures for the Future!
Værnes Airport Commuter Terminal concrete slabs:

The use of low grade manufactured sand

- 28800 m² slabs, 350 mm thick
- 10000 m³ concrete
- Non-reactive aggregates
- Low-alkali binder or CEM II/A-V
- High flexural strength requirement
- Frost resistance

Problem: local crushed rock and local natural sand are both alkali reactive!
Solution developed in cooperation between Skanska and Norbetong

- Non-reactive crushed rock from Nord-Fosen
- Combined sand
  - 60% non-reactive manufactured sand from Nord-Fosen
  - 40% reactive local natural sand
- CEM II/A-V binder
- "Normal" binder content
- Relatively high dosage of SP
  - Slightly retarded concrete
- Prolonged mixing time

Manufactured sand from Nord-Fosen

- Low grade - no processing after crushing
- High content of fines, 11% < 0.125 mm
Slab production

- Bidwell paver
- Slump measure 220 mm
- Placing of concrete in front of paver by concrete pump
- Brushed finish
- Extensive use of curing membrane

Challenge: Very viscous concrete. Normal slump for this production process is approx. 140 mm
Results and conclusion

- High quality slabs
  - No separation or segregation
  - Superb wear properties
- High flexural strength
- Acceptable variation in fresh and hardened concrete properties

- Low grade manufactured sand can be used successfully for special purposes
- Production must be adapted to "deviating" concrete properties
Chapter 9 – Concrete aggregates

- Both in the PAST and TODAY it is MOST COMMON to use sand aggregates from NATURAL gravel deposits [...]

- In more recent years, it has also become common with partial mix of sand produced from CRUSHED ROCKS (the so-called “CRUSHED SAND/ MACHINE SAND” [...]

Crushed sand, Manufactured sand & “Engineered sand”
Using “crushed sand”...
... without a “PRESCRIPTION” from a DOCTOR:

- Crushed sand 🙄 крушка 😞 !!!
- Crushed sand 🙄 крушка 😞 !!!

Desired slump
Too high plastic viscosity [μ]

Types of "crush sand"

- Crushed sand
- Crushed sand
- Crushed sand
- Crushed sand
- Natural sand

Cumulative % passing

80-100 NOK/t

0.7 mm

0.075

Sieve size [mm] 7.5
Types of "crush sand"

- Low quality crushed fine aggregate
- Crushed/Manufactured sand
- ENGINEERED sand
  - VSI
  - FINES OPTIMIZATION
  - MICROPROPORTIONING

ENGINEERED SAND - TOOLBOX

Cumulative % passing vs Equivalent size [µm]
ENGINEERED SAND – HOW TO

New type of crushed sand to replace natural sand in concrete production

Study by Rolandas Capovilas

Sand from the Rocks

New type of crushed sand to replace natural sand in concrete production.

FROM STOCKPILE TO SAND

The availability of natural sand for concrete production is an increasing challenge, which is sometimes overwhelmed by aggregate producers. This means that the industry has a huge need to solve this challenge by finding suitable technology for crushed sand production.

NORCEM

HEIDELBERG CEMENT Group
COIN – Concrete Innovation Center

COIN FA 2.3

High quality manufactured sand for concrete

Transportation and sustainability

Svein Willy Danielsen
SINTEF

We can estimate that close to 80% of the sand/gravel ever taken out of the nature, has been consumed in our generation.

How do we continue from there?
Access to materials resources will be one of the major global drivers in the years to come

(Prof. Roger Flanagan UK)

Some international key figures

- Global demand for aggregates is some 15 billion tons/year
- Expected to increase to 22 billion, where China alone will account for some 6 billion
- European aggregate industry produced >3 billion tons in 2005, at a value of >40 billion €
  - 47% sand/gravel, 45% crushed hard rock
  - The remaining part was recycled and artificial materials
  - Production took place in 28,000 quarries
- European concrete production is almost 600 mill m³, and uses approx 1,2 billion tons of aggregates per year
### % distribution for some countries

<table>
<thead>
<tr>
<th></th>
<th>Crushed</th>
<th>Recycled</th>
<th>Of European total prod.</th>
<th>Of Eur. no. of quarries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway</td>
<td>83</td>
<td>&lt;1</td>
<td>3,2</td>
<td>16</td>
</tr>
<tr>
<td>Sweden</td>
<td>77</td>
<td>10</td>
<td>3,1</td>
<td>6,5</td>
</tr>
<tr>
<td>Netherlands</td>
<td>0</td>
<td>42</td>
<td>1,6</td>
<td>0,7</td>
</tr>
<tr>
<td>Germany</td>
<td>48</td>
<td>9</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>UK</td>
<td>62</td>
<td>20</td>
<td>6,8</td>
<td>4,6</td>
</tr>
<tr>
<td>France</td>
<td>57</td>
<td>2,5</td>
<td>15</td>
<td>9,5</td>
</tr>
<tr>
<td>Spain</td>
<td>71</td>
<td>&lt;1</td>
<td>7,5</td>
<td>6,8</td>
</tr>
</tbody>
</table>

**Mineral aggregates can only be extracted where nature has placed them**
But the aggregates have to be used where society needs them

And that is not necessarily the same place
Transport and emissions – Norway

<table>
<thead>
<tr>
<th>Transport</th>
<th>Domestic market, million tonnes</th>
<th>Million tonne - km</th>
<th>Ktonn CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car, crushed rock</td>
<td>34</td>
<td>616</td>
<td>80</td>
</tr>
<tr>
<td>Car, sand/gravel</td>
<td>11</td>
<td>233</td>
<td>30</td>
</tr>
<tr>
<td>Ship, domestic</td>
<td>11</td>
<td>2000</td>
<td>30</td>
</tr>
<tr>
<td>TOTAL, domestic</td>
<td>56</td>
<td>2850</td>
<td>140</td>
</tr>
</tbody>
</table>

In addition: 22 million tonnes for export and off-shore

Sources: NGU and Odd Hotvedt
Sustainability:

Resource management is the key – access to resources the main challenge.

Any encroachment upon nature should be justified by increased values for the society, both relating to the products made and to the area left for later use.
Local production – less transport – less emissions

Tunnels

Sub-surface quarrying

MASS BALANCE

Excavations

Less predictable rock properties

Sustainability concept

Requirements

Environmentally friendly
4 Environmental friendly concrete structures

December 3rd 2014

Chairman: Serina Ng

Binders with low emission and reduced resource consumption

09.10 – Fly ash-limestone synergy
Klaartje De Weerdt (SINTEF/NTNU)
Knut O. Kjellsen (Norcem)

Accelerators for fly ash cement
Klaartje De Weerdt (SINTEF/NTNU)
Espen Rudberg (Mapei)

Calcined clay
Klaartje De Weerdt (SINTEF/NTNU)

Calcined marl
Klaartje De Weerdt (SINTEF/NTNU)
Geir Norden (Saint-Gobain Weber)

– 09.55 Plasticizers for SCMs
Klaartje De Weerdt (SINTEF/NTNU)

Utilisation of concrete in low energy building concepts

09.55 – Concrete and Passive House
Olafur Wallevik (SINTEF)

ZEB-concrete and LCA
Kristin Holthe (Byggutengrenser)

–10.35 Insulating concrete
Olafur Wallevik (SINTEF)
COIN FA 1.1

Binders with low emission and reduced resource consumption

Klaartje De Weerdt, NTNU/SINTEF

COIN proposal

1. Reduced CO₂ emissions
2. High tensile strength
3. High flowability and stability
4. Low permeability
FA 1.1 objective (COIN application)

- The overall goal:
  To identify and document general purpose cementing materials that will decrease CO2-emissions by at least 30% compared to an average Portland cement clinker (about 900 kg CO2 per ton).

- A sublime idea from the project leader:
  Combining fly ash or blast furnace slag (aluminate rich) with limestone filler to form a ternary blend.
  This would lead to a larger fraction of the limestone reacting to calcium carboaluminate hydrate, $Ca_3Al_2O_6-CaCO_3\cdot11H_2O$, which might result in a strength increase.

Content

1. Fly ash–limestone synergy (PhD Klaartje De Weerdt)  
   → Knut O. Kjellsen, Norcem

2. Accelerators for fly ash cement (PhD Kien Dinh Hoang)  
   + further work (Harald Justnes)  
   → Espen Rudberg, Mapei

3. Calcined clay (PhD Tobias Danner)

4. Calcined marl (Tone Østnor)  
   → Geir Norden, Saint Gobain Weber

5. Plasticizers for SCMs (Serina Ng)
Content

1. Fly ash–limestone synergy (Klaartje De Weerdt) → Knut O. Kjellsen, Norcem

2. Accelerators for fly ash cement (Kien Dinh Hoang) + further work (Harald Justnes) → Espen Rudberg, Mapei

3. Calcined clay (Tobias Danner)

4. Calcined marl (Tone Østnor) → Geir Norden, Saint Gobain Weber

5. Plasticizers for SCMs (Serina Ng)

Fly ash – limestone synergy

«Blended Cement with Reduced CO₂ Emission – Utilizing the Fly Ash-Limestone Synergy»

- Higher strength for cement with fly ash+limestone than clinker replacement with fly ash alone.
- Fly ash contributes with more aluminates when combined with limestone:
  → calcium carboaluminate hydrates ↑ (proposal)
    → stabilizes ettringite (voluminous) ↑
    → lower porosity ↓
    → higher strength ↑

Dr. Klaartje De Weerdt
NTNU thesis 2011:32
Fly ash – limestone synergy

Strength increase replacing 5% FA with L

28 days strength

9%

all mixes 35% cement replacement

Fly ash – limestone synergy

Backscatter electron image

Limestone particle

Reaction rim
Fly ash – limestone synergy

Norcem experience
Knut O. Kjellsen, R&D Manager, Norcem

- Hypothesis by Harald Justnes (SINTEF): Fly-ash + limestone => chemical reaction

- The ‘fly ash – limestone synergy’ activity was very successful:
  - Scientific idea
  - Excellent researchers
  - Scientific work within the frame of the Cement Standard
Fly ash – limestone synergy

- Norcem product development project
  - 'Fly ash - limestone synergy effect' forms an important technical basis for a new cement product

Content

1. Fly ash–limestone synergy (Klaartje De Weerdt)
   → Knut O. Kjellsen, Norcem

2. Accelerators for fly ash cement (Kien Dinh Hoang)
   + further work (Harald Justnes)
   → Espen Rudberg, Mapei

3. Calcined clay (Tobias Danner)

4. Calcined marl (Tone Østnor)
   → Geir Norden, Saint Gobain Weber

5. Plasticizers for SCM’s (Serina Ng)
Accelerators for fly ash cement

“Hardening Accelerator for Fly Ash Blended Cement”

- Fly ash is much slower reacting than cement → finding a good hardening accelerator
- Kien found a ternary hardening accelerator for cement with 30% fly ash fulfilling EN 934-2:
  - >120% compr. strength at 24 h and 20°C
  - >130% compr. strength compared 48 h and 5°C
  - strength >90% at 28 d for both

Dr. Kien Dinh Hoang
NTNU thesis 2012:366

---

Accelerators for fly ash cement

!!! XYZ-accelerator was patented by MAPEI !!!

<table>
<thead>
<tr>
<th>Temperature</th>
<th>2 days</th>
<th>28 days</th>
<th>1 day</th>
<th>28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°C</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>+62%</td>
<td>+14%</td>
<td>+30%</td>
<td>+11%</td>
</tr>
</tbody>
</table>

---

Dr. Kien Dinh Hoang
NTNU thesis 2012:366
Further accelerator development

MAPEI wished to replace the «Z» in the XYZ-formulation
ref. COIN report nov 2014

Accelerators for fly ash cement

Mapei experience
Espen Rudberg
**Product development at Mapei**

- New accelerator tested in M45 and M60 concrete at low temperature and room temperature (also for other cements)
- This work has given ideas for new products (also in other business areas)

![Graph showing product development](image)

**Content**

1. Fly ash–limestone synergy (Klaartje De Weerdt)  
   Knut O. Kjellisen, Norcem
2. Accelerators for fly ash cement (Kien Dinh Hoang)  
   + further work (Harald Justnes)  
   Espen Rudberg, Mapei
3. Calcined clay (Tobias Danner)
4. Calcined marl (Tone Østnor)  
   Geir Norden, Saint Gobain Weber
5. Plasticizers for SCMs (Serina Ng)
Calcined clay as SCM

“Reactivity of Calcined Clays”

- Fly ash is slowly reacting
  Need to look for alternative supplementary cementing materials (SCMs)
- A COIN State-of-the-Art report concluded that calcined clays could be promising
- Initial tests of calcined “ordinary blue clay” dug out of the ground were so interesting that partner Saint Gobain Weber financed a separate PhD study

Content

1. Fly ash–limestone synergy (Klaartje De Weerdt) → Knut O. Kjellsen, Norcem
2. Accelerators for fly ash cement (Kien Dinh Hoang) + further work (Harald Justnes) → Espen Rudberg, Mapei
3. Calcined clay (Tobias Danner)
4. Calcined marl (Tone Østnor) → Geir Norden, Saint Gobain Weber
5. Plasticizers for SCMs (Serina Ng)
Calcined marl (CM) as SCM

- Marl is a clay containing some calcium carbonate making it unsuitable for expanded clay products
- Large and unexploited resource

Tone A. Østnor
done sufficient work on marl to warrant a PhD.
Calcined marl (CM) as SCM

Improved chloride resistance!!

Calcined marl (CM) as SCM
Calcined marl (CM) as SCM

Conclusion: Calcined marl is an effective pozzolan

+ Good compressive strength at both 1 and 28 days, even for 50% cement replacement; Strength continues to increase to 2 year
+ Chloride ingress significantly decreased up to 50% marl
- Carbonation rate increase with increased cement replacement as for most blended cements.

Calcined clay and marl as SCM

Saint Gobain Weber experience
Geir Norden
Content

1. Fly ash–limestone synergy (Klaartje De Weerdt)
   → Knut O. Kjellsen, Norcem
2. Accelerators for fly ash cement (Kien Dinh Hoang)
   + further work (Harald Justnes)
   → Espen Rudberg, Mapei
3. Calcined clay (Tobias Danner)
4. Calcined marl (Tone Østnor)
   → Geir Norden, Saint Gobain Weber
5. Plasticizers for SCMs (Serina Ng)

Plasticizers for SCMs

- SCMs will affect the workability of mortar and paste
- The activity focused on finding the best plasticizer for mortar with SCM such as fly ash (FA) and calcined marl (CM) as two extremes in terms of water demand
- A range of plasticizers were tested: lignosulphonate and naphthalene based plasticizers were compared with 3 modern polycarboxylate super-plasticizers

Dr. Serina Ng employed SINTEF since Jan 2013
Cement replaced by FA and CM

Different SPs (LS, NSF, SX) 0.2% for different FA and CM replacement

- More FA - lower flow resistance
- More CM - higher flow resistance
  SPs could not plasticize >40%CM

Hypothesis:
- FA interacts little with SP
- CM interacts strongly with SP

..but where is the FA1.1 leader?

"Nobody knows where the rabbit jumps" as we say in Norway, without further comparison.... 😊

Harald Justnes
Utilisation of concrete in low energy building concepts – Industry initiatives and perspectives

Concrete innovation in Norway 2007-2014
December 3, 2014 in Trondheim
Kristin Holthe, Multiconsult / Coordinator CEAP

Low energy / Zero Emission Buildings challenge the materials

• GHG emissions of production

• GHG emissions over the whole life cycle: Production – Building use phase – End of life

• Environmental documentation

• The concrete industry is working on several areas
Production of cement and concrete

The industry is working on several areas to reduce overall Green House Gas Emissions:
- Cement
  - Additives, use of flyash and slag, increased use of alternative fuel and Carbon Capture Storage
- Concrete
  - The use of e.g. flyash and optimize the recipie
- Low carbon classification system Committee in The Norwegian Concrete Association (Norsk betongforening)

Low carbon cement

environmental cement

low carbon concrete

environmental concrete

green concrete
Environmental documentation of concrete

- EPD-generator: 3 parts verified environmental documentation according to international agreed standards
- The industry itself may develop EPDs for own products

Concrete in buildings - Use phase

- Potential for CO₂ uptake in concrete constructions, both during use and concrete recycling
- Thermal mass in buildings and its potential for contributing to reduction in energy use, and thus GHG emissions.
- Solutions that combine sound absorption and energy storage/use of thermal mass in buildings
Thermal mass

- T-BOX concept - increased knowledge of usage of thermal mass in concrete structures

- Developed by the Norwegian Precast Concrete Federation in cooperation with their members prior to CEAP
- Under the CEAP, the concept was further developed to meet future regulatory requirements for energy performance

Energy efficiency of buildings | Storage of thermal mass
The cooperation between Concrete Innovation Centre (COIN) and the CEAP started in late 2013:

- **Thermal mass:**
  - Collate current results from pilot buildings and assess the need for further work
- **Life cycle assessments:**
  - Collate experiences from LCA and greenhouse gas assessments of pilot buildings and identify methodological challenges for future work
- The cooperation has resulted in e.g. a *workshop in 2013* which involved both themes, where state-of-the art solutions on both themes were given and resulting in spin-off ideas for further R&D projects.

**Thermal Mass | Future needs for R&D**

- Some results exits, on use of thermal mass / use of concrete (pilot buildings)
- **Future needs** regarding thermal mass:
  - Bring forward *more* lessons learned from pilot projects and use of energy calculation tools
  - Calculations results on kWh, GHG emissions, costs for different design solutions
  - Establish *simplified models and tools* for how to further exploit thermal mass
  - Establish *guidelines* for design for optimal use of thermal mass / also based on pilot experiences
The Concrete Environmental Action Plan (CEAP) 2012-2015

- Why and who
  - Create a **new arena** for cooperative approach to common challenges
  - Main organizations with **long traditions in developing new knowledge about concrete** for a large number of members

Goal/vision of the CEAP

- Agreed goals, priorities and actions will give the concrete industry a high awareness of the environmental performance of its final products and of the production phase of these.
- By promoting existing initiatives and projects, as well as establishing a specific amount of new research and development projects (R&D projects), CEAP’s goal are to be achieved through:
  - Building on existing knowledge
  - Contribute to new knowledge
  - Implement plans and results
Financing organizations and industry own efforts

The CEAP is financed by three organizations:
• The Norwegian Ready Mixed Concrete organization
• The Norwegian Concrete Association, NCA
• The Norwegian Precast Concrete Federation

Secretary
• Brilliant Building

Financing
• Allows a project coordinator to contribute to overview and create arenas for synergies and initiate and conduct projects
• Important - industry own effort (hours) and financing own specific projects and activities under the CEAP (in addition)

Information to be found here: www.miplan.no
5 The road towards new concrete research and innovation

10.50 – 11.50 Panel debate – concrete innovation and dissemination
Kjell Skjeggerud (Norcem), Jan Eldegard (Byggutengrenser), Elisabeth Schjolberg (Multiconsult), Anders Sjaastad (Yngres Betongnettverk) and Tor Arne Martius-Hammer, introducer (SINTEF)
Moderator: Lisbeth Alnaes, SINTEF

11.50 – 12.00 Summary and concluding remarks
Terje F. Rønning
Innovation

RCN’s success factor concerning innovation:

"Created opportunities for innovation and increased competitiveness among user partners and expectations of social impacts".

Innovation

is

a new product,

a new service,

a new production process, application or organisation

that is launched in the market or used in production to create economic values. A new idea or invention is not an innovation until it has come to practical application and creates value.
**COIN innovations**

**Products:**
- Cement(s)
- Hardening accelerator
- Calcined clay

**Services:**
- CrackTestCoin
- FRC guideline

**Production processes/applications:**
- Fibre reinforced walls
- Artic sea structures without abrasion casing
- Manufactured sand

---

**COIN innovation opportunities**

**Products:**
- Calcined marl
- Admixtures
- Low thermal conductivity structural concrete
- Technology for production of advanced LWA

**Services:**
- Surface quality classification system
- Guidelines
- Utilization of thermal mass
- Performance based spec./test. (e.g. ASR)

**Production processes/applications:**
- FRLWAC
- Hybrid concrete
- SCC?
For debate

- How can we contribute to that what is created in COIN becomes innovations?

- How can we, as an industry, in the future ensure that ideas and research results become innovations?
  - How to get research inst. and industry together to develop research topics with sufficient innovation and implementation potential?
  - Dissemination and implementation of R & D results in general
  - Organizing of R & D projects where innovations are the target
What did we learn in school today ..... 

..........

BUT we had great fun!
Construction industry
- Often considered as assembling of standard components

But
- Frequently we need tailor made solutions

And, generally
- The only way to improve value creation for a construction project is to interact

IF
- We want to innovate
- We want to learn

THEN
- We must do so outside the normal tendering process of the construction sector
- We must create an organisational environment
- We must involve the Sector and Academia
- Everybody needs a strategy of its own and one of interaction
- Influence the RCN & EU (funding;) Calls!
- JOINT TARGETING & CREATIVE PROCESSES
Thank you!

&

Welcome back at some occasion…?
**SinTEF Building and Infrastructure** is the third largest building research institute in Europe. Our objective is to promote environmentally friendly, cost-effective products and solutions within the built environment. SinTEF Building and Infrastructure is Norway’s leading provider of research-based knowledge to the construction sector. Through our activity in research and development, we have established a unique platform for disseminating knowledge throughout a large part of the construction industry.

**COIN – Concrete Innovation Center** is a Center for Research based Innovation (CRI) initiated by the Research Council of Norway. The vision of COIN is creation of more attractive concrete buildings and constructions. The primary goal is to fulfill this vision by bringing the development a major leap forward by long-term research in close alliances with the industry regarding advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.