Nordic Concrete rheology workshop
- Trondheim, Norway 3–4 October 2011

COIN Project report 35 – 2011
Nordic Concrete rheology workshop
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FA 2 Competitive constructions
SP 2.1 Robust highly flowable concrete and SP 2.3 High quality manufactured sand for concrete

COIN Project report 35 – 2011
COIN Project report no 35
Klaartje De Weerdt (editor)
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FA 2 Competitive constructions
SP 2.1 Robust highly flowable concrete and SP 2.3 High quality manufactured sand for concrete

Keywords:
Concrete aggregate, rheology, SCC - self consolidating concrete, manufactured sand

Project no.: 3D005950

ISSN 1891–1978 (online)

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Address: Forskningsveien 3 B
POBox 124 Blindern
N-0314 OSLO
Tel: +47 22 96 55 55
Fax: +47 22 69 94 38 and 22 96 55 08
www.sintef.no/byggforsk
www.coinweb.no

Cooperation partners / Consortium Concrete Innovation Centre (COIN)

Aker Solutions
Contact: Jan-Diederik Advocaat
Email: jan-diederik.advocaat@akersolutions.com
Tel: +47 67595050

Saint Gobain Weber
Contact: Geir Norden
Email: geir.norden@Saint-gobain.com
Tel: +47 22887700

Norcem AS
Contact: Terje Rønning
Email: terje.ronning@norcem.no
Tel: +47 35572000

NTNU
Contact: Terje Kanstad
Email: terje.kanstad@ntnu.no
Tel: +47 73594700

Rescon Mapei AS
Contact: Trond Hagerud
Email: trond.hagerud@resconmapei.no
Tel: +47 69972000

SINTEF Building and Infrastructure
Contact: Thor Arne Hammer
Email: thor.hammer@sintef.no
Tel: +47 73596856

Skanska Norge AS
Contact: Sverre Smeplass
Email: sverre.smeplass@skanska.no
Tel: +47 40013660

Spenncon AS
Contact: Ingrid Dahl Hovland
Email: ingrid.dahl.hovland@spenncon.no
Tel: +47 67573900

Norwegian Public Roads Administration
Contact: Kjersti K. Dunham
Email: kjersti.kvalheim.dunham@vegvesen.no
Tel: +47 22073940

Unicon AS
Contact: Stein Tøsterud
Email: sito@unicon.no
Tel: +47 22309035

Veidekke Entreprener ASA
Contact: Christine Hauck
Email: christine.hauck@veidekke.no
Tel: +47 21055000
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 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

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
Introduction

SINTEF and NTNU organize a NORDIC CONCRETE RHEOLOGY WORKSHOP, 3-4 October 2011 in Trondheim. This workshop is held over two days and will be combined with a Nordic SCC Net meeting. Researchers from different Nordic research institutes working on these topics e.g. CBI (Sweden), DTI (Denmark), ICI (Iceland), NTNU and SINTEF (Norway) are participating.

Some major industrial users will participate, sharing their experiences in the field related to concrete rheology and the use of manufactured sand.

Both researchers and industrial users were encouraged to sign up for workshop and share their experiences.

Workshop

The idea is to give an insight on today’s ongoing research and experiences in the field of concrete rheology in the Nordic countries.

The participants were asked to prepare a presentation and a short abstract. In order to create an informal and including workshop, the contributions have been accepted as received. The participants are therefore solely responsible for the quality of each contribution.

Nordic SCC Network meeting

The Nordic SCC Network has the objective to exchange results and knowledge in order to establish an improved basis for the use of Self Compacting Concrete. Annual meetings are hosted by members of the network. In this occasion, it was opted to combine the Nordic SCC Network meeting with a concrete rheology workshop.

Organizers

The Concrete Innovation Centre (COIN) is a centre for research based innovation supported by the Norwegian Research council and industrial partners. In order to achieve the goal of innovation for concrete industry, communication and cooperation between different research centers and with the industry are crucial. For more information on COIN please visit our website (www.coinweb.no).
## Participants

<table>
<thead>
<tr>
<th>name</th>
<th>company</th>
<th>Country</th>
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<tbody>
<tr>
<td>Sven-Henrik Norman</td>
<td>Velde AS</td>
<td>Norway</td>
</tr>
<tr>
<td>Reidar Velde</td>
<td>Velde AS</td>
<td>Norway</td>
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<tr>
<td>Tero Onnela</td>
<td>Metsa</td>
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<td>Øystein Mortensvik</td>
<td>Rescon Mapei</td>
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<td>Espen Rudberg</td>
<td>Rescon Mapei</td>
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<tr>
<td>Bård Pedersen</td>
<td>SVV</td>
<td>Norway</td>
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<td>Lars Busterud</td>
<td>BASF</td>
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<td>Sverre Smeplass</td>
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<td>Knut Kjellsen</td>
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<td>Ernst Mørtsell</td>
<td>Norbetong</td>
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<td>Nikola Mikanovic</td>
<td>HTC</td>
<td>Germany</td>
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<td>Øyvind Sæter</td>
<td>Unicon</td>
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<td>Eivind Heimdal</td>
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<td>Poul Licht</td>
<td>Omya</td>
<td>Danmark</td>
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<td>Christine Hauck</td>
<td>Veidekke</td>
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<td>Bernt Kristiansen</td>
<td>AF</td>
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<td>Stefan Jacobsen</td>
<td>NTNU</td>
<td>Norway</td>
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<tr>
<td>Mette Geiker</td>
<td>NTNU/ DTU</td>
<td>Norway/ Denmark</td>
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<tr>
<td>Børge Wigum</td>
<td>NTNU/Norstone</td>
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<tr>
<td>Ya Peng</td>
<td>NTNU</td>
<td>Norway</td>
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<tr>
<td>Rolands Cepuritis</td>
<td>NTNU</td>
<td>Norway</td>
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<td>Tor Arne Martius Hammer</td>
<td>SINTEF</td>
<td>Norway</td>
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<td>Klaartje De Weerdt</td>
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<td>Mari Bøhnsdalen Eide</td>
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<td>Peter Billberg</td>
<td>CBI</td>
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<td>Björn Lagerblad</td>
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<tr>
<td>Peter Simonsson</td>
<td>LTU</td>
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<td>Jon Elvar Wallevik</td>
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<td>Olafur Wallevik</td>
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<tr>
<td>Jon Spangenberg</td>
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<tr>
<td>Jan Skocek</td>
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<tr>
<td>Claus Pade</td>
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<tr>
<td>Lars Nyholm Thrane</td>
<td>DTI</td>
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Program

Monday 3. October

10:30 11:00 Registration

11:00 11:30 Welcome speech - COIN
Bård Pedersen SVV SINTEF
Tor Arne M. Hammer SINTEF
Klaartje De Weerdt

11:30 12:15 LUNCH

MANUFACTURED SAND

12:15 12:30 Manufactured aggregates for concrete – why, where and how?
Svein Willy Danielsen SINTEF

12:30 12:45 Manufactured sand in concrete. Practical experiences from aggregate and sand production and concrete mix design.
Sven-Henrik Norman Velde AS

12:45 13:00 Filler and filler quality of crushed rocks in concrete production
Björn Lagerblad CBI

13:00 13:45 DISCUSSION MANUFACTURED SAND + COFFEE
Børge Wigum NTNU/ NorStone

13:45 14:00 Creating a manufactured sand - Factors to consider and methods of processing
Tero Onnela Metso

14:00 14:15 Effect of aggregate crushing on fresh concrete
Rolands Cepuritis NTNU

14:15 14:45 DISCUSSION MANUFACTURED SAND + COFFEE
Bård Pedersen SVV

SCC STABILITY

14:45 15:00 Measurements of rheological properties of mortar using the V-funnel test
Lars Nyholm Thrane DTI
Claus Pade
Klaartje De Weerdt SINTEF

15:00 15:15 Rheological Properties of SCC Stabilized With additional filler or chemical stabilizer
Peter Billberg CBI

15:15 15:30 Some Fresh Properties of Powder-, VMA- and Combination-Type SCC
Ya Peng NTNU

15:30 15:45 SCC Stability: STAR review and plans for PhD research
Peter Billberg CBI

15:45 16:30 DISCUSSION SCC STABILITY + COFFEE

RHEOLOGY

16:30 16:45 On the influence of entrained air on rheology of paste and mortar
Tor Arne Martius-Hammer SINTEF

16:45 17:00 “Rheology according to Olafur”
Olafur Wallevik NMI

17:00 17:30 DISCUSSION (Train to city centre leaves at 17:56)
Claus Pade SINTEF

19:00 DINNER at Rica Nidelven

Concrete Rheology Workshop: Trondheim, 2011
## Tuesday 4. October

### SCC FIELD EXPERIENCES

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Presenter</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>09:00</td>
<td>How polycarboxylate superplasticisers affect the rheology of self-compacting concrete</td>
<td>Øystein Mortensvik</td>
<td>RESCON MAPEI</td>
</tr>
<tr>
<td>09:15</td>
<td>Sensitivity of SCC proportioning to variations in raw materials</td>
<td>Sverre Smeplass</td>
<td>SKANSKA</td>
</tr>
<tr>
<td>09:30</td>
<td>Experiences with SCC - challenges met in the field today</td>
<td>Bernt Kristiansen</td>
<td>AFgruppen</td>
</tr>
<tr>
<td>09:45</td>
<td>DISCUSSION FIELD EXPERIENCES + COFFEE</td>
<td>Tor Arne Martius Hammer</td>
<td>SINTEF</td>
</tr>
<tr>
<td>10:30</td>
<td>Concrete with high flyash content - Ready mix production</td>
<td>Øyvind Sæter</td>
<td>UNICON</td>
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<tr>
<td>10:45</td>
<td>Smart Dynamic Concrete, a new generation of highly fluid concretes</td>
<td>Lars Busterud</td>
<td>BASF</td>
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<tr>
<td>11:00</td>
<td>DISCUSSION FIELD EXPERIENCES</td>
<td>Knut Kjellsen</td>
<td>Norcem</td>
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### MODELLING

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<th>Affiliation</th>
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<tbody>
<tr>
<td>12:30</td>
<td>Explicit and implicit cfd-calculations of SCC: A numerical study</td>
<td>Jon Spangenberg</td>
<td>DTU</td>
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<tr>
<td>12:45</td>
<td>Modeling of flow induced inhomogeneities in self-compacting concrete</td>
<td>Jan Skocek</td>
<td>DTU</td>
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<td>13:00</td>
<td>Rheometer-4SCC used as a stability meter for SCC</td>
<td>Jon Elvar Wallevik</td>
<td>NMI</td>
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<tr>
<td>13:15</td>
<td>Steel fibres in fresh concrete; packing-, lubrication phase-, fibre jamming- and proportioning parameters</td>
<td>Stefan Jacobsen</td>
<td>NTNU</td>
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<tr>
<td>13:30</td>
<td>DISCUSSION MODELLING</td>
<td>Stefan Jacobsen</td>
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### NORDIC SCC NET MEETING

<table>
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<tr>
<td>14:30</td>
<td>Klaartje De Weerdt</td>
<td>SINTEF</td>
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</table>
Session 0

WELCOME
In 2005 the Research Council of Norway announced a call for CRI "as a tool to stimulate the industry to further innovation"

The purpose of the CRI is to build up and strengthen Norwegian research groups that work in close collaboration with partners from innovative industry and innovative public enterprises.

Centres for Research-based Innovation (CRI)

Focus Areas

1) Environmental friendly concrete structures
   - Binders with low emission and reduced resource consumption
     - All round environmentally friendly binder systems (PhD finished)
     - Admixtures to control hydration development (PhD)
     - Alternative pozzolans ((PhD))
   - Utilisation of concrete in low energy building concepts

2) Competitive construction
   2.1 Stable and robust highly flowable concrete with controlled surfaces ("1/2" PhD)
     - Test methods for evaluation of stability
     - Materials development
     - Production systems
     - Classification system and methods for aesthetic quality of concrete surfaces
2) Competitive construction

2.2 High tensile ductile strength concrete (2 PhDs)
- Test methods for FRC
- Materials development
- Production methods
- Guidelines for design and execution

2.3 High quality manufactured sand for concrete (‘1/2 PhD)
- Production techniques related to geological origin
- Concrete mix design
- Fresh concrete properties
- Volume stability

3) Technical performance

3.1 Crackfree concrete (PhD)
- Binder systems
- Calculation tools

3.2 Service life
- Chloride threshold value (PhD - finished)
- AAR-test methods (PhD)
- Electrical resistivity in concrete (PhD)
- Chloride ingress mechanisms (PhD)

3.3 Structural performance
- Development of Super LWA(C) (PhD)
- Performance of advanced concrete materials and combinations (2 PhD)
- Concrete in arctic marine environment (PhD)
COIN 2.3
High quality manufactured sand for concrete
Bård Pedersen

Background
- The project group was established in 2008 based on an initiative from NorStone (HC group)
- The motivation for this activity was the resource situation in Norway which will be reaching a critical level within a decade or so.

Project members
- NorStone: Børge Johannes Wigum, Gaute Veland
- Veidekke Industri: Lilian Uthus Mathisen
- Norsk Stein: Odd Hotvedt
- Nord-Fosen Pukkverk
- NorBetong: Ernst Mertsell
- Rescon Mapei: Espen Rudberg
- Metso Minerals: Tero Onnela
- SINTEF: Svein Willy Danielsen
- NTNU: Prof. Stefan Jacobsen, PhD students Ya Peng and Rolands Cepuritis
- Skanska: Sverre Smeplass
- NPRA: Bård Pedersen (previously NorStone)
- Velde pukk – not yet formalized

Focus areas
- Crushing technology
  - Cone crushing vs. VSI
  - Crushing parameters (feed, speed etc.)
  - Effects on particle shape, fines content etc.
  - Relation to geological parameters

Classification systems to optimize the fines characteristics
- Centrifugal air classification. Can be adjusted for "cut-points" between 20 and 100 microns

Mix design and rheology
- Development of concrete mix design for competitive properties and reverse/iterative effect on aggregate product development
- Aggregate vs. cement and admixtures interaction/synergies
- Link to COIN 2.1 (stability of SCC)
Characterization and verification methods
- Characterization of fillers (PSD, surface area, shape etc.)
- Particle packing studies
- Screening tests such as NZ Flow cone

Some activities in 2011
- Case study Nord-Fosen Pukkverk:
  - Fresh concrete properties
  - Possibilities for improved processing of aggregates
- Master thesis of Rolands Cepuritis:
  - "Effects of Concrete Aggregate Crushing on Rheological Properties of Concrete and Matrix"
  - to be presented during this workshop

Changes in project organization
- Børge Johannes Wigum replaces Bård Pedersen as Project Manager
- Velde Pukk is invited to join COIN 2.3
COIN FA 2.1
Robust highly flowable concrete

Active Project members
1. NTNU - Prof. Stefan Jacobsen, PhD student Ya Peng
2. SINTEF - Klaartje De Weerdt, Mari Bøhnsdale Eide
3. Skanska - Sverre Smeplass
4. Rescon Mapei - Espen Rudberg
5. Norbetong – Ernst Mørstell
6. Norcem – Knut O. Kjellsen
7. International advisor – Olafur Wallevik

Focus of the project
1. SCC – stability issues
2. Concrete surface classification tools and system

SCC - STABILITY

SCC - stability
• NTNU - Master thesis of Britt B. Marstrander (2010-2011)
  Bleeding and stability

SCC - stability
• NTNU - PhD project of Ya Peng on the development of novel techniques to assess stability of SCC (concrete and matrix)
SCC - stability

- SINTEF – Laboratory testing
different methods of stabilizing SCC

Surface classification

- No Norwegian surface classification system
- Several other countries DO have classification specifications, for example:
  - Sweden
  - Denmark
  - Germany
  - Austria
- The Norwegian building industry want to develop a new specification tool

Surface classification tool

- SINTEF – Concrete Surface Classification tool
Surface classification

- SINTEF – Concrete Surface Classification tool

BetongGUI

Surface classification

- SINTEF – Concrete Surface Classification tool

Pore distributions

Greyscale variations

www.coinweb.no
Session 1

MANUFACTURED SAND
Concrete aggregates from crushed hard rock - why, where, how?

Svein Willy Danielsen
SINTEF Building and Infrastructure

By considering the development in construction activities, 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?

The availability of materials will be one of the important global market drivers in the years to come

(Prof. Roger Flanagan UK)

Mineral aggregates can only be extracted where nature has placed them

So quarries may have to be located in the countryside where constraints against development are intense.

Or alternatively in densely populated areas with protests against dust, noise and traffic

But the aggregates have to be used where society needs them

Which may result in traffic pollution and excess use of energy

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
Europe has approx 500 mill people
- Expected average consumption of mineral aggregates
  10 tons per capita
  - Total of 5 bill tons per year Europe wide
- Assuming an average equivalent road transport
distance of 40 km
  - 200 billion ton-km per year for aggregate
  transport, which means approx 20 billion tons of CO2
  emission annually
- Two key questions:
  - Where do we find these resources on a long range?
  - How long will society accept this CO2 emission?

Norwegian relevance
- Large total resources (sand/gravel)
  - Theoretically 12 m³ → 450 years
- Much less available resources (50 → 15%)
- Land use conflicts
- Geological issues / technical quality
- Location, practical availability
- Size, production economy
- About 50% of total resources too far from realistic markets
- Shortage near most populated areas within 10 – 30 years

% 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>
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<td>72</td>
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<td>1.8</td>
<td>16</td>
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<td>Sweden</td>
<td>61</td>
<td>10</td>
<td>2.8</td>
<td>6.5</td>
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<td>UK</td>
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<td>Spain</td>
<td>65</td>
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Development in sand/gravel versus crushed rock (Norway)

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<td>Production value million NOK</td>
<td>1000</td>
<td>900</td>
<td>900</td>
<td>780</td>
<td>590</td>
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<tr>
<td>Crushed</td>
<td>800</td>
<td>1350</td>
<td>1859</td>
<td>1825</td>
<td>1955</td>
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<tr>
<td>Total</td>
<td>1800</td>
<td>1920</td>
<td>2759</td>
<td>2585</td>
<td>2540</td>
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<tr>
<td>% sand/gravel</td>
<td>56</td>
<td>47</td>
<td>33</td>
<td>29</td>
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Four essential phases in aggregate business

1. Inventory and planning
2. Quarrying and production
3. Use of aggregates in construction
4. Reclamation of mined-out area
Sustainability:

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

Any encroach 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.

Aggregate technology

Developments in production and use of manufactured aggregates in Norway

- A holistic approach to enable local supply and production
- Utilize local resources of sand and hard rock
- Minimize long transport of remote materials
- Obtain a no-waste production
- Plan for an optimum mass balance in production and market
- Minimize the need for depositing surplus products
- Two directions for technology development
- Improved aggregate production from hard rock
- A tolerant concrete mix design that plays with the aggregates
- Development of integrated, industrial plants
- Aggregate quarry
- Materials production (asphalt, concrete)
- Waste handling/recycling

Materials technology has to a large degree been developed in dependence of the aggregate resources available, and thus of the local/regional geological conditions

What can we achieve by using crushed rock aggregates in concrete?

- New developed technology opens new possibilities
  - Aggregate production
  - Concrete proportioning
  - Utilise the properties of different rock types
  - More design opportunities
  - Have a more industrialised production
  - Less surprises
  - Utilise surplus sizes
  - Mass balance
  - Less need for fines deposits – “no-waste production”
  - Competitive – but different – materials properties
Pre-conditions to make concrete with exclusively crushed aggregates:

- Suitable rock type
- Cubicity in the medium grain size fraction
- Specific proportioning – not just replace the natural sand
- Control of the 0-2 mm grading

Crusher Particle Shape

- Secondary and Tertiary Compression Crusher Sand
- BarmacSAND™

Crushed hard rock aggregates for concrete

- A need
- A challenge
- And an opportunity

Future action and research

1. Tools for mineral resource management
2. Concepts and technologies for optimum production and use

Research topics

- Concepts for competitive use of manufactured aggregates
- Technology to benefit from specific rock properties
- Utilization of secondary aggregates/marginal resources
- Concepts to constantly obtain mass balance (100% utilisation)
- Concepts to use more kinds of local materials, all new materials technology?
- Integrated plant concepts, with cost effective production
- More economically feasible subsurface quarrying, combining with establishing underground space
Manufactured sand in concrete. Practical experiences from aggregate and sand production and concrete mix design.

Velde Pukk – Rock properties

Feldspar (48%)
Quartz (48%)
Amphibolite (2%)
Mica (1%)
Chlorite (1%)

End product properties

Properties of end products:
- Micro Deval, test value 5, category MDE 10
- PSV, value 51, category PSV 68
- Los Angeles, test values Coarse 12, Fine 24, category LA 10
- Nordic abrasion value Category AN 10
- Flakiness Index of 5-22mm fractions: values 2-8, Category FI 15

Typical moisture content
The particle matrix method used in mix design

Matrix phase – FlowCyl - Filler

Matrix phase – FlowCyl - Additives

Water absorption / moisture
Filler and filler quality of crushed rocks in concrete production

Björn Lagerblad (CBI)
Mikael Westerholm (CBI)
Hans-Erik Gram (Cementa)

What is a filler
• The “fluid” phase consists of filler-cement-pozzolan-Water. The aggregate filler are defined as particles < 63 µm and mainly consist of individual mineral particles.
• In natural aggregates it is mainly rounded quartz and feldspar and clays.
• In crushed rocks it is depends on the rock type. With granitoid rocks it is crystals of quartz, K-feldspar, biotite, muscovite and often some hornblende.

The importance of grain shape
• Particles from crushed rocks are more angular and flaky than natural aggregate
• The fine material consists of free minerals
• The shape of the particles is related to the form of the individual mineral
• The mineral composition of the rocks will decide the shape of the particles
• Granites contain mica that is a flaky mineral.
• The mineralogy of the rock will decide the behavior of the paste.

A flaky particle needs more space to move. Thus more paste/fine material is needed.

Micas in the filler will cause problems.

Rheology of mortar (0-2 mm) with crushed rocks. As it comes and resorted to optimal grain distribution

Effect of fine materials (0-0,25 mm) on rheology

Mineral distribution in 0.125-0.25 mm

Comparision between filler and 0.125-0.25

<table>
<thead>
<tr>
<th>Provenance</th>
<th>Blende</th>
<th>Filler-Finkorn</th>
<th>Prom</th>
<th></th>
<th>Blende</th>
<th>Filler-Finkorn</th>
</tr>
</thead>
<tbody>
<tr>
<td>K 57</td>
<td>14.9</td>
<td>(12.4)</td>
<td>1.8</td>
<td>(7.4)</td>
<td>3.8</td>
<td>(7.4)</td>
</tr>
<tr>
<td>K 41</td>
<td>37.4</td>
<td>(12.4)</td>
<td>1.8</td>
<td>(7.4)</td>
<td>3.8</td>
<td>(7.4)</td>
</tr>
<tr>
<td>K 30-1</td>
<td>15.9</td>
<td>(12.4)</td>
<td>1.8</td>
<td>(7.4)</td>
<td>3.8</td>
<td>(7.4)</td>
</tr>
<tr>
<td>K 30-2</td>
<td>16.9</td>
<td>(12.4)</td>
<td>1.8</td>
<td>(7.4)</td>
<td>3.8</td>
<td>(7.4)</td>
</tr>
</tbody>
</table>

SEM 38 micrometer

SEM 38-63 micrometer

Image analysis of filler minerals

Counting of mineral grains of filler  i SEM Only larger grains are counted

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Blende</th>
<th>Klorit</th>
<th>Hornblende</th>
<th>Fältspat</th>
<th>Plagioklas</th>
<th>Kvarn</th>
</tr>
</thead>
<tbody>
<tr>
<td>K 57</td>
<td>14.9</td>
<td>(12.4)</td>
<td>1.8</td>
<td>(7.4)</td>
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<td>(7.4)</td>
<td>3.8</td>
<td>(7.4)</td>
</tr>
</tbody>
</table>

In ( ) semiquantitative analysis in X-ray diffraction

Flow valued for different fillers. K27 is limestone and the other from crushed granites and granodiorites.

Flow for mixes with cement

The grains of K29 is coarser than cement. K57 has a lot of mica.

Filler is mixed with water. At a certain amount of water the mix can flow. When more water is added it will flow more.
Strength of concretes with static w/c

- Wet ground quartz filler, w/c = 0.48
- 40% replacement, 260 kg Cem, 173 kg filler
- 40% addition, 433 kg Cem, 173 kg filler

Wet ground quartz filler, w/c = 0.48
Requires more SP

Use of good filler

- Compressive strength for filler replacing cement

Grain distribution in concrete

What is a good filler

- Consist of round cubic grains
- A good size distribution that includes the shape of cement and pozzolanas
- It can be analysed by
  - Sand equivalent test
  - Laser sieve
  - Packing
  - Punke test
  - Flow.
Manufacturing Sand

Factors and methods to consider

Areas of Application - Manufactured Sand

- Manufactured sand has been used for many years in a variety of concrete applications
  - Dam projects
  - Highway and airport paving
  - Bridges
  - Power plants
  - All types of industrial and commercial construction
  - Concrete products (pipes, blocks and pre-casts) of all kind
  - Plasters and mortars, where sand has a full role as aggregate
  - Asphalt, road building, earth fillings, bricks, glass etc.

Areas of Application for Air Classification

Manufacturing sand

To achieve a sand that meets specifications for concrete and asphalt, the sand grading is often needed to adjust.

The ‘superfines/filler/dust’ (<125µm) often needs to be reduced to amounts similar to natural sands to meet specifications.

Superfines are formed as a normal part of any crushing or grinding process.

In natural sands the ‘rock’ superfines have normally already been removed by various natural processes and the clay superfines are washed out during sand production.

How do Natural Sand Deposits Occur?

Natural sand is formed by natural physical and chemical weathering and erosion processes.

The sand is then often transported and sorted by natural means.

Sand is often stratified into different particle size bands.

Manufacturing Asphalt Sands

The majority of the air classification units in the USA have been installed for asphalt sand production.

Typically 0/4mm sand is produced with a high speed cone crusher with 15% 75µm (200 mesh).

The 75µm normally needs to be <5% to achieve ASTM asphalt specification.

This processing is normally carried out with a gravitational inertial unit.
Manufacturing Concrete Sand

**Rock Characteristics**

- The production of a quality manufactured sand is not a process that can be achieved by accident.
- Careful thought is required and a total approach is best to achieve quality products.
- Manufacturing sand requires a greater understanding of the source rock then normal crushing and screening.
- This is due to chemical and physical characteristics that exist in fine aggregates.

**Clean Source Rock**

- The first factor to consider is the cleanliness of the feed rock.
- All feed should be scalped as required at the primary crusher to remove any potential clay.
- Clay is detrimental to the strength of the concrete as it reacts adversely with the cement.

Concrete Sand

- Concrete sand is a high value product where natural sands are unavailable due to natural or environmental restrictions.
- Traditional ‘quarry dust’ is a by-product that has poor shape and high ultrafines content that making it a very poor substitute for natural sand.
- Natural concrete sand is well shaped (rounded), well graded (typically 40-70% passing 600µm) with all clay and ultrafines washed out.
- The 0/4mm quarry dust is often produced from compressive crushing with poor shape, high ultrafines (15-25%), low 600µm (25-35%) and a high percentage of +1mm.

**What is aimed for in Manufactured Sand?**

- Low water absorption of 1-5%.
- Free of inpurities.
- Good surface texture.
- Continuous grading throughout the curve.
- Cubical shape.
- Meets local specification.
- Consistent grading of the sand.

Manufacturing Asphalt Sands

**Air classification advantage**

- Big savings achieved over traditional wet processing.
- The dry feed requires significantly less oil to heat compared to a wet feed.
- Filler does not require further processes such as thickeners, lagoons etc.
- Asphalt sand specification are quite variable worldwide and the ASTM asphalt specifications are quite stringent.

**MANUFACTURING CONCRETE SAND**

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Manufacturing Concrete Sand

Rock Type

The grain size will effect the grading curve produced from the crushing process

The finer grained rock producing more ultrafines

Once the rock has been crushed to it's grain size, it requires a significant amount of energy to crush the individual grains

Particle Shape

Characteristics

Flaky Particles:
- Poor Workability
- High Water Demand
- High Cement Demand

Elongated Particles:
- Poor Workability
- High Water Demand
- High Cement Demand

Cubical Particles:
- Excellent Workability
- Excellent Finishability
- Reduced Cement Demand
- Higher Compressive and Flexural Strength

Manufacturing Concrete Sand

Preceding Crushing and Screening Process

The processing the rock receives is one of the key factors on the quality of the end product

More crushing stages => better shape and gradation

Accurate final screening is needed to control the top size of the sand as this needs to be in spec

To control moisture, aim for a primary stockpile being the only exposed storage with all conveyors and screens covered

Crusher Selection – Dependant on Sand Type

Cones

Cone Crushing
- The correct feed must be presented and the cone operate in the correct setting
- Choke fed so as to achieve inter-particle crushing

Impact Crushing
- The rotor speeds need to be high enough to shape and grade
- Closed circuit should always be considered so that the correct gradation can be achieved

Comparison

Most Suitable Sand Producers

Vertical Shaft Impactors

High Speed Cones

Ref. Toshi Ohashi
High speed cone crusher

CONE CRUSHED MANUFACTURED SAND
Advantages
- Higher energy efficiency
- Higher capacity for same installed power
- Lower energy consumption per tonne of sand
- Generate sand with a more favorable size distribution
- Lower generation of ultrafines
- Higher utilization flexibility – Can be used in other crushing stages
- Higher reduction ratio – Lower circulating load
- Cubical product
- Less sensitive to rock hardness

BARMAC VSI MANUFACTURED SAND
Advantages
- Capability to process fine feed and non-scaled feed
- Good tolerance to moisture
- Good tolerance to heterogeneous and irregular feed
- Produces rounded cubical particles
- Smooth surface
- Larger VSI allow higher performances
- Constant performance independent of wear parts life
- Shape correction in all particle size range

Low speed Cone crusher vs. VSI product

..and the sand grading more specifically
Example: Crushing and screening process

Processing manufactured sand

- Remove natural fines
  - Inclusion, moisture, coarse feed
- Choke fed high speed cone crusher
  - Choking chamber design
- Cone crusher in closed circuit to control VSI feed (top size & stability)
- Last crushing stage VSI in closed circuit
  - Gives flexibility and possibility to re-grind 3-5mm fraction
- Remove filler with air classifier (AC)
  - In effectiveness feed
  - Moisture, tonnage, shape, grading, density
  - Lots of 0-2mm sand grading is typically stable and rock specific
  - So: control tonnage and moisture
  - Desired amount of filler removal is found by adjusting air flows
- Finally, blend needed amount 3-5mm sand to reach in spec grading

Sand curve according to IS383

AC unit separation performance utilised 100%
Gravitational Inertial (GI) Classifier

- For cut points from 300μm to 63μm
- GI is a perfect choice for the construction industry for filler removal
- Secondary air is drawn to induce a scrubbing effect on near size particles
- Note that this returning, scrubbing feature is what gives this classifier its unique high efficiency and control of ultrafine removal

Manufactured sand for a big dam project

AC30GI Installation

Three Gorges Dam in Yangtze river

- Material: hard and abrasive granite
- In sand production VSI replaces partly rod milling
- Operating cost significantly lower for VSI compared to rod milling
Any Questions?
Thank you for your time
The performance of the VSI crushers is considerably different from the cone crushers. They are capable of producing cubical particles in all size range while the disadvantage is the large amount of fines generated. Though almost no research with fresh concrete has been done.

Factors affecting on the quality of crushed fine aggregate are not so distinct the main reason being that there is hardly any research made for the very fine particles.

The main objectives of the research were following:

1. Examine if tip (rotor) speed of a vertical-shaft impactor (VSI) and crusher type for the last crushing stage (VSI or cone crusher) affect grading, shape, surface texture and filler properties of 0/2 mm crushed sand fraction from different bedrocks to an extent measurable in fresh concrete and matrix rheology tests.

2. Verify which of the fundamental rheological parameters of concrete (\(\eta\), \(\mu\), slump and slump-flow) correlate with crushed aggregate properties like filler type, particle size distribution, flakiness index, specific surface, loose and compacted packing, flow time (rheology) in New Zealand’s flow-cone etc.

MATERIALS AND PROCESSING TESTS:

<table>
<thead>
<tr>
<th>No</th>
<th>Quarry</th>
<th>Producer</th>
<th>Rock type</th>
<th>Crushability, %</th>
<th>Description*</th>
<th>VSI type</th>
<th>VSI tip speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tau</td>
<td>HardStone AB</td>
<td>Mylonite</td>
<td>23</td>
<td>89% of fine and 20% of tertiary cone crusher</td>
<td>Barmax</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>Jotka</td>
<td>Norseby AB 4c</td>
<td>Melenagranit 34</td>
<td>4th step cone crusader GP 50 (5100 ES feed)</td>
<td>Barmax</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Jotka</td>
<td>Norseby AB 4c</td>
<td>Granite 41</td>
<td>5th step cone crusader Sandel H 56 M product</td>
<td>Barmax</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

Each product prepared in two 0/2 mm variations using laboratory sieve-shakers:

1. Filler content reduced to a given amount (10%) that is equal for all the manufactured sands.

2. Most of the filler removed (1% left) and replaced with additional 9% of limestone filler.

For Tau 45 m/s and 60 m/s 0/2 mm products with 10% crushed filler content, the energy input by increasing the tip speed would give any «real» benefits in the end product, i.e. concrete production. This has to be looked at in the light of mass balance, increased wear costs and the total CO\(_2\) emissions of the production process.

Some preliminary research has indicated that the tip speed of the VSI can reasonably affect the particle shape. Thus the aggregate production industry (and the society as whole) would need feedback if it’s reasonable to choose VSI instead of cone crushers and if the energy input by increasing the tip speed would give any «real» benefits in the end product, i.e. concrete production. This has to be looked at in the light of mass balance, increased wear costs and the total CO\(_2\) emissions of the production process.

As the advantage of the cone crushers usually the ability of limiting the amount of waste material produced is given while the disadvantage is the poor shape in most fraction sizes. The performance of the VSI crushers is considerably different from the cone crushers. They are capable of producing cubical particles in all size range while the disadvantage is the large amount of fines generated. Though almost no research with fresh concrete has been done.
**SOME RESULTS - GRADING**

Particle size distribution of Tau 0/2 mm crushed sands:

**PROCESSING TESTS**

Metso Minerals Research and Test Center in Tampere (full-scale test plant and rock laboratory):

**AGGREGATE CHARACTERIZATION RHEOLOGY TESTS**

0/2 mm sand characterization:

- Particle size distribution (PSD);
- Water absorption;
- Flakiness (non-standard bar-sieves for material retained on 2 mm, 1.6 mm and 1.25 mm sieves);
- Flow time in New Zealand Flow-cone according to NZS 3111:1986 ;
- Loose and compacted packing.

Concrete proportioning using Particle-Matrix model: highly flowable concrete with a reference slump ~200 mm, $D_{max}$ of 16 mm, matrix content 320 l/m$^3$.

Rheological parameters determined in concrete rheology tests (BML-Viscometer 3 by ConTec):

- Fresh concrete slump and slump-flow values. Testing carried out on flow-table. Slump and slump-flow values were determined before and after 5 dumps on the flow-table;
- Flow curves: “Bingham plots” - $\tau = \gamma + \eta$;
- Compressive strength at age of 28 days.

**COMPACTED PACKING MEASUREMENTS**

«Aggregate producer friendly» compacted packing measurements:

1. Steel cylinder with the same geometry as original flow-cone cup
2. 3.11 kPa static pressure
3. Vibrations (compaction) in lab.
4. Sieve-shaker for 90 sec.

**SOME RESULTS – CONCRETE RHEOLOGY**

Slump values showed very good relation to the Bingham yield stress.
SOME RESULTS – VSI TIP SPEED INCREASE COST ANALYSIS

Is it reasonable to increase the VSI tip speed?

Factors considered:

**DRAWBACKS:**
- More energy needed (kWh/t);
- Higher wear costs;
- Different PSD, more fines generated;
- Reduced output (t/h).

**BENEFIT:**
- An increase in the VSI tip speed would allow reduce the matrix amount and thus the cement content kg/m³ of concrete to maintain the same workability.

N.B.: Costs used (cement price, power (kWh) price etc.) are informative and correspond to some average prices (excluding VAT) in the Norwegian market.
Is packing or maximum packing fraction an unambiguous parameter?

The relation (packing-rheology) is better when particle shape, surface roughness and filter properties (shape and PSD) of the material are more similar.

- Packing is not an unambiguous parameter. The same as in case of so widely used PSD-aggregates with equal or very similar packing values can still have indefinite amount of very different specific surface value combinations. Specific surface of aggregates has been related to rheology of concrete since the time of Powers (1968).

What if we combine them?

<table>
<thead>
<tr>
<th>Approach proposed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) equivalent paste thickness</td>
</tr>
<tr>
<td>( \tau = \frac{1 - \phi}{s} )</td>
</tr>
<tr>
<td>b) &quot;closeness&quot; of proximity</td>
</tr>
<tr>
<td>( &quot;closeness&quot; = \frac{1 - \phi}{s} )</td>
</tr>
</tbody>
</table>

- Relative packing fraction (particle suspended in paste matrix)
- MS packing fraction (Particles in the compacted packing density state)
ACKNOWLEDGEMENTS:
TO ALL OF THE PEOPLE WHO HELPED ME WITH SOME THINGS – THERE’S A LOT OF THEM!
TO THE CONTRIBUTING COMPANIES/ INSTITUTIONS:

THANK YOU FOR THE ATTENTION!
Session 2

SCC STABILITY
Measurements of rheological properties of mortar using the V-funnel test

L. N. Thrane, C. Pade, M. Kasegaard, T. Madsen

Rheology workshop
NTNU Trondheim

The V-funnel is one of many existing standard test methods. 10 liters of material are filled into a funnel. The emptying time is recorded and taken as a measure of “viscosity”.

European standard EN 206-9 suggests two different viscosity classes based on V-funnel testing:

VF1: < 9 sec  
VF2: 9-25 sec.

This paper presents initial work on assessment of the rheological behaviour from the V-funnel test.

Motivation

The V-funnel is one of many existing standard test methods.

Approach

1. Prepare setup to measure weight over time.
2. Write down analytical equations for apparent viscosity in the V-funnel.
3. Prepare mortar samples with quite different rheology.
4. Compare results with values measured using the 4C-Rheometer.

Experimental setup

V-funnel is made of plywood. The V-funnel was hanging on three loadcells. The load cells are connected to a datalogger and the weight is logged at a frequency of 8 s⁻¹.

Video recordings were taken from the top.

Analytical equations for apparent viscosity

Shear rate [s⁻¹]:

\[
\dot{\gamma} = \frac{6Q}{\pi D^3}
\]

Q is the flow rate [m³/s]
D is the diameter of an equivalent circular tube outlet [m].

Shear stress [Pa]:

\[
\sigma = \frac{\Delta P R}{2L}
\]

\(\Delta P\) is the pressure difference between the top and bottom of the orifice* [Pa],
L is the length (0.150 m),
R is the radius of the outlet [m].

*Based on the weight measurement the height of suspension is estimated. The height is used to calculate the pressure difference.
Analytical equations for apparent viscosity

Apparent viscosity (Pa·s):

\[ \eta_{\text{app}} = \frac{q}{\dot{V}} \]

Assumption for outlet diameter:

- Cross sectional area of the rectangular outlet is equal to the cross sectional area of a circular outlet.
- \( D = 0.075 \) m
- \( D = 0.058 \) m

Mortar compositions

Initial tests were carried out with two different mortar compositions. The aim was to use mortars with quite different plastic viscosity.

The yield stress was kept low in order for viscosity to be the dominant flow parameter.

The first mortar was proportioned using Spanish raw materials including angular shaped aggregate and limestone filler.

The second mortar was based on Danish raw materials including rounded aggregate and fly ash.

<table>
<thead>
<tr>
<th>Cement [kg/m³]</th>
<th>Lime filler [kg/m³]</th>
<th>Water [kg/m³]</th>
<th>Sand [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>498</td>
<td>255</td>
<td>216</td>
<td>443</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cement [kg/m³]</th>
<th>Fly ash [kg/m³]</th>
<th>Water [kg/m³]</th>
<th>Sand [kg/m³]</th>
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</thead>
<tbody>
<tr>
<td>441</td>
<td>204</td>
<td>230</td>
<td>325</td>
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</tbody>
</table>

Results

<table>
<thead>
<tr>
<th>Low viscosity</th>
<th>High viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Test</td>
</tr>
<tr>
<td>13:07</td>
<td>4C-Rheometer</td>
</tr>
<tr>
<td>13:11</td>
<td>V-funnel</td>
</tr>
<tr>
<td>13:17</td>
<td>V-funnel</td>
</tr>
<tr>
<td>13:48</td>
<td>4C-Rheometer</td>
</tr>
<tr>
<td>13:54</td>
<td>V-funnel</td>
</tr>
</tbody>
</table>
Results

Summary

Based on simple assumptions and flow curve analysis (weight versus time) the results of apparent viscosity have been compared to the plastic viscosity measured by the 4C-Rheometer.

Results seem to correspond well when using an equivalent outlet diameter of 0.082 m, which corresponds to the assumption that the rectangular orifice of the Vfunnel can be approximated by a circular orifice of equal cross sectional area.

Further investigations

Assessment of the boundary condition. The analytical approach assumes no-slip boundary conditions. However, if this achieved in typical V-funnels made of steel or plywood? Testing using a V-funnel with a rough surface is therefore needed to assess the effect if any of different boundary conditions.

Assessment of the effect of yield stress on the apparent viscosity determined from the V-funnel test. If the apparent viscosity is taken as a measure of plastic viscosity this is valid for zero yield stress materials (Newtonian fluids). Introducing a yield stress, the question is to what extent this will dominate the estimation of apparent viscosity. In particular, it is of interest for suspensions in the slump flow range from 500 to 600 mm, which are commonly used for simple applications.

Assessment of other assumptions. For instance, the calculations of apparent viscosity assume a levelled height over the orifice. However, to which extent a downward curved surface affect the calculations should be investigated.
Rheological properties of self-consolidating concrete stabilized with fillers or admixtures

Hedda Vikan - Norwegian Public Road Administration
Klaartje De Weerdt - SINTEF Building and Infrastructure

Self-Consolidating Concrete (SCC)?

Definition
SCC fills the formwork and surrounds the reinforcement without the need of vibration or compaction, and without considerable segregation influencing the constructions function and durability.

Self-Consolidating Concrete (SCC)?

Why use SCC?
- Better work environment
- Improved placing of concrete
  → However, stagnated at a low market share for in-situ casting in Norway

Why don’t we use SCC?
- Can exhibit a lower robustness against fluctuations in the concrete production
  → Higher demand of quality control

Objective of the project
- Stabilizing SCC in two ways:
  - fines and/or filler,
  - chemical stabilizer
- Investigating the influence of method of stabilization on the rheological properties of SCC, both on concrete and matrix
- Later on, the effect of these rheological properties on the final surface quality will be evaluated.

The materials
- Cement:
  - CEM II/A-V 42.5R Portland fly ash cement
- Filler:
  - sieved from crushed 0/8mm sand (C)
  - sieved from washed/sieved 0/2mm sand (W)
  - Limestone (LS)
- Aggregates:
  - Gneiss/Granite aggregates 0/8mm and 8/16mm

The materials
- Chemical stabilizer:
  - S1 – polymer with high molecular weight
  - S2 – cellulose derivative
- Super plasticizer:
  - SP1 – acrylic
  - SP2 – lower molecular weight, longer side chains and higher charge density
- Retarder
  - Gluconate based set retarder – reduce the effect of hydration on the measurements
Principle of experiments

1. Stabilize SCC by adding:
   - Filler or
   - Chemical stabilizer
2. Maintain the slump flow by:
   - adopting Super Plasticizer (SP) dosage
3. Evaluate rheology and stability

Recipes

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>S1</td>
<td>1.2%</td>
<td>1.2%</td>
</tr>
<tr>
<td>S2</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>S2</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

Matrix

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>40 kg/m³</td>
<td>40 kg/m³</td>
</tr>
<tr>
<td>Limestone</td>
<td>80 kg/m³</td>
<td>80 kg/m³</td>
</tr>
<tr>
<td>Crushed 08 mm</td>
<td>40 kg/m³</td>
<td>40 kg/m³</td>
</tr>
<tr>
<td>Crushed 08 mm</td>
<td>80 kg/m³</td>
<td>80 kg/m³</td>
</tr>
<tr>
<td>Washed 02 mm</td>
<td>40 kg/m³</td>
<td>40 kg/m³</td>
</tr>
<tr>
<td>Washed 02 mm</td>
<td>80 kg/m³</td>
<td>80 kg/m³</td>
</tr>
</tbody>
</table>

Concrete

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fillers</td>
<td>40 kg/m³</td>
<td>40 kg/m³</td>
</tr>
<tr>
<td>Fillers</td>
<td>80 kg/m³</td>
<td>80 kg/m³</td>
</tr>
<tr>
<td>w/c</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>f/c (%)</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Matrix - apparent viscosity</td>
<td>2.00 m</td>
<td>2.00 m</td>
</tr>
</tbody>
</table>

Experiments

**Concrete**
- T = G + H.f (4SCC rheometer)
- Slump flow [mm]
- T500 [s]
- Visual Segregation Index (VSI)

**Matrix**
- \( \tau = \mu + \gamma \) (parallel plate)
- Thixotropy
- Gel strength
- Static yield stress

Results

**SP dosage – slump flow**

- Aim:
  - slump flow of 675±15 mm
- Consequence
  - varying SP dosage

- Trend that chemical stabilizers require higher SP dosage than filler to obtain the same slump flow

**Rheology - Viscosity**

- Concrete - T500
  - The highest filler dosage has the strongest effect. The effect of chemical stabilizer is similar to that of the lower dosage of filler added.
  - The effect is similar for both super plasticizers used.

- Matrix – apparent viscosity
  - Inline with concrete results
Rheology - Yield stress
Concrete – G (4SCC rheometer)
- Decreasing trend of yield stress with stabilization

Matrix – apparent viscosity
- Depend on the SP dosage and type
  - SP1: chemical stabilizers strongest effect stress
  - SP2: additional limestone filler greatest effect

Stability – Visual Segregation Index
- Difference VSI mixer and VSI flow board
  - The concrete is generally rated more unstable in the mixer than on the flow board
  - Stabilization potential - strongly depending on super plasticizer used:
    - SP1: S1, LS and W are able to stabilize both on board and in mixer
    - SP2: generally unstable in mixer and stable on board

Conclusions
- VISCOSITY
  - Stabilization → increase in viscosity
    - High filler content (24% per cement) → most significant increase in viscosity
    - In line with Krieger-Dougherty
    - The effect did not depend strongly on the SP used.

- YIELD STRESS
  - Depends on the SP used (matrix results)
    - SP1: chemical stabilizer – strong increase in yield stress
    - SP2: limestone powder (24%) – strong increase in yield stress

- STABILITY
  - VSI does not give conclusive results – difference between on flow board and in mixer
  - Stabilization effect of filler or chemical stabilizer depends strongly on SP type used.

Suggestions for further work
MATERIALS:
- Combinations of chemical stabilizers and fillers

STABILITY TESTS
- Alternative stability tests e.g. sieve segregation test

FULL-SCALE EXPERIMENTS
- Select 2 stabilized concretes for full-scale experiments (wall elements)
  → evaluate effect of concretes with different rheological properties on the final surface quality.

Acknowledgements
COIN for facilitating this project
www.coinweb.no
Some Fresh Properties of Powder-, VMA- and Combination-Type SCC

Peter Billberg

Project Aim
Evaluate how the different parameters:
- W/C ratio
- Powder type
- VMA type
- Type of SCC (powder-, VMA-, combination-)
influence the sensitivity of fresh SCC to over- or underestimated aggregate (sand) moisture.
Error range: +/- 1 weight-% of sand moisture
(≈ 10 litres per m³)

Slump Flow

Filling Capacity

Viscometer ConTec 4

Solid Materials
CEM II/A-LL 42.5 R (Byggcement)
Aggregate 0-8 mm and 8-16 mm, Natural
LP1: Crystalline limestone, D₀.₅ = 40 microns
LP2: Crystalline limestone, D₀.₅ = 25 microns
**Chemical Admixtures**

SP1: PCE, 35% solids
SP2: PCE, 30% solids  Configured also for stability
SP3: PCE, 35% solids

VMA1: Modified starch
VMA2: Microbial anionic polysaccharide
VMA3: High molecular weight ionic polymers
VMA4: Polysaccharide

**Mix Design - Reference Mixtures**

<table>
<thead>
<tr>
<th>Material</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>300</td>
<td>375</td>
</tr>
<tr>
<td>Water</td>
<td>210</td>
<td>188</td>
</tr>
<tr>
<td>W/C</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>CA</td>
<td>30%</td>
<td>40%</td>
</tr>
<tr>
<td>SP Type</td>
<td>SP1</td>
<td>SP1</td>
</tr>
<tr>
<td>Powder Type</td>
<td>LP1/LP2</td>
<td>LP1/LP2</td>
</tr>
<tr>
<td>Powder weight</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>

**Slump Flow Responses - Refs**

![Slump Flow Responses Graph]

**Slump Flow Area**

![Slump Flow Area Graph]

**Yield Stress Area**

![Yield Stress Area Graph]

**Slump Flow Area vs. Yield Stress Area**

![Slump Flow Area vs. Yield Stress Area Graph]
**Correlation Slump Flow - Yield Stress**

\[ y = 0.0009x^2 - 1.73x + 819 \]

\[ R^2 = 0.925 \]

**Correlation Slump Flow - FC**

\[ y = 0.22x-71 \]

\[ R^2 = 0.95 \]

## Rheology Area

- Yield stress (Pa)
- Plastic viscosity (Pa s)

## Powder/Comb./VMA Mixtures

Cement = 375, W/C = 0.5, Powder = LP2

<table>
<thead>
<tr>
<th>SCC Type</th>
<th>Powder</th>
<th>Comb.</th>
<th>VMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP2 weight</td>
<td>100</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>CA</td>
<td>40%</td>
<td>35%</td>
<td>30%</td>
</tr>
<tr>
<td>SP Type</td>
<td>1, 2, 3</td>
<td>SP1</td>
<td>SP1</td>
</tr>
<tr>
<td>VMA Type</td>
<td>1, 2, 3</td>
<td>1, 2, 3, 4</td>
<td>1, 2, 3, 4</td>
</tr>
</tbody>
</table>

- Low, various, dosages

## Results: Yield Stress Area

<table>
<thead>
<tr>
<th>Ref 2 3</th>
<th>SP Type</th>
<th>1 2 3 4</th>
<th>VMA Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400</td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
</tr>
</tbody>
</table>

## Results: Rheology Area

<table>
<thead>
<tr>
<th>Ref 2 3</th>
<th>SP Type</th>
<th>1 2 3 4</th>
<th>VMA Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400</td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
</tr>
</tbody>
</table>
Conclusions

The more free water (higher W/C or coarser powder), the more robust the SCC becomes.

Type of SP is important for robustness. SP2 and SP3 are better than SP1 due to enhanced stabilizing ability.

For the powder-type SCC, VMA3 performed best (slump flow, yield stress, Filling Capacity)

For the combination-type SCC, VMA2 and VMA4 performed best.

Strong correlations between slump flow and yield stress and between slump flow and Filling Capacity.

Thank you!
SCC Stability Review & PhD Research

Ya Peng (NTNU)
Stefan Jacobsen (NTNU)
Klaartje De Weerdt (SINTEF)
Bård Pedersen (VEGVESEN)
Oct. 03, 2011

Contents
- Theoretical analysis – stability of SCC
  - Bleeding – Kozeny-Carman equation
  - Particle sedimentation
- Test measurement methods on stability
  - An overview
- PhD research

Stability of SCC
- Stability
  - Dynamic (during the casting process)
  - Static (all placement and casting operations have been completed)
- What's the phenomena of instability
  - Particle sinking – Segregation – unhomogeneous and inconsistent strength
  - Water flowing – bleeding – water-rich pockets and surface laitance
- What causes the static instability of SCC
  - Higher workability with chemical admixture
  - Configuration of the form and presence of obstacles
  - Density difference

Theoretical analysis – bleeding
- Original Kozeny-Carman equation (KCE) based on viscous flow of a Newtonian fluid through a bed of particles:
  \[
  \frac{\Delta P}{L} = \frac{8}{9} \frac{c_{st}}{k_{N}} \left( \frac{D}{k_{N}^2} \right)^{1/3} \frac{c_{st}}{D} \left( \frac{D}{k_{N}^2} \right)^{2/3} \nabla \rho
  \]
  Combined with:
  
  \[
  \nabla \rho = \rho_c - \rho_f = \varepsilon \rho_f
  \]
  Change the formula to show the bleeding rate:
  \[
  \frac{\Delta P}{L} = \frac{8}{9} \frac{c_{st}}{k_{N}} \left( \frac{D}{k_{N}^2} \right)^{1/3} \frac{c_{st}}{D} \left( \frac{D}{k_{N}^2} \right)^{2/3} \varepsilon
  \]
  - The term in the square brackets is inverse permeability, \( c_{st} \) is specific surface
  - The Kozeny constant (Carman constant) is often used as 5, but much experimental evidence including some cement paste tests by T.C. Powers (1968) suggested that \( k_{N} = f(\varepsilon) \), i.e. the constant is a function of porosity.

VMA effect – on fluid viscosity
- Example: VMA effect on viscosity of the fluid – pilot test result
Use of KCE for matrix and concrete
- KCE valid for streamline flow
- Determine the flow regime with Modified Reynolds number: \( Re_{\mu} \)
- Based on above calculation result, Min. \( Re_{\mu}=2 \times 10^6 \)
- Kozeny-Carman valid for cement paste and concrete bleeding
- Correspondingly, when \( Re_{\mu}=2 \times 10^6 \), the motion factor between fluid and solid based on Carman correlation:
  \[
  \frac{\mu}{\rho} = \frac{3}{4} \frac{h}{l}
  \]
  (for laminar flow)

Theoretical conclusion for bleeding
- Fillers and VMA – effect on bleeding:
  - the effect on bleeding of reducing the powder density is smaller than the effect of increasing the specific surface
  - The effect of increasing the fineness should be quite possible to obtain in practice by increasing the cement fineness or replacing parts of the cement by other materials such as fine fillers and/or pozzolana
  - the effect of increasing the liquid viscosity is more effective than using the filler (previously with VMA)
- For matrix, when consider the powders or VMA affect on stability, the volume fraction must be used instead of w/c, w/b or w/p.

Measured bleeding
- Filter paper tests with master student Britt. on cement paste with SP

Table 1.1 – Particle sinking velocity & relative matrix viscosity

<table>
<thead>
<tr>
<th>Particle size (mm)</th>
<th>Particle sinking velocity (m/s)</th>
<th>Relative matrix viscosity (Pa·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>0.012</td>
<td>0.024</td>
</tr>
<tr>
<td>0.012</td>
<td>0.024</td>
<td>0.056</td>
</tr>
<tr>
<td>0.030</td>
<td>0.060</td>
<td>0.103</td>
</tr>
<tr>
<td>0.060</td>
<td>0.120</td>
<td>0.204</td>
</tr>
<tr>
<td>0.100</td>
<td>0.200</td>
<td>0.335</td>
</tr>
<tr>
<td>0.200</td>
<td>0.400</td>
<td>0.678</td>
</tr>
</tbody>
</table>

Use of Stoke’s law for concrete

Theoretical sinking velocity

Fig. 1.1 Particle sinking velocity in Newtonian streamline fluid

Fig. 1.2 Particle sinking velocity in Bingham fluid
Preliminary finding of the research

- Lower w/c-, w/b-ratio and/or superplasticizer-dosage (SP/c-ratio) increase stability and therefore robustness of cementitious materials;
- Greater fines content increases stability;
- Many researchers claimed that viscosity modifying admixture (VMA) can be used to reduce the variability of the mixtures, thus increasing the stability and robustness;
- Large aggregate size and high density decrease stability and vice-versa. However, within common ranges of SCC admixture and densities of aggregate, Bomen and Shah argued that the most important factor that governs the rate of sedimentation is the aggregate size;
- VMA improves stability significantly, the effect on rheology could be both to increase viscosity and yield stress.
- The maximum packing fraction ($\Phi/\Phi_{\text{max}}$) expresses the spacing of the particles and relates to stability.

Research project introduction

- A PhD project about rheology and stability affected by mineral additives and fillers
- The research focus on the relations between stability and both material parameters:
  - Phenomena: particle sedimentation, distribution / flocculation, bleeding, yield stress build-up etc.
  - Factors: volume fraction, specific surface area of particles, density, liquid plastic viscosity, $\Phi/\Phi_{\text{max}}$, yield stress, etc.
- Materials: SP, VMA, fillers (lime, concrete, fly ash (within cement), silica fume, etc.)
- Test methods: Experimentally and practically there is a need for measurement methods for settlement, bleeding and static yield stress to evaluate the effect of different material parameters on stability.

Sedimentation model

- Particle sedimentation
- Bleeding
- Density difference: vibronic test / UPV test
- Flux difference: hydrostatic pressure test
- Rheology properties: Parallel plate rheometer, Gel strength, $\mu$, $\tau$, changing vs. time
- Max. packing density, Contribute $\Phi/\Phi_{\text{max}}$
- Viscosity of the fluid, Centrifuge or filter test combine with parallel plate rheometer
- Particle distribution, External radiation e.g. X-ray, y-ray, microphone
- Bleeding

Test methods overview

- Stable settlement e.g. porosity, void ratio, y-ray, microscopes
- Stability radiation e.g. Radiodensity curves, NIR, magnetic lenses
- Rheological properties e.g. Radiation potential, potential, conduction
- Physical properties e.g. Sedimentation balance, pressure measurement
- Direct methods e.g. sampling, physical measurements
- Visual measurement method, Calcium sedimentation test (ASTM C861)
- Radiation absorption / X-ray, y-ray measurement, Photo (Red, Blue, yellow, green)
- Direct stability test, Image analysis method, Multi-per equipment conductivity approach, Air meter test, Systemic bleeding test, Folding test

Earlier settlement and bleeding tests: (ASTM C243-paste & mortar, C232-concrete)
- Power’s method (use floating panel to check surface level of fresh paste and concrete)
- Methods by L Josserand and F.de Larrard (track for bleeding water or filter paper)
- Bleeding test method used by Sawaide and Iketani

Test methods set-up for matrix stability

- Particle sedimentation
- Plate test
- Viscosity of the fluid
- Parallel plate rheometer
- Contribute $\Phi/\Phi_{\text{max}}$
- Rheology properties
- Yield stress build-up
- Stability
- Bleeding
- Density difference
- Flux difference
Static yield stress build-up

Thanks you for comments!

Ya Peng, Oct. 03

Ya.Peng@ntnu.no
Stefan.Jacobsen@ntnu.no
Session 3

RHEOLOGY
On the influence of entrained air (EA) on rheology of paste and mortar

Tor Arne Martius-Hammer  
Kåre Johansen  
Concrete Innovation Centre  
SINTEF Byggforsk

Motivation

- Role of EA in the Particle-Matrix-Model (PMM)
- EA as a tool to improve workability of SCC?

PMM (Mørtsell 1996)

The volume relation between matrix and particles

Matrix properties  
(filler modified cement paste)

Concrete workability

Particle properties  
(particles >125μm)

Workability function

Matrix properties

FlowCyl determines the flow resistance, $\lambda_Q$, of the matrix material which is closely related to viscosity

Flow resistance
Experiments

- Testing pure cement pastes with w/c = 0.35 with 0 – 15% air content
- Testing the influence of increasing the air content from 3 – 13% in mortars with w/c = 0.50
- Testing the influence of increasing the matrix content with 7% in mortars with 3% air

Experiments

- Slump and slumpflow (120 mm and 300 mm cone)
- Flow resistance number (FlowCyl)
- Viscosity and yield shear stress (ConTec 4 Rheometer)

Cement paste

![Cement paste diagram](image)

![Graph showing slump, slumpflow, and yield shear stress](image)
Conclusion

EA reduces slightly consistency of cement paste. Nevertheless, it contributes to increased consistency of mortars, because of increased paste(matrix)-aggregate ratio.

EA may be considered as part of "matrix" in the PMM, but with an "efficiency factor" less than 1
The importance of shear rate in concrete rheology

Olafur H. Wallevik, ICI Rheocenter, Innovation Center Iceland, Reykjavik Uni. & Sherbrooke University

Content

Introduction to rheology
Flowcurve
Rheograph
Importance of correct rate of shear
Cement admixture interaction
Importance of mixing energy
Degree of dispersion due to agitation
How to alter the viscosity
Rheology; The key to Eco-SCC®

Eco-SCC® Total powder: ≥ 315 kg/m³

Bingham model

τ₀: yield value (Pa)
μ: plastic viscosity (Pa·s)

τ = τ₀ + μγ

γ: rate of shear

H-B: n>1
Bingham

Flow curve for Herschel–Bulkley (n≠1) and Bingham (n=1) fluids.

τ = τ₀ + kγⁿ

Einstein

“Everything should be as simple as possible, but not simpler”, Einstein
Rheometers measures torque (T) and velocity (N):

\[ T = G + \frac{4\pi R_i h}{R_i^2 - 1/R_i^2} \left( \frac{1}{R_i^2} - \frac{1}{R_i^2} \right) \mu \gamma + \frac{4\pi \tau_0 h}{R_i^2 - 1/R_i^2} \ln \left( \frac{R_o}{R_i} \right) \]

\[ N = \tilde{G} + \tilde{H} N \]

Rate of shear:

\[ \tau = \tau_0 + \mu \gamma \]

Using Newtonian shear rate for non-Newtonian fluids would be wrong:

- If R-R equation:
  - Yield value: 367 Pa
  - Pl. viscosity: 25 Pa·s

- If Newtonian shear rate:
  - Yield value: 480 Pa
  - Pl. viscosity: 30 Pa·s

Estimation of shear rate for non-Newtonian fluid can be complex:

REINER-RIWLIN equation to calculate the Bingham parameters:

\[ \dot{\gamma} = \frac{T}{2\pi \gamma^2 h} - \frac{\tau_0}{\mu} - \frac{4\pi \tau_0 h}{R_i^2 - 1/R_i^2} \ln \left( \frac{R_o}{R_i} \right) \]

An example:

- Plastic viscosity: 23 Pa·s
- Yield value: 812 Pa
- Inner cylinder, Ri: 0.1 m
- Outer cylinder, Ro: 0.145 m
- Height: 0.199 m

Drawing from Heirman et al.
**An example**

- Plastic viscosity: 23 Pa·s
- Yield value: 812 Pa
- Inner cylinder, Ri: 0.1 m
- Outer cylinder, Ro: 0.145 m
- Height: 0.199 m

Drawing from Heirman et al.

**Now use R-R equation to calculate rate of shear**

\[
\dot{\gamma} = \frac{2}{R_i^2 - R_o^2} \left( \frac{R_i}{R_o} \right)^2 - 1
\]

**Now use equation for Newtonian fluid to calculate rate of shear**

\[
\tau = \mu \dot{\gamma}
\]

**Now use equation for H-B [n=1.8] to calculate rate of shear**

\[
\dot{\gamma} = \left( \frac{\tau - \tau_0}{k} \right)^{1/n}
\]

**Bingham model**

\[\tau = \tau_0 + \mu \dot{\gamma}\]

- \(\tau_0\): yield value (Pa)
- \(\mu\): plastic viscosity (Pa·s)

The plastic viscosity tells the force/stress necessary to increase the rate of flow.

"Everything should be as simple as possible, but not simpler", Einstein

**We use shear rate**
Similar to the R-R eq., the analytical solution for a H-H fluid

\[ \tau = \tau_0 + \mu \cdot \dot{\gamma} + c \cdot \dot{\gamma}^2 \]

D. Feys, R. Verhoeven, G. De Schutter, Evaluation of time-independent rheological models applicable to fresh Self-Compacting Concrete, Appl. Rheol. 17:5 (2007), 562-44.


Modify the R-R equation for retrieving M-B

D. Feys, et al.

R-R: Reiner–Riwlin

M-B: Modified Bingham

\[ \tau = \tau_0 + \frac{225}{128 \pi^2 R^5} \rho g \Omega^2 \]

Rheology

Don’t have to be expensive

\[ \rho: \text{the density of the material (kg/m}^3\text{)} \]

\[ g: \text{the gravitational acceleration (m/s}^2\text{)} \]

\[ \Omega: \text{the total volume of the sample (m}^3\text{)} \]

\[ R: \text{the radius of the spread (m)} \]


Stress strain curve & static yield stress

Mixer (efficient) is very important
The average cement content in “normal” SCC is about 500 kg/m³

Proposed classification in respect of powder content
(Not including the fines in the aggregates)

- **Rich SCC**: ≥ 550 kg/m³
- **Normal powder content SCC**: 500 ± 50 kg/m³
- **Lean SCC**: 415 ± 35 kg/m³
- **Green SCC**: 350 ± 35 kg/m³
- **Eco-SCC®**: ≤ 315 kg/m³

**Eco-SCC® Definition**
- Environmental and economical alternative,
- Where the total binder/powder content
  - Cement, FA, silica fume, BFS, limestone filler
  - Is 315 kg/m³ or below
  - Not including filler from aggregates

**Mixing: Degree of agitation affects very the plastic viscosity**

**Evaluating effect of (mixing) agitation energy: Rheomixer**

**Final remarks**
- The classic equation for calculating rate of shear is only valid for Newtonian liquid
- Bingham approach should be used for cementitious materials due to its simplicity
- Reiner-Riwlin equation in excellent tool
- In particular shear thickening can be problem
  - Modified Bingham can be a solution
Sand: EN versus Cookstown

Same mix design:
- EN-sand: very fluid mortar
- Cookstown: very stiff mortar

And 2 types of PC (SP)
Adva 151 & Adva 560

Aggregates
- Tullyrain 20 mm
- Armagh City 10 and 20 mm (not used)
- Crozier 14 mm
- Emersons 10 mm
- Cookstown 2 mm

Grading
Grading

Cumulative PSD [%] vs Size [mm]

Grading Curves:
- Cookstown
- Emersons
- Crozier 14
- Tullyrain 20
- PSD

Grading Table:

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>0</th>
<th>24.0</th>
<th>3.4</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Grading Results:
- OPC_525_0.66_0.87 – w/c = 0.38
- OPC_600_0.6_0.87 – w/c = 0.34 (+ST)
- OPC_675_0.54_0.87 – w/c = 0.30

SCC-series with OPC (IR)

Yield value [Pa]

- Without Stabilizer
- With Stabilizer

Name Code: Cement type_Cement content_PC content_ST content (% per cement weight)

OPC_600_0.0_0.87 – w/c = 0.34 (no ST)
OPC_600_0.6_0.87 – w/c = 0.34 (+ST)

Name Code: Cement type_Cement content_PC content_ST content (% per cement weight)

OPC_675_0.54_0.87 – w/c = 0.30

Without Stabilizer
With Stabilizer

Equation:
y = 0.106x - 16.933
R² = 0.9616

Yield value [Pa] vs Cement content [kg/m³]

Equation:
y = -186.25x + 109.64
R² = 0.9753

Compressive strength [MPa] vs Cement content [kg/m³]

P. Viscosity [Pa s]

VMA

Compressive strength [MPa] vs Cement content [kg/m³]

w/c-ratio [-]

Linear (2d)

Equation:
y = -186.25x + 109.64
R² = 0.9753
525 kg/m³ SR-Cement
No stabilizer (VMA)

M5 with 300 kg/m³ DKOPC cement and 33 kg/m³ silica fume

Field test feb 2011:
Cement 400 kg/m³

First lab test:
Cement 670 kg/m³
Session 4

SCC FIELD EXPERIENCES
How polycarboxylate superplasticisers affect the rheology of self-compacting concrete

Espen Rudberg (M.Sc)
Øystein Mortensvik (M.Sc)
Dag Vollset (MIA)

Superplasticizers
- BASF Glenium
- Chryso Chrysofluid
- Grace Adva
- Mapei Dynamon
- Remei Carboxyl
- Sika Viscocrete/Sikament

Well, what is a superplasticizer then?
- Polycarboxylates
- Defoamer
- Water
- (Stabilizer)
- (Accelerator)
- (Retarder)
- (Air entrainer)

But what does it do?
Reduces the yield stress!
...but does it anything more?

Different polymers, different result?

Yield Stress (Pa)
Shump flow (mm)
Time (min)
Different polymers, different result?

Let's get technical!

- Raw material
- Polymerization process
- Different molecular weight and charge
- Different lengths and densities of side chains

Different polymers, but same result?

<table>
<thead>
<tr>
<th></th>
<th>SR-N 5 min</th>
<th>SR-N 30 min</th>
<th>RMC-630 5 min</th>
<th>RMC-630 30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump (mm)</td>
<td>190</td>
<td>190</td>
<td>310</td>
<td>310</td>
</tr>
<tr>
<td>Slump flow (mm)</td>
<td>350</td>
<td>350</td>
<td>360</td>
<td>350</td>
</tr>
<tr>
<td>Tom’s method (mm)</td>
<td>420</td>
<td>410</td>
<td>420</td>
<td>400</td>
</tr>
<tr>
<td>Yield Stress (Pa)</td>
<td>320</td>
<td>328</td>
<td>326</td>
<td>340</td>
</tr>
<tr>
<td>Plastic viscosity (Pa*s)</td>
<td>62</td>
<td>65</td>
<td>75</td>
<td>76</td>
</tr>
</tbody>
</table>

Crushed and natural

<table>
<thead>
<tr>
<th></th>
<th>Slump flow</th>
<th>T500</th>
<th>T end</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi. 9</td>
<td>620</td>
<td>2.1</td>
<td>16</td>
</tr>
<tr>
<td>Bi. 13</td>
<td>615</td>
<td>1.5</td>
<td>12</td>
</tr>
</tbody>
</table>

**Normal** measurements

Rheological measurements

<table>
<thead>
<tr>
<th></th>
<th>Yield Stress</th>
<th>Plastic Viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi. 9</td>
<td>43.86</td>
<td>35.02</td>
</tr>
<tr>
<td>Bi. 13</td>
<td>44.78</td>
<td>25.12</td>
</tr>
</tbody>
</table>
Murphy’s Law Applies to SCC!
Preliminary results from fullscale test

Sverre Smeplass, Skanska
Klaartje De Weerdt, SINTEF
Mari Bøhnsdalen Eide, SINTEF

Background
Low grade (C30/37) SCC’s in Norway are normally based on:
• Natural sand 0/8 mm, moderate to high fines content (5-8% < 125 μm)
• CEM II A/V
• No added fillers
• No chemical stabilization
• Moderate to high dosages of co-polymers

“Marginal” concrete

• SF = 650 mm for walls, T₁₅₀ ~ 1 sec
• SF = 550 mm for slabs

Low total matrix volume - low viscosity matrix
SCC vulnerable to:
• Dosage deviation, cement, water, additives
• Normal variation in aggregate moisture
• Normal variation in aggregate fines content

Full scale test supplied with laboratory investigation

Objective I
What’s the effect on
• rheology
• stability
• pumpability
• pore building in wall surfaces
of stabilizing a “marginal” SCC, SF= 675 mm by adding:
• filler
• chemical stabilizer
(SF maintained by adding plasticizer)

Objective II
What’s the effect on
• filler content and grading of 0/8 mm sand
• moisture content
Concrete

- Reference “marginal” concrete based on a well proven low grade SCC (NorBetong)
  - w/c increased to 0.65
  - sand/aggregate ratio was reduced to 0.55 to reduce filler content
  - matrix volume reduced to 310 l/m³
  - SF adjusted to 675 mm by adding plasticizer
- Trial batches were performed at the ready-mix plant
- Somewhat unstable, but “acceptable” SCC

Table 1: Parameters of the three different SCCs used

<table>
<thead>
<tr>
<th></th>
<th>Unstable</th>
<th>Filler</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/c</td>
<td>0.65</td>
<td>0.678</td>
<td>0.65</td>
</tr>
<tr>
<td>w/p</td>
<td>0.49</td>
<td>0.42</td>
<td>0.49</td>
</tr>
<tr>
<td>f/c (limestone filler) [%]</td>
<td>0.0</td>
<td>22.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Admixtures % of C</td>
<td>% of C</td>
<td>% of C</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Retarder</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>0.0</td>
<td>0.0</td>
<td>2.09</td>
</tr>
<tr>
<td>Matrix volume</td>
<td>310</td>
<td>332</td>
<td>310</td>
</tr>
</tbody>
</table>

(*) due to an error in the moisture content of the sand the w/c ratio of the filler stabilized SCC is 0.678 instead of 0.65

Table 2: Weighed in quantities for the production of the different SCCs

<table>
<thead>
<tr>
<th>Materials [kg/m³]</th>
<th>Unstable</th>
<th>Filler</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM II/A-V 42.5 R</td>
<td>278.3</td>
<td>278.2</td>
<td>278.3</td>
</tr>
<tr>
<td>Limestone powder</td>
<td>62.5</td>
<td>0.0</td>
<td>62.5</td>
</tr>
<tr>
<td>Free water</td>
<td>178.2</td>
<td>177.8</td>
<td>178.2</td>
</tr>
<tr>
<td>Sand 0/8 mm</td>
<td>1035.7</td>
<td>1001.2</td>
<td>1035.7</td>
</tr>
<tr>
<td>Aggregate Width 8/16 mm</td>
<td>1847.4</td>
<td>1810.2</td>
<td>1847.4</td>
</tr>
<tr>
<td>Air entrainer</td>
<td>1.81</td>
<td>1.81</td>
<td>1.81</td>
</tr>
<tr>
<td>SF</td>
<td>630</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td>SP</td>
<td>1.81</td>
<td>1.81</td>
<td>1.81</td>
</tr>
<tr>
<td>Retarder</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>0.0</td>
<td>0.0</td>
<td>2.09</td>
</tr>
<tr>
<td>Density (theoretical)</td>
<td>2343</td>
<td>2343</td>
<td>2343</td>
</tr>
</tbody>
</table>

Table 3: Dosage of SP added at ready mix plant and upon arrival with corresponding slump flow (SF) spread

<table>
<thead>
<tr>
<th></th>
<th>Unstable</th>
<th>Filler</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>545</td>
<td>500</td>
<td>625</td>
</tr>
<tr>
<td>SP [% of cement]</td>
<td>0.16</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>SF [mm]</td>
<td>670</td>
<td>665</td>
<td>680</td>
</tr>
<tr>
<td>Time between mixing and testing</td>
<td>70-90</td>
<td>70-90</td>
<td>80-70</td>
</tr>
</tbody>
</table>

Table 4: Properties of the different SCCs

<table>
<thead>
<tr>
<th></th>
<th>Unstable</th>
<th>Filler</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>2427</td>
<td>2368</td>
<td>2408</td>
</tr>
<tr>
<td>AC [%]</td>
<td>0.3</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>SU [mm]</td>
<td>685</td>
<td>660</td>
<td>670</td>
</tr>
<tr>
<td>T500 [s]</td>
<td>0.66</td>
<td>0.58</td>
<td>1.44</td>
</tr>
<tr>
<td>V50 [mm]</td>
<td>94.0</td>
<td>93.6</td>
<td>93.8</td>
</tr>
<tr>
<td>Segregated fraction [%]</td>
<td>16.5</td>
<td>28.2</td>
<td>38.4</td>
</tr>
</tbody>
</table>
Preliminary conclusions - rheology

- All three concretes were considered to be unstable, even the stabilized ones. Hence rheological measurements should be interpreted with care.

- The unstable concrete was the most difficult to pump. Hence pumping indicated that the unstable concrete was most unstable.

- Chemical stabilization seems to work well according to the rheological measurements with BML and Contec (increase in viscosity).

- Sieve segregation test indicated increased segregation adding chemical stabilizer!
Experiences with SCC challenges met in the field today

Bernt Kristiansen AF Gruppen AS

Examples of use of SCC in AF

«Kepplar-star», autumn 1999

Test with SCC and tradisjonal concrete

SCC Normal
Normal

SCC

Casting with SCC

<table>
<thead>
<tr>
<th>Betongregneprosjektet</th>
<th>SCC</th>
<th>FB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, 0 – 8 mm</td>
<td>1083</td>
<td>1074</td>
</tr>
<tr>
<td>Stein, 8 – 16 mm</td>
<td>750</td>
<td>755</td>
</tr>
<tr>
<td>Sement, anlegg</td>
<td>405</td>
<td>378</td>
</tr>
<tr>
<td>silica</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Vann</td>
<td>110</td>
<td>108</td>
</tr>
<tr>
<td>Sikament 130</td>
<td>4,5</td>
<td>4,5</td>
</tr>
<tr>
<td>Sikament 92</td>
<td>5,5</td>
<td>5,5</td>
</tr>
<tr>
<td>AER</td>
<td>0,6</td>
<td>0,3</td>
</tr>
<tr>
<td>Tot. vann</td>
<td>168</td>
<td>163</td>
</tr>
<tr>
<td>v/(c+s)</td>
<td>0,40</td>
<td>0,41</td>
</tr>
</tbody>
</table>
SCC is not the only answer on perfect concrete surface

Inside walls, B30M60 in inside walls

Criteria for use og SCC, B30M60 in inside walls

• SCC is a casting method:
  • Choice of formwork
    • Surface
    • Dense formwork
    • Climbing speed (stigehastighet)
  • Casting volume
    • Area of formwork
    • The concrete must be pumped
      • Normally concrete scoop (tobo) is used
  • Concrete
    • «Uniform» delivery
    • No separation
Experience, B30M60

SCC COULD be interesting economically but the variation was too big.
Too much adjustment of the concrete on site.

Sørenga, 2006-2010

Concrete ca. 110,000 m³
SCC ca. 30,000 m³

Wall

Casting walls

• SCC, SF 62 cm, -3 + 5 cm
• Every batch controlled
  • SynkFlow
  • Segregation
• Casting method
  • Pipeline through the roof
  • Submerged pipe in the concrete, 1 m
  • Trapdoor (Støpeluker)
  • "guillotine"
**Casting with pressure and guillotine**

**Guillotine**

**Concrete composition**

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>C40 65 % FA</td>
</tr>
<tr>
<td>Fly ash</td>
<td>201</td>
</tr>
<tr>
<td>Silica fume</td>
<td>131</td>
</tr>
<tr>
<td>Sand 0-8 mm</td>
<td>660</td>
</tr>
<tr>
<td>Pozz 8-18 mm</td>
<td>188</td>
</tr>
<tr>
<td>Pozz 18-32 mm</td>
<td>744</td>
</tr>
<tr>
<td>Air 151 kg/m³</td>
<td>5.45</td>
</tr>
<tr>
<td>Micro Air kg/m³</td>
<td>0.08</td>
</tr>
<tr>
<td>Vum (total) kg/m³</td>
<td>150</td>
</tr>
<tr>
<td>Efficiw (w+2w-0.7a)</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**Aggregate**

- Density concrete: 2.42 kg/dm³
- Density: 3.05 kg/m³
- Fraction: 8-18 mm og 18-32 mm

**SCC walls, Sørenga**

*Very good surfaces*
Floor, Bubbledeck 2006, 7000 m³
Sogn Arena

B35M45
SF 58 cm

On site Plywood is normally underlay for concrete-testing. On fabrikk steel is often used.

Results from testing

• Factory:
  • Steel: SU = 580,
  • T50: SU = 600 → T50 = 1.9 sek.

• Construction site:
  • Steel: SU = 610 mm
  • Plywood: SU = 630 mm
  • Veneer (Finér): SU = 560 mm
  • T50
    • SU = 600 → T50 = 1.9 sek
    • SU = 650 → T50 = 1.5 sek

• Experience:
  • Calibrate underlayer
  • Calibrate change of SF depending on
    • Time from producing
    • Casting, pumping etc.

Walls under ground, from 2006

> 60% of walls underground is SCC, B35M40

Gladenveien 2011
Challenges met in the field today

Wishes for the future:
• Control on admixtures
• Open time, SF
• Retarding effects, setting time
Challenges met in the field today
Wishes for the future:
• Control on admixtures
  • Open time, SF
  • Retarding effects, setting time
• Pasta
  • No risk for segregation with different W/C-levels
  • Setting time under control
    • with different temperatures

Segregation

Segregation

Challenges met in the field today
Wishes for the future:
• Control on admixtures
  • Open time, SF
  • Retarding effects, setting time
• Cementing material (pasta)
  • Stabil with different W/C-levels
  • Setting time
    • with different temperatures
• Concrete
  • «Uniform» concrete in all classes
    • «Robust» SCC
TAKK FOR OPPMERKSOMHETEN
Concrete with high fly ash content

Experiences from readymix production
M.Sci. Øyvind Sæter

Low heat concrete with high fly ash content
- As little hydration heat as possible
- Close to critical water demand
- Fly ash used to reduce cement
- Cement reduction 32-40%

Challenges
- Workability
- Production process
- Experienced workability
- Air content

**Concrete with high fly ash content**

<table>
<thead>
<tr>
<th>Material</th>
<th>40% FA LHC C35/45</th>
<th>32% FA LHC C35/45</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52.5 N</td>
<td>kg/m³ 201</td>
<td>kg/m³ 250</td>
</tr>
<tr>
<td>Water</td>
<td>kg/m³ 140</td>
<td>kg/m³ 140</td>
</tr>
<tr>
<td>Silika k=2</td>
<td>kg/m³ 16</td>
<td>kg/m³ 0</td>
</tr>
<tr>
<td>Flyash k=0.7</td>
<td>kg/m³ 130 (65%)</td>
<td>kg/m³ 125 (50%)</td>
</tr>
</tbody>
</table>

**Production**
- Production
  - RMC produced in plants with high volume of normal concrete
  - Most of HFC produced at a plant with ~1000 m³ RMC/day
  - High flow rate of raw materials
  - Raw material and RMC quality control is essential for stable production
  - Moisture control is important
  - “Not so good” materials – what then
  - Do not use?
  - Material already in production line/pipe?
  - Enough materials available?
  - RMC quality check
  - Workability
  - Stability
  - Air content

**Workability – RMC site**
- Mixing
  - Mixing cycle and mixing time is important
  - Generally need more time before stable workability reading (wattmeter)
  - Minor change in mixing cycle -> major impact on workability
  - Moisture control of aggregates
  - Superplastiziser
- Quality control
  - Raw material (aggregates)
  - Concrete Fresh properties... "continuously"
- When it fail...
  - Remix with additives – careful with superplastiziser
  - Temporary plant "shutdown" as the concrete jams between mixer and truck
  - Waste concrete

**Experiences**

Bjørvika infrastructure 2005-2012
- 120,000 m³ of low heat concrete
- Fly ash: 40% of powder (65% of OPC)

Hardanger bridge 2010-2012
- Fly ash: 33% of powder (50% of OPC)

Økern road junction 2010-2013
- With 2 kg/m³ 6mm micro pp-fiber for fire protection
- Fly ash: 33% of powder (50% of OPC)

Unicon LHC for "housing" 2008-
- Fly ash: 33% of powder (50% of OPC)
- Last 12 months: 15% of ready-mix volume in OSLO
  - SKB: 5%
  - Slump S4: 10%
Workability – Construction site

- Customers demand
  - S4, typical 200-220 mm slump
  - Visually looks like slump 160-200, measures 200-220
  - Superplastiziser have great impact on experienced workability

<table>
<thead>
<tr>
<th>Additive</th>
<th>Slump</th>
<th>Flow diameter t=5</th>
<th>Flow diameter t=60</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS 1</td>
<td>200</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td>TSS 2</td>
<td>210</td>
<td>450</td>
<td>370</td>
</tr>
</tbody>
</table>

- SCC
  - 2-5 sec to reach T500
  - Up to 650 mm without (or little) chemical/filler stabilization
  - High density aggregates, significant stabilization needed above 650 mm

- “Rubber” concrete problem
  - High slump loss after pumping (or before)
  - Caused by too little water available

Air content

- Air content is variable...
  - Variations in fly ash have significant impact on air content
  - Experienced 100% change in air dosage from one FA delivery to another
  - Keep an eye on loss of ignition

- Raw material control
  - Not so easy
  - High volume, 50-150 tons FA per day

- Quality control during start-up is a critical success factor
  - Continuous control during production
    - Every 50m³

Summary

Low heat concrete with high fly ash content
- Concrete designed close to critical water demand
- Small amount of water to cover all particles
- Change in water demand or moisture of aggregates have great impact on workability if not discovered before production
- Changes in fly ash components (loss of ignition) have impact on air content. The higher fly ash content the greater the impact.

Good workability – but it behaves “different”
- Visually estimated to slump 160-180 mm. Measured 200 mm
- SCC uses “long time” (2-5 sec) to T500
- The effect increases with fly ash content
- Walls: Cast as normal
- Flooring etc: “No problem...” but not simply either.
  - “...you got to learn casting again”.

Thank you
Smart Dynamic Concrete
For day-to-day use

Properties & general advantages

- SDC for C25 – 35 MPa (or more, if required)
- Slump flow 500 – 720mm
- T50 > 2 sec
- Cement content 300 – 380 kg/m3
- No filler addition
- Simplified mix design procedure
- Logistic simplification
- More robust because of RheoMATRIX
- Rheological properties controlled by Glenium (yield value) and RheoMATRIX (plastic viscosity)
- Cost effective

Market Needs
Challenges

- Triggered by industry

  - Energy efficiency to reduce CO2 emissions
  - Higher durability specs require perfect covering of reinforcement
  - Process economy to save time + money with an increasing demand for higher fluid

Market Needs
Customer

- Customer needs
  - Highly fluid + robust
  - Cost effective
  - Reducing placing time
  - Boosting productivity
  - Shortening construction time
  - Outstanding quality
Smart Dynamic Construction (SDC)

For a new generation of highly fluid concretes

Innovative system solution
- Robust mix design with <380 kg fines
- Tailor-made GLENIUM superplasticizer
- Exclusive, latest technology VMA with self-organizing molecules which enables unmatched concrete robustness

Solving the dilemma
- Cost effectiveness
- Self-compaction
- Robustness

Traditionally
- Vibrated Concrete (TVC)

Self-Compacting Concrete (SCC)

Robust mix
- No vibration

Low stickiness
- High speed

Good price
- Great surface

Features & Costs

Material cost per m³ concrete

<table>
<thead>
<tr>
<th>Features</th>
<th>TVC</th>
<th>SDC</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fines</td>
<td>100%</td>
<td>107%</td>
<td>125%</td>
</tr>
<tr>
<td>Slump flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

KryoSEM picture: VMA molecule structure

Traditionally
- Vibrated Concrete (TVC)

Self-Compacting Concrete (SCC)

Robust mix
- Low stickiness
- Good price

No vibration
- High speed
- Great surface

Smart Dynamic Concrete

Norwegian example

C37/B30 Flooring S4/S5(220mm)

<table>
<thead>
<tr>
<th>Material</th>
<th>In kg Pro m³</th>
<th>In kg Pro m³</th>
<th>In kg Pro m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>178</td>
<td>195</td>
<td>178</td>
</tr>
<tr>
<td>Cement</td>
<td>302</td>
<td>330</td>
<td>302</td>
</tr>
<tr>
<td>V/C ratio</td>
<td>0.59</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>Filler(SF)</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>2.4</td>
<td>5.0</td>
<td>3.9</td>
</tr>
<tr>
<td>VMA</td>
<td>1.5(old)</td>
<td>1.0(new)</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1118</td>
<td>1156</td>
<td>1115</td>
</tr>
<tr>
<td>Aggr.</td>
<td>750</td>
<td>650</td>
<td>750</td>
</tr>
</tbody>
</table>

C37/B30 Flooring S4/S5(200mm)

<table>
<thead>
<tr>
<th>Material</th>
<th>In kg Pro m³</th>
<th>In kg Pro m³</th>
<th>In kg Pro m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>186</td>
<td>206</td>
<td>186</td>
</tr>
<tr>
<td>Cement</td>
<td>326</td>
<td>400</td>
<td>326</td>
</tr>
<tr>
<td>V/C ratio</td>
<td>0.57</td>
<td>0.52</td>
<td>0.57</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>2.91</td>
<td>5.0</td>
<td>3.9(new)</td>
</tr>
<tr>
<td>VMA</td>
<td>1.8(new)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1110</td>
<td>1150</td>
<td>1220</td>
</tr>
<tr>
<td>Aggr.</td>
<td>718</td>
<td>584</td>
<td>625</td>
</tr>
</tbody>
</table>

Smart Dynamic Concrete

100% crushed sand+aggregate

<table>
<thead>
<tr>
<th>Material</th>
<th>In kg Pro m³</th>
<th>In kg Pro m³</th>
<th>In kg Pro m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>178</td>
<td>195</td>
<td>178</td>
</tr>
<tr>
<td>Cement</td>
<td>302</td>
<td>330</td>
<td>302</td>
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<tr>
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<tr>
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<td>13</td>
<td></td>
<td></td>
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<tr>
<td>Superplasticizer</td>
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<td>5.0</td>
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</tr>
<tr>
<td>VMA</td>
<td>1.0(new)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
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<td>1150</td>
<td>1220</td>
</tr>
<tr>
<td>Aggr.</td>
<td>750</td>
<td>650</td>
<td>750</td>
</tr>
</tbody>
</table>

Construction benefits

Adding value to concrete

Benefits
- Economical
  - Savings on fines
  - Up to 40% faster placing
  - Up to 5x higher labor productivity
  - Easy to produce
- Ecological
  - Less fines, less CO2
  - Higher durability
- Ergonomic
  - No vibration
  - No noise
  - Low stickiness

Multi-win situation
- Specifier + general contractor
- Ready-mix producer

Contractor

The Innovation

Centerpiece of this unique concept

Technology
- Robust mix design
- Tailor-made superplasticizer
- Exclusive VMA

Features
- Fines < 380 kg
- 60-70 cm slump flow

Benefits in the field of
- Economics
- Ecology
- Ergonomics

Smart Dynamic Construction
RheoMATRIX supported Concrete Stability

Adding 10 l/m³ water

New

Old VMA vs RheoMATRIX

- No segregation
- + 0.6 – 1.2 kg/m³ vma

No segregation

Segregation

Summary

Technology
- Robust mix design
- Tailor-made superplast.
- Exclusive VMA

Features
- Fines < 380 kg
- 60-70 cm slump flow
- Self-compacting

Benefits in the field of
- Economics
- Ecology
- Ergonomics

Old VMA vs RheoMATRIX

- SDC makes unique mix-design optimization possible
- SDC combines the advantages of both, TVC and SCC

- RheoMATRIX is the key to solve paradox requirements: robustness (stability) + fluidity + low stickiness
- SDC is cost effective: it saves labor and material costs

Building the Best Team in Industry

Thank you for your attention!
Buildability of concrete structures
Processes, Methods and Material
Peter.Simonsson@LTU.se

Buildability of concrete structures
- Components in thesis:
  - Buildability and Lean Construction
  - Standardization
  - IT
  - Innovations
  - Working environment
  - Introducing innovations in production
    - E.g. SCC

Introduction
“ If you refuse to look back and do not dare to look ahead you need to look out”
Tage Danielsson
A late Swedish: Poet, Actor, Writer, Comedian, Director

What does buildability comprise?
Definition:
”the extent to which the design of a project facilitates ease of construction”
Source: CIRIA -96
Through buildability:
– Create conditions for optimal construction
– Use resources in the best manner
– Create durable construction

Buildability for a bridge is influenced by:
- Early involvement of contractor
- Workplace structuring
- Available space on-site
- Production planning
- Prefabrication

According to a questionnaire survey performed by the researcher

Combining Lean and Buildability
- Lean Construction
  - Eliminate waste, Minimizing lead times and inventory
- Buildability definition:
  - "the extent to which the design of a project facilitates ease of construction"
  - "Design for – ease of construction"

<table>
<thead>
<tr>
<th>Design for</th>
<th>Ease of Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production lead</td>
<td>Lean lead</td>
</tr>
<tr>
<td>Foundation lead</td>
<td>IT</td>
</tr>
<tr>
<td>Design phase</td>
<td>Lean</td>
</tr>
<tr>
<td>Design for</td>
<td>VFM</td>
</tr>
<tr>
<td>Purchasing</td>
<td>Efficiency</td>
</tr>
</tbody>
</table>

Buildability tools
- Lean tools
  - Production methods
  - Communication
  - Standardization
  - Working environment
    - Efficiency

Combining Buildability and Lean

- Expected effects on construction process:
  - Repetitive work
  - Enhanced working environment
  - Understandable work instructions
  - Improved productivity

Potential SCC

- Shorten construction time
- “Releasing” resources
- Improved quality
- Improved working environment

Market share SCC in-situ cast

- Denmark ~ 30%
- Norway ~ 5% (large projects)
- Finland ~ 1-2%
- Iceland ~ 1%
- France ~ 2%
- GB ~ 1%
- Netherlands ~ 1%
- USA ~ 2.5-3.5%
- Japan - ?
  - Sweden ~ 8% (locally 30%)

Working environment

- 69% of all reported workrelated injuries within construction industry SWE 2005 was WMSDs
- WMSDs caused by ergonomic risk factors:
  - Heavy lifting
  - Work in awkward positions
  - Repetitive work (not productive repetitive work)
  - Stress and mental factors

Example

- 279 cases of WMSDs (muscles, skeleton etc) reported for concreters 2004 (in Sweden)
- Cost for sick leave 14 M kr/year – for society
  - No costs for companies is counted here
- Can be extrapolated to EU -> approx 214 M €/år

Working environment

- Costs for society and the construction industry considering deaths, WMSDs and invalidity within EU:
  - ~75 billion Euro annually or ~8.5% of construction costs
- In SWE a bit lower
Working environment measurement

Encompassing
- Ergonomic studies
- Vibrations in hands and arms
- Sound measurement

Ergonomic measuring methods

- ErgoSAM analyses
  - A computer based working environment program used within the car manufacturing industry
  - Detailed
- QEC analysis (Quick Exposure Check)
  - Focus on physical site factors
  - Performed by workers and management together
- PLIBEL analysis
  - Checklist, factors affecting the ergonomics

Observations of workers in action
- Affecting Back, Shoulders/arms, Wrist and Neck
- Video filming of work cycles, casting

Working environment

Typical work postures when compacting traditional concrete

Will be performed over 200 times when casting this wall

Working environment

Concrete casting
- Traditional cycle mean value 18.2 (needs immediate attention!)
- SCC Work cycle mean value 5.7 (acceptable!)

Making sure skilled workers are healthy and able to stay in construction

QEC

- QEC% value = (E/Emax) * 100
- E = Exposure value for body area
- Emax = Exposure value for maximal potential body area

Risknivå  Föreslagen åtgärd  QEC% värde

1: Acceptable risk
   Acceptable arbetsställning ≤ 40%

2: Moderate risk
   Utredning och förändringar behövs
   Förändringar kan bidra 40-49%

3: High risk
   Omdimensionering och förändringar behövs snart
   Förändringar kan bidra 50-69%

4: Very high risk
   High risk already over 50%
   Omdimensionering och förändringar behövs snart
   Förändringar kan bidra 70%

Vibrations Hand-Arm

EU Directive 2002/44/EC:
- Average value per day 2,5 m/s²
- Max value 5 m/s²
- Vibration injuries might appear with lower exposure than 2,5 m/s²
Vibrationer resultat

<table>
<thead>
<tr>
<th></th>
<th>Pneumatic vibrator</th>
<th>Electric vibrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left hand &gt;8 hrs</td>
<td>1.93 m/s²</td>
<td>1.57 m/s²</td>
</tr>
<tr>
<td>Right hand &gt;8 hrs</td>
<td>1.67 m/s²</td>
<td>4.12 m/s²</td>
</tr>
</tbody>
</table>

Allowed working time

<table>
<thead>
<tr>
<th></th>
<th>Pneumatic vibrator</th>
<th>Electric vibrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left hand &gt;8 hrs</td>
<td>&gt;8 hrs</td>
<td>&gt;8 hrs</td>
</tr>
<tr>
<td>Right hand &gt;8 hrs</td>
<td>&gt;8 hrs</td>
<td>5.9 hrs</td>
</tr>
</tbody>
</table>

Results not final
Only one project studied
Needs verification

According to Arbetsmiljöverkets (2005) recommendations:
- Values below < 80 dBA ok
- 80-85 dBA hearing aid
- > 85 dBA Necessary to change the working situation!

If the vibration sound is eliminated, sound level decreases with at least 10 dB(A)!

SCC - economy

Total economy for a project:
- Higher productivity when casting
- Reduced cost for sick leave enhanced working environment
- Lower site costs (establishment mm)

Important to consider the comprehensive picture to be able to introduce SCC since its more expensive to manufacture

Plan SCC castings, example RV73

- Planned casting, TVC
  - Need for many workers
  - Expensive casting
  - “Low” productivity
- Outcome SCC
  - Faster casting
  - Same No of workers
  - Cheaper casting despite “to many workers”
- Optimized casting SCC
  - Divide workers in two teams
  - Less hrs needed
  - Cheaper casting
  - Higher productivity

Plan so that the workers have other work tasks at hand!
Möjlig kostnadsbesparing genom SKB

<table>
<thead>
<tr>
<th>Köstnhv/dag</th>
<th>Ant hv i proj</th>
<th>Ant dagar</th>
<th>Total lönekostnad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2600</td>
<td>10</td>
<td>15</td>
<td>666 000</td>
</tr>
</tbody>
</table>

Bodhyra/mån

<table>
<thead>
<tr>
<th>Ant vecko</th>
<th>Ant maskiner</th>
<th>Total kostnad</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>20</td>
<td>45 000</td>
</tr>
</tbody>
</table>

Maskinhyra

<table>
<thead>
<tr>
<th>Ant vecko</th>
<th>Ant maskiner</th>
<th>Total kostnad</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 000</td>
<td>15</td>
<td>45 000</td>
</tr>
</tbody>
</table>

Total profit: 0,1 + 0,3 + 0,7 = 1 Mkr

Assume 3 weeks shorter construction time through better planning

Summa 351 7 429 1 470 3 186 14 436

SKB

<table>
<thead>
<tr>
<th>Köstnhv/dag</th>
<th>Ant hv i proj</th>
<th>Ant dagar</th>
<th>Total lönekostnad</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>4</td>
<td>1</td>
<td>178 27 428</td>
</tr>
</tbody>
</table>

11 250 m³ can be casted with SCC

Decreased casting costs – 829 573 kr

“Saved” working time 2970 h (69 v)

Plan workers time so they have alternative tasks at hand during castings!

Advantages with SCC, working environment:
- 3 times reduction of physical strain
- No mechanical vibration results in less sound pollution at site
- Eliminating of potential vibration damage
- Skilled workers stay in the construction industry

Economic advantages SCC:
- Reduction of site costs considering casting
- Minimized waste of workers time
- Helps keeping timeframe

Other benefits with SCC:
- Improved quality, e.g. tunnel linings
- Increases the image of concrete

Performance of adapted SCC
- Two sets of slump flow and T50
- SCC-a vertical parts of a bridge e.g. front wall and column
- SCC-b horizontal elements e.g. bridge deck and large foundations

Robustness in relation to steady production

• properties of the fresh concrete were documented by means of visual inspection, workability and rheology tests.
SCC in my research
Robustness in relation to steady production
VMA,

Trying to sum up
“If you refuse to look back and do not dare to look ahead you need to look out”

Combining Lean and Buildability

Introduktion
• 69% av alla inrapporterade arbetsrelaterade skador i Sverige 2005 var WMSDs (WMSD = Work related MusculoSkeletal Disorder)
• WMSDs orsakade av ergonomiska risk faktorer:
  – Tunga lyft
  – Arbete i påfrestande ställningar
  – Momentana ensidiga arbeten
  – Stress och mentala påfrestningar
• Kostnader för samhället och byggindustrin map dödsfall, skador och invaliditet inom byggindustrin i EU är ~75 miljarder Euro årligen eller ~8.5% byggkostnaderna

Conclusions
Difference between the two risk assessment methods
QEC:
  • Both worker and researcher work together in the study
PLIBEL:
  • Asks the worker how he or she experience the work task
  • The researcher does not consider own experience

Introduce changes:
• Prefabricated reinforcement solutions
• Left concrete form systems
• SCC
  as a mean to increase productivity at site, a need to create projects that are buildable and able to be constructed, i.e. constructions that we know in advance are practically feasible and productive.
Buildability and Lean

- Buildability i.e. "the extent to which the design of a building facilitates ease of construction"
- Buildability - design for "ease of construction"
- Lean construction - planning of a productive flow of work tasks and resources

Självkompakterande betong – ett självklart val för bättre ekonomi och arbetsmiljö

Arbetsmiljö och ekonomi, SKB

Innehåll
- Introduktion
- Mätning av arbetsmiljö
- Resultat arbetsmiljö
- Ekonomi
- Diskussion

Cube-model

Resultat från ErgoSAM; tre belastningstyper:
- Arbetsställning (1-3)
- Kraft (1-3)
- Frekvens (repetition) (1-3)

Ansträngningsnivå = Kraft x Arb.ställning x Frekvens
Värsta fallet 3 x 3 x 3 = 27

Resultat

Traditionellt vibrerad betong: 18,2

0 < X < 6 Acceptabel Grön
6 ≤ X < 9 Acceptabelt korta stunder Gul
9 ≤ X ≤ 27 Oacceptabelt Röd

SKB är 3 ggr bättre!
Session 5

MODELLING
Numerical simulations of SCC flow, e.g. to predict development of inhomogeneities during casting of SCC

Jon Spangenberg, Phd-student
Supervisor: Jesper H. Hattel
Co-Supervisor: Mette R. Geiker and Henrik Stang

FTP project Partners:

Outline

• Programming flow of SCC
• Channel flow test
• SCC segregation experiment
  • Setup
  • Results
• Simulating segregation experiment with Flow3D
  • Continuous phase
  • Particles
  • Results

Programming flow of SCC

Governing equations:
• Mass conservation equation
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \Rightarrow \frac{\partial \rho}{\partial t} = 0 \]
• Momentum conservation equation
\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = \nabla \cdot \mathbf{f} + \mathbf{S} \]

Solving the equations in order to obtain:
Pressure and velocities
Propagation of SCC carried out with the Volume Of Fluid (VOF) method
Material model:
Bi-viscosity model

SCC segregation experiment

• Form filling of beam
• Dimensions: 4.0x0.3x0.2 m
• Casted from one end
• Casting duration 160 seconds
• Volume fraction measured in 9 sub-regions
• Three aggregate fractions measured

Results:
Simulating experiment with Flow3d

SCC calculated with an one way momentum coupling between continuous phase and aggregates

Continuous phase
• Calculated as a single phase
• Considered as paste and a percentage of the finest aggregates
• Modeled with bi-viscosity material model
• Modeled with density and rheological parameters of the SCC

Simulating flow of SCC with Flow3d

Aggregates
• Represented as a volume fraction scalar
• Considered as spheres

Settling velocity equation
\[
\mathbf{a} = \frac{\mu (\rho - \rho_s)}{12\mu_{\text{eff}}}
\]

Volume fraction equation
\[
\phi_{\text{agg}}^{n+1} = \phi_{\text{agg}}^n \left( 1 - \frac{2}{3} \frac{\mathbf{a} \cdot \mathbf{V}}{\phi_{\text{agg}}^n \mathbf{F}_\text{agg} + \phi_{\text{agg}}^n \mathbf{F}_\text{agg}} \right) + \frac{\mathbf{V} \cdot \mathbf{F}_\text{agg}}{\phi_{\text{agg}}^n \mathbf{F}_\text{agg} + \phi_{\text{agg}}^n \mathbf{F}_\text{agg}}
\]

SCC segregation experiment

Experimental and numerical results:

Thank you
Modelling of flow induced inhomogeneities in self compacting concrete

Jan Skoček

Co-authors:
- Oldřich Švec
- Mette R. Geiker

Cooperation:
- N. Roussel
- J. Spangenberg
- J. Hattel
- H. Stang
- P. Szabo

Outline

- Model
  - Motivation & requested features
  - Methods & implementation

- Applications
  - Analysis of phenomena, processes and mechanisms observed during casting of SCC
  - Full-scale simulations of casting process

- Conclusions and perspectives

Model

- Motivation
  - Simulate flow of SCC as a flow of suspension of rigid particles in non-Newtonian fluid

- Requested features of the model
  - Fluid Dynamics Solver
  - Non-Newtonian fluid rheology
  - Free surface flow
  - Particle Suspension
    - Fluid – Particles interaction – two-way coupled
    - Accurate dynamics of particles
    - Particle – Particle interactions (collisions, forces...)
  - Efficiency (real-size laboratory experiments, details of structures...)
  - Accuracy

Fluid Dynamics Solver

- Lattice Boltzmann Method
  - Comes from the Kinetic theory and cellular automata

- System evolves due to propagation of fictitious particles and their collisions (dissipation)
  - Simple implementation and reasoning
  - Most of the code is local (shear stress tensor...)
  - Simple parallelization
  - Simple implementation of free surface

Particles

- Rigid solid bodies – spheres, cylinders, ellipsoids
- Runge-Kutta Fehlberg integration of equations of motion with adaptive time sub-stepping
- Continuous forcing (e.g. repulsion, lubrication)
- Instantaneous collisions – friction, coefficient of restitution
**Immersed boundary method**

**Applications – Effect of spheres on viscosity**

**Applications – segregation in suspension**

**Applications - LBox**

**Plate casting**

- Plate 1.6 x 1.6 x 0.15 m was casted
- Rheology:
  - Plastic viscosity = 75 Pa s
  - Yield stress = 45 Pa
- Steel fibers 80/60 = 0.5%
• The plate was cut into 3 x 8 beams
• 12 middle sections of size 200x150x150 (blue) were CT scanned

Skeletonized CT scans into Orientation tensors (3D ellipsoids)

Comparison

Conclusions and perspectives
• Model is accurate and efficient
  - Robust, stable, without any fitting parameters
  - Parallel implementation in progress
• Further studies on effective rheological properties and segregation
  - Poly-dispersity
  - Aspect ratio of ellipsoids and cylinders
  - Fibers – orientation, interaction
  - Surface properties of aggregates
  - Yield stress values
• Collaborations are welcome
Rheometer-4SCC used as a stability meter for SCC

Jon E. Wallevik: ICI Rheocenter, Innovation Center Iceland, jon.w@innovation.is

Source literature:
  - Sponsors of the project were: NFR, Norcem, Elkem, Skanska, Unicon, Norbetong, BASF, Rescon Mapei, Betong Øst og Veidekke.

Dynamic vs. static stability tester

- As the rheometer is segregating the SCC by mechanical means (by rotating impeller), it could be considered as a “dynamic” stability tester
- “Static” stability testers (by gravity) would then be for example the
  - Surface settlement test [2]
  - Sieve segregation resistance test [5].


Navn på blanding =>
Bl. 15 Bl. 18 Bl. 15 SS Eklogitt Årdal Fiber
Sement 370 375 380 390 390 390
Vann 184 185 180 163 163 163
Matriks 340 350 360 344 343 343
v/p 0,41 0,39 0,35 0,32 0,32 0,32
m 0,45 0,45 0,43 0,38 0,38 0,38
Sement type STD FA STD FA STD FA ANL FA ANL FA ANL FA
> 8 mm Årdal Årdal Årdal Årdal Årdal Årdal Årdal Årdal
< 8 mm (sand) Årdal Søberg Årdal Årdal Årdal Årdal Årdal Årdal
UKE 10 UKE 10 UKE 10 UKE 26 UKE 26 UKE 26
Experimental setup

- Increase in SP and water
  - Start with a stable concrete
  - The SP content is increased stepwise and stability is visually assessed, as well as RSI is measured with Rheometer-4SCC
  - The water content is increased stepwise and stability is visually assessed, as well as RSI is measured with Rheometer-4SCC

Make the SCC unstable by two different methods

- Reduced $\tau_0$ and $\mu$
- Density of the matrix is reduced

“Fasitt”: Actual stability of SCC is evaluated by visual observation = Visual segregation index (VSI), by Knut Lervik/SINTEF

Different observations from mixer and the slump flow (the slumpflow observations could be very misleading)

- Visual observation (Fasitt)

The aim is to get a good correlation between the RSI from Rheometer-4SCC and the concrete actual stability (Fasitt)
Rheological segregation index
RSI by the Rheometer-4SCC

RSI = 0 => no (i.e. zero) segregation
RSI = 0.5 => borderline of being acceptable concrete; (RSI > 0.5 => SCC too unstable)
RSI = 1 => complete segregation (collapse)

… same as for the KL_VSI

The first version of the prototype RSI function – RSI_1

\[ RSI_{A} = \dfrac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}}} \]

The value of RSI_1 goes from 0, when \( T_{\text{max}} = T_{\text{min}} \), up to 1 när \( T_{\text{min}} = 0 \).

A completely stable SCC => RSI = 0

\[ RSI = \dfrac{\alpha}{\sqrt{H \cdot f_{\omega} + G}} - \beta = 0 \]

\[ \frac{\alpha}{\sqrt{H \cdot f_{\omega} + G}} = \beta \]

\[ \left( \frac{\alpha}{\beta} \right)^2 = H \cdot f_{\omega} + G \]

\[ k \cdot (\rho_s - \rho) \cdot V \leq A \cdot (\mu \cdot \tau + t_0) \]

\[ k > 1 \]

Test setup for the Rheometer-4SCC

Gives instability
Gives stability

\[ k \cdot (\rho_s - \rho) \cdot V \leq A \cdot (\mu \cdot \tau + t_0) \]

\[ k \cdot (\rho_s - \rho) \cdot V \geq A \cdot (\mu \cdot \tau + t_0) \]

\[ \xi \quad \text{Confinement effect ("lattice effect")} \]

• Grading curve
• Surface properties
• Angularity
• etc.
Point: $\alpha$ and $\beta$ can represent diverse material properties with respect to segregation and stability.

\[
RSI = \frac{\alpha}{\sqrt{H \cdot f_m + G}} - \beta
\]

Example: The larger density of Eklogitt (relative to Årdal) should bring larger segregation. But this tendency could be partially compensated by larger angularity in the Eklogitt. [7]

Stability is difficult to observe directly. Within the range of acceptable SCC, gaining a good correlation in this domain is important.

RSI from 0.5 to 1 is defined as from non-acceptable SCC to complete collapse (total sp reak).

RSI from 0 to 0.5 is the interval that corresponds to an acceptable SCC. As the RSI value close up to 0.5, the SCC becomes more critical.

A "RSI - map" which is divided into 4 zones:

- RSI = 0 (KL_VSI_BL = 0) => SCC stable! A relatively large variation in SP or water is needed to make it unstable.
- RSI = 0.5 (KL_VSI_BL = 0.45) => SCC on borderline, a small variation in SP or water is critical here.

Here is the area of interest, which tells us how much the SCC is unstable.

Use of computational techniques

...SO...

- The results show that the current impeller system gives in about 20% false results and thus 80% correct readings.
- To increase the proportion of correct readings, a new type of impeller system might be a solution to that (or a new test setup in angular velocity).
- Testing a new idea is very resource demanding in terms of laboratory labor and data analysis
  - Testing new concept took minimum 4 individuals, testing for a 1 week
- As a first step of analysis, Computational Fluid Dynamics (CFD) could be used to analyze what type of impeller system would have the largest (or most desired) "pushing mechanism" (as in aggregates being pushed away from the impeller).
- CFD/Discrete Element Method?
\[ \omega = 3 \text{ rad/s} \quad \mu = 45 \text{ Pa.s} \quad \tau_0 = 0 \text{ Pa} \]

Vertical force = 2.9 Nm

Vertical force = 3.6 Nm

Examining streamlines relative to “stationary” impeller system (rotating coordinates)

Stability index for mixer (Knut Lervik, SINTEF)

<table>
<thead>
<tr>
<th>Criteria for non acceptable SCC is between 0.4 and 0.5 (≈ 0.45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 / 0.1</td>
</tr>
<tr>
<td>0.2 / 0.3</td>
</tr>
<tr>
<td>0.4 / 0.5</td>
</tr>
<tr>
<td>0.6 / 0.7</td>
</tr>
<tr>
<td>0.8 / 0.9</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

Stability index for slumpflow (Knut Lervik, SINTEF)

<table>
<thead>
<tr>
<th>Criteria for non acceptable SCC is between 0.5 og 0.6 (≈ 0.55)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 / 0.1</td>
</tr>
<tr>
<td>0.2 / 0.3</td>
</tr>
<tr>
<td>0.4 / 0.5</td>
</tr>
<tr>
<td>0.6 / 0.7</td>
</tr>
<tr>
<td>0.8 / 0.9</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

• As the rheometer is segregating the SCC by mechanical means (rotating impeller), it could be considered as a “dynamic” stability tester

• “Static” stability testers (by gravity) would then be for example the:
  - Surface settlement test [2]
  - Wet sieving stability (segregation test) [3,4], also know as the Sieve segregation resistance test [5]


Steel fibres in fresh concrete: packing, lubrication phase, jamming and proportioning parameters

Nordic Concrete Rheology Workshop Trondheim
October 3-4 2011
Stefan Jacobsen, Mette Geiker, Oliver Berget Skjølsvik and Giedrius Zirgulis

Content

- Background & objective
- Parameters
  - Particle-Matrix proportioning with calculated packing of aggregate fibre mix
  - Fibre, thickness and packing relations to rheology
- Calculating matrix- and particle volumes for SFRC
  - CPM for SFRC proportioning
  - Inverse CPM analysis fresh SFRC mixes (Årdal agg., Dramix)
- Further work, conclusions and acknowledgement

Background; Fibre effects on fresh concrete
- Particle packing and lubricating phase volume
- Thickness of lubricating phase
- Rotational overlap

Objective
- Optimize SFRC
- Proportioning and rheology prediction tool for SFRC

Particle-Matrix proportioning using packing of aggregate – fibre mix
- Compressible Packing Model (CPM) for packing calculations
- Angularity – packing (Ψ-Φ) relations for fibre established (model and experiments)
- Fibres introduced in CPM as «Equivalent packing diameter» dₚ depending on angularity and fibre volume diameter d_v
- Matrix volume calculated
- (Thickness-, packing- and fibre rotation parameters)
- (simulated/experimental relations to rheology hopefully established)
Thickness vs mortar rheology

Packing vs concrete rheology (SFRC&OC)

Matrix w/b = 0.45, CSF/b = 0.05, 3.8 % Vol-% fiber < 0.125mm, 1.9 % SP
0 and ≈0.9 % dramix fibre of concrete, Dmax = 16mm, Sl.Fl.=550-650mm
Concrete (with and without fibres) :BMl viscometer
Matrix: BML ConTec4 viscometer

CPM for SFRC proportioning - input

Maximum packing density of mix of aggregates and fibres
- Grading of aggregate fractions
- Length and diameter of fibres (1 or 2 types of steel fibre simultaneously)
- Maximum packing density of
  - Volume fractions of aggregates (grain classes) \( \Phi_i \)
  - \( \phi_i \) – though calculated from a regular packing model
- \( \Phi_{\max} \) – packing of matrix and particles
- Compaction index (K)
- Assumptions
  - Wall effect and loosening effect – constant according to [deLarrard 1999] – Can be changed to input data

Fibre rotational overlap
- As above
- Calculated spacing of fibre centres

Matrix volume and Thickness of “fibre lubricating matrix” around fibres (t_c)
- As above
- Based matrix volume/particle void volume (= particle dilution, degree of matrix dominance, matrix/particle void saturation factor k)
- Maximum particle size of “fibre lubricating matrix” around fibres: \( d_p/X \); \( d_p \) equivalent packing diameter of fibre; \( X \)

Example Packing analysis and proportioning

Standard Årdal aggregate and Dramix 35/65 steel fibres

Aggregate fractions
- 0-8 mm washed
- 8-11 mm
- 11-16 mm

Assumptions
- Limit between matrix and particles: 0.125 mm
- Maximum particle size of “fibre lubricating matrix” around fibres: \( d_p/X=3 \)

Example - CPM with fibre - Maximum packing \( \Phi_m \)

(Årdal aggregate + 35 mm Dramix fibre mixes)

Adding approx 1% vol fibres to a mix with max. \( \Phi_m \): \( \Phi_m = 0.02 \) (0.7%)

Example \( \Phi/\Phi_m \) for matrix volume = 2 x (1-\( \Phi_m \))

(Årdal aggregate + 35 mm Dramix fibre mixes)

Assumptions
- Matrix vol = 2 x (1-\( \Phi_m \))
- Air voids part of matrix
Example - Matrix volumes (1-Φ)

<table>
<thead>
<tr>
<th>Volume l/m³</th>
<th>Ø 0.0%</th>
<th>Ø 0.5%</th>
<th>Ø 1.0%</th>
<th>Ø 1.5%</th>
<th>Ø 2.0%</th>
<th>Ø 2.5%</th>
<th>Ø 3.0%</th>
<th>Ø 3.5%</th>
<th>Ø 4.0%</th>
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<tbody>
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<td>690</td>
<td>699</td>
<td>708</td>
<td>718</td>
<td>727</td>
<td>736</td>
<td>745</td>
<td>754</td>
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<td>627</td>
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<td>647</td>
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<td>668</td>
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<tr>
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<td>496</td>
<td>499</td>
<td>502</td>
<td>504</td>
<td>507</td>
</tr>
</tbody>
</table>

Example - Thickness of lubricating matrix for \( d_{fiber} / 3 \) (Årdal aggregate + 35 mm Dramix fibre mixes)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Volume l/m³</th>
<th>Ø 0.0%</th>
<th>Ø 0.5%</th>
<th>Ø 1.0%</th>
<th>Ø 1.5%</th>
<th>Ø 2.0%</th>
<th>Ø 2.5%</th>
<th>Ø 3.0%</th>
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<tbody>
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<td>45.0%</td>
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<tr>
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<td>464</td>
<td>473</td>
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<tr>
<td>40.0%</td>
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<td>471</td>
<td>474</td>
<td>476</td>
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<tr>
<td>90.0%</td>
<td>100.0%</td>
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<td>0.0%</td>
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<td>0.0%</td>
<td>488</td>
<td>490</td>
<td>492</td>
<td>494</td>
</tr>
</tbody>
</table>

Existing mixes with varying matrix quality (but constant Årdal aggregate + 65 mm Dramix fibre)

Fibre(CPM) for SFRC proportioning - Flow chart

Conclusions

An extended Compressible Packing Model (CPM) for SFRC was applied
- Maximum packing density of mix of aggregates and fibres
- Thickness of “fibre lubricating matrix” around fibres (tc) and packing relations to mix rheology
- Fibre rotational overlap

The model was applied to standard Årdal aggregate and Dramix 35 steel fibres to illustrate the possible predictions

Predicted packing densities and observed flow contradicted expectations – more extensive data are needed – suggested research is identified

Further work (preliminary)

- Verification of CPM fibre-particle-matrix proportioning programme
- Parameter study/Sensitivity analysis
  - Aggregate grading variations
  - Air content variations
  - Definition of matrix
  - Definition of lubricating phase around fibres (or interacting aggregates) and associated particle phase
  - Matrix requirements for constant flow
- Comparison to simulations of flow (collaboration with DTU)
- Comparison to observations of flow
- Optimisation of mixes / guidelines for mix design
Acknowledgements

- Assistance from
  - Sindre Sandbak, Sintef
- Funding from COIN TG 2
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