GREEN CONCRETE II
Presentation of the project and introduction to the new cement types developed
Concrete: the most destructive material on Earth
Presentation of the project
Green Concrete I

• Centre for Green Concrete 1998-2002
  • New knowledge of environmentally friendly concrete types
  • New green concrete solutions in modern infrastructure projects

• Results
  • Rapid Cement (CEM I) with 10% increased strength
  • Documentation of concrete types with 30% or more reduced CO₂ footprint
  • Utilisation of waste materials from the concrete sector or other industries and utilities
  • New strategies for structural design or maintenance assessed
  • Demo bridge in green concrete
  • CO₂ screening of the green concrete bridge
A “green” concrete bridge

<table>
<thead>
<tr>
<th>kg/m³</th>
<th>Reference</th>
<th>A0</th>
<th>A1</th>
<th>A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low alkali cement (CEM I SR 5)</td>
<td>317</td>
<td>317</td>
<td>238</td>
<td>320</td>
</tr>
<tr>
<td>Rapid Cement (CEM I)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>32</td>
<td>32</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td>Ash from incineration of sewage sludge</td>
<td></td>
<td></td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>Silica fume</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>3,6</td>
<td>3,6</td>
<td>9,3</td>
<td>6,1</td>
</tr>
</tbody>
</table>
Development since 2002

Large projects demand highly durable concrete produced with low CO₂ emission

The Society demands CO₂ reduction and increased use of renewable energy

Financial crisis shifts focus to job creation

Coal-fired power station being phased out

https://commons.wikimedia.org/wiki/File:Nordjyllandsv%C3%A6rket.jpg

Large projects demand highly durable concrete produced with low CO₂ emission
Challenges for cement and concrete

• Green transformation of cement and concrete production shall contribute to the climate targets if the society

• It shall still be possible to make safe and durable constructions

• Competitiveness with other materials shall be maintained

• Competition has to be on a level playing field and not based on prejudice preconceived opinions
Long time underway......

23-06-2010: First meeting of partners
03-09-2010: First application submitted
13-12-2010: First rejection received
14-10-2011: Expression on interest submitted
16-12-2011: Second application submitted
15-05-2012: Second rejection received
25-04-2013: Expression of interest submitted
09-09-2013: Third application submitted
16-12-2013: Project approved
10-04-2014: Cooperation agreement signed
01-09-2014: Kick-on seminar
Green Concrete II

Green Transformation of Cement and Concrete Production

- Budget: EUR 3.9 million (DKK 29 million), 50% funded by the Danish Innovation Fund
- Duration: 2014-2019
- Partners from the entire value chain of construction
- Focus on infrastructure
Focus - buildings or civil constructions

95% of cement consumption
Concrete adapted according to use

5% of cement consumption
Long, guaranteed durability
The vision

• Danish concrete will also be produced with low clinker content in a future after 2030 without Danish fly ash

• **Employment** in Danish construction related industries will grow with potential for export of materials and solutions

• **Emissions of CO\(_2\)** from Danish cement production will be reduced so as to contribute to meeting the Danish climate targets
  • Target: 500,000 tons reduced CO\(_2\) emission in 2050
New cement types

FUTURECEM
What is FUTURECEM?

- **FUTURECEM** is a robust, patented technology which enables production of durable concrete with reduced clinker content compared to conventional concrete.

- Based on the fact that a mixture of fine-grained limestone and calcined clay develops higher strength when mixed with Portland clinker than expected by blending the two components.
Principle behind FUTURECEM?

- Strength development of FUTURECEM is caused by a **filler effect**, **pozzolanic reaction** and **synergy** between limestone and calcined clay.

- The **synergy effect** is caused by carbonate from limestone reacting with aluminium from calcined clay.

- The **optimum composition range** is a ratio of limestone:calcined clay between 10:90 and 50:50.
Cement development at Aalborg Portland

1990-1991: **Synergy effect** discovered by Aalborg Portland

- Objective was to develop a high-strength cement with low clinker content. Calcined kaolin or smectite and limestone mixtures were tested.
- Development of BASIS Cement (CEM II/A-LL) fulfilled the project targets. The calcined clay was therefore not needed to obtain high clinker replacement.

2008-2011: **FUTURECEM** Project

- Increased focus on CO₂ reduction prompted this project. The basic technology was documented and further developed. Patent application was submitted.

2011-2014: **SCM** Project

- Development of production equipment together with FLSmidth. Production of pilot-scale cement used to construct demo wall in RMC.

2014-2019: **Green Concrete II** Project

- Durability testing and testing in full-scale RMC constructions: a rail bridge, a road bridge and indoor wall and floor.
Reactivity of clay minerals

- Kaolinitic clays show highest reactivity
- Illitic clays have almost no reactivity
- Smectitic clays have some reactivity
- Calcination time and temperature is less critical for kaolinite than for smectite
  - This could affect which calcination technology should be used

Numbers besides these abbreviations indicate calcination temperature rounded down to the nearest hundred degrees (°C).

C. He, B. Osbaeck, E. Makovicky (1995)

30% cement replacement

Reactivity = f (Calcination temperature, retention time, particle size and porosity, raw clay composition, ...)

SCM Project 2011-2014
Raw materials in Denmark

- **Chalk**
  - Fine-grained limestone
  - Used in Aalborg Portland’s cement production

- **Kaolin**
  - Low kaolinite content in most Danish clay
  - Kaolin deposit on island of Bornholm depleted
  - Deposits are found in several places in Europe
    - Used for production in white cement

- **Plastic clay**
  - Clay with very high content of clay minerals
  - Main clay mineral: smectite
    - "Bentonite"
Manufacturing method

- **Flash calciner**
  - High temperature
  - Fast heating rate
  - Short retention time (s)
  - Fine raw meal (mm)
  - Low moisture content of raw meal

- **Rotary kiln**
  - Low temperature
  - Slow heating rate
  - Long retention time (min)
  - Coarse raw meal (cm)
  - High moisture content of raw meal
  - Existing equipment can be used
Danish clay as raw material

- As expected, kaolin performs better in terms of strength.
- Both flash calciner and rotary kiln seems to be suitable for production of calcined clay based on smectite.
FUTURECEM workability and compatibility with fly ash

• The workability tend to be better with calcined clay based on smectite than kaolinite

• Even though the supply of fly ash in North Europe declines, fly ash or bio-derived fly ash will be available for several years to come

• Fly ash significantly improve workability of concrete with FUTURECEM, thus enabling less water or admixtures to be added
Standardisation

- Use of limestone-calcined clay cement must be accepted in the national adaptations of the European concrete standard.

- Limestone-calcined clay cement is not allowed in the present Danish National Adaptation Document to the European concrete standard.

- The results from Green Concrete will contribute to achieve this.

- Limestone-calcined clay cement is allowed in the European cement standard: CEM II/A-M and CEM II/B-M.
  - Minimum clinker content: 65%
  - Limestone + calcined clay: 12-35%
  - Higher clinker substitution demand a revision of the cement standard.

European cement standard EN197-1
# FUTURECEM with Danish clay compared to RAPID Cement

<table>
<thead>
<tr>
<th></th>
<th>FUTURECEM</th>
<th>RAPID Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type (EN 197-1)</strong></td>
<td>CEM II/B-M (Q-LL) 52.5N</td>
<td>CEM I 52.5N</td>
</tr>
<tr>
<td><strong>Clinker</strong></td>
<td>62.1%</td>
<td>90.8%</td>
</tr>
<tr>
<td><strong>Limestone</strong></td>
<td>16.7%</td>
<td>4.6%</td>
</tr>
<tr>
<td><strong>Calcined clay</strong></td>
<td>16.7%</td>
<td></td>
</tr>
<tr>
<td><strong>Gypsum</strong></td>
<td>4.5%</td>
<td>4.6%</td>
</tr>
<tr>
<td><strong>1 day strength (MPa)</strong></td>
<td>15-17</td>
<td>21-25</td>
</tr>
<tr>
<td><strong>28 day strength (MPa)</strong></td>
<td>62-68</td>
<td>65-69</td>
</tr>
<tr>
<td><strong>Density (kg/m³)</strong></td>
<td>3010</td>
<td>3140</td>
</tr>
<tr>
<td><strong>Initial setting time (min.)</strong></td>
<td>110-140</td>
<td>125-155</td>
</tr>
<tr>
<td><strong>Na₂Oeq (%)</strong></td>
<td>1.0</td>
<td>0.5-0.64</td>
</tr>
</tbody>
</table>

Possible composition of a general purpose cement for ready-mix concrete based on our results.

Challenge: To produce a high-strength (52.5N) cement with low clinker content. This has proven to be possible.
Concrete can be produced which is similar to conventional Danish concrete.

- Colour similar, slightly reddish.

Composition:

- 75% CEM I (Rapid) + 25% Fly ash
- 69% CEM I (Rapid) + 14% limestone + 17% calcined clay
- 69% CEM I (Rapid) + 31% calcined clay

P/(P+GMF) = 0.5  P/(P+GMF) = 0.91
Durability

This subject will be discussed by:
- Alexander Michel, DTU
- Lars Nyholm Thrane, DTI

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clinker (%)</td>
<td>60.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Gypsum (%)</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Calcined clay (%)</td>
<td>16.9</td>
<td>28.1</td>
</tr>
<tr>
<td>Limestone (%)</td>
<td>18.4</td>
<td>7.2</td>
</tr>
<tr>
<td>Cl (%)</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Na$<em>2$O$</em>{eq}$ (%)</td>
<td>0.99</td>
<td>1.15</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalent w/c</td>
<td>0.40</td>
<td>0.42</td>
</tr>
<tr>
<td>28d strength (MPa)</td>
<td>49.1</td>
<td>48.2</td>
</tr>
</tbody>
</table>
Production, design and casting

This subject will be discussed by
- Ib Jensen and Jørgen Schou, Unicon
- Claus Nielsen, DTI
- Lars Nyholm Thrane, DTI
Demo bridges

- Danish road and rail bridges are designed to very strict prescriptive standards

- Sections of three test bridges has been produced with experimental concrete to test performance based design

- Limestone-calcined clay content has been limited to <20% because of these strict conditions
  - In one bridge, 12% fly ash was added, which is normal bridge dosage

This subject will be discussed by.
- Ib Jensen and Jørgen Schou, Unicon
- Claus Nielsen, DTI
- Lars Nyholm Thrane, DTI
Indoor demo wall and floor

• Cast in new concrete laboratory at the Danish Technological University this month

• Typical indoor concrete

This subject will be discussed by
• Lars Nyholm Thrane, DTI

Foto: Torben Eskerod
Process, fuel and transport to Aalborg, CO₂ per ton of clay

- Smectite, Denmark
  - Rotary kiln
  - Calcined on site
  - No heat recovery
  - 14% biomass

- Smectite, Denmark
  - Rotary kiln
  - Calcined on site
  - Partial heat recovery
  - 90% biomass

- Kaolinite, East Europe
  - Flash calciner
  - Calcined in Aalborg
  - Partial heat recovery
  - 14% biomass

RAPID Cement:
- 860 kg CO₂/ton cement
- 500 kg CO₂/ton cement

Model study performed by Aalborg Portland
Estimated CO₂ emissions per ton of FUTURECEM, including grinding.

- **Smectite, Denmark**
  - Rotary kiln
  - Calcined on site
  - No heat recovery
  - 14% biomass
  - 34% clinker replacement

- **Smectite, Denmark**
  - Rotary kiln
  - Calcined on site
  - Partial heat recovery
  - 90% biomass
  - 34% clinker replacement

- **Kaolinite, East Europe**
  - Flash calciner
  - Calcined in Aalborg
  - Partial heat recovery
  - 14% biomass
  - 50% clinker replacement

Model study performed by Aalborg Portland
Even with fly ash it is possible to reduce CO$_2$ footprint

- FUTURECEM concrete works well with fly ash
- CO$_2$ savings **higher** than achieved with fly ash alone
- An important effect of FUTURECEM will be to **avoid increased CO$_2$ emissions** when fly ash disappears
- The cement standard limits this possibility

<table>
<thead>
<tr>
<th>Binder composition (kg/m$^3$)</th>
<th>P25 SCC</th>
<th>A35 Conventional slump concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference</td>
<td>Test</td>
</tr>
<tr>
<td>CEM I</td>
<td>220</td>
<td>339</td>
</tr>
<tr>
<td>FUTURECEM Cement</td>
<td>252</td>
<td>360</td>
</tr>
<tr>
<td>Siliceous fly ash</td>
<td>77</td>
<td>45</td>
</tr>
<tr>
<td><strong>Total binder</strong></td>
<td><strong>297</strong></td>
<td><strong>297</strong></td>
</tr>
<tr>
<td>Plasticizer</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Air entraining agent</td>
<td>0.7</td>
<td>0.4 (-33%)</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>2.3</td>
<td>2.9 (+25%)</td>
</tr>
</tbody>
</table>
The cement standard limits the achievable CO\textsubscript{2} reductions

- The potential CO\textsubscript{2} reduction is **limited by the minimum clinker content of 35\%** in Portland-composite cements
  - Illustrated in the DTU demo concrete. CO\textsubscript{2} footprint achieved was only similar to CEM I + fly ash because clinker substitution was limited by the cement standard
  - In the upcoming revision, Portland-composite cements, CEM II/C with limestone+slag, limestone+fly ash and limestone+natural pozzolan will be allowed
  - Limestone-calcined clay cement **should also be included** in the CEM II/C class
    - This will increase the potential for CO\textsubscript{2} reduction
    - Work is underway to achieve this revision of the standard
Next steps

• **Trial cement production** of FUTURECEM in full-scale

• **Deliveries to a variety of concrete applications** and customers to gain experience in the usability of FUTURECEM in different concrete applications

• Understanding the **market value** of green cement

• Acceptance of limestone-calcined clay cement in the Danish NAD to the European **concrete standard**

• Allow limestone-calcined clay cement with up to 50% clinker substitution in the **European cement standard**
We are one big step further, but not yet there....
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