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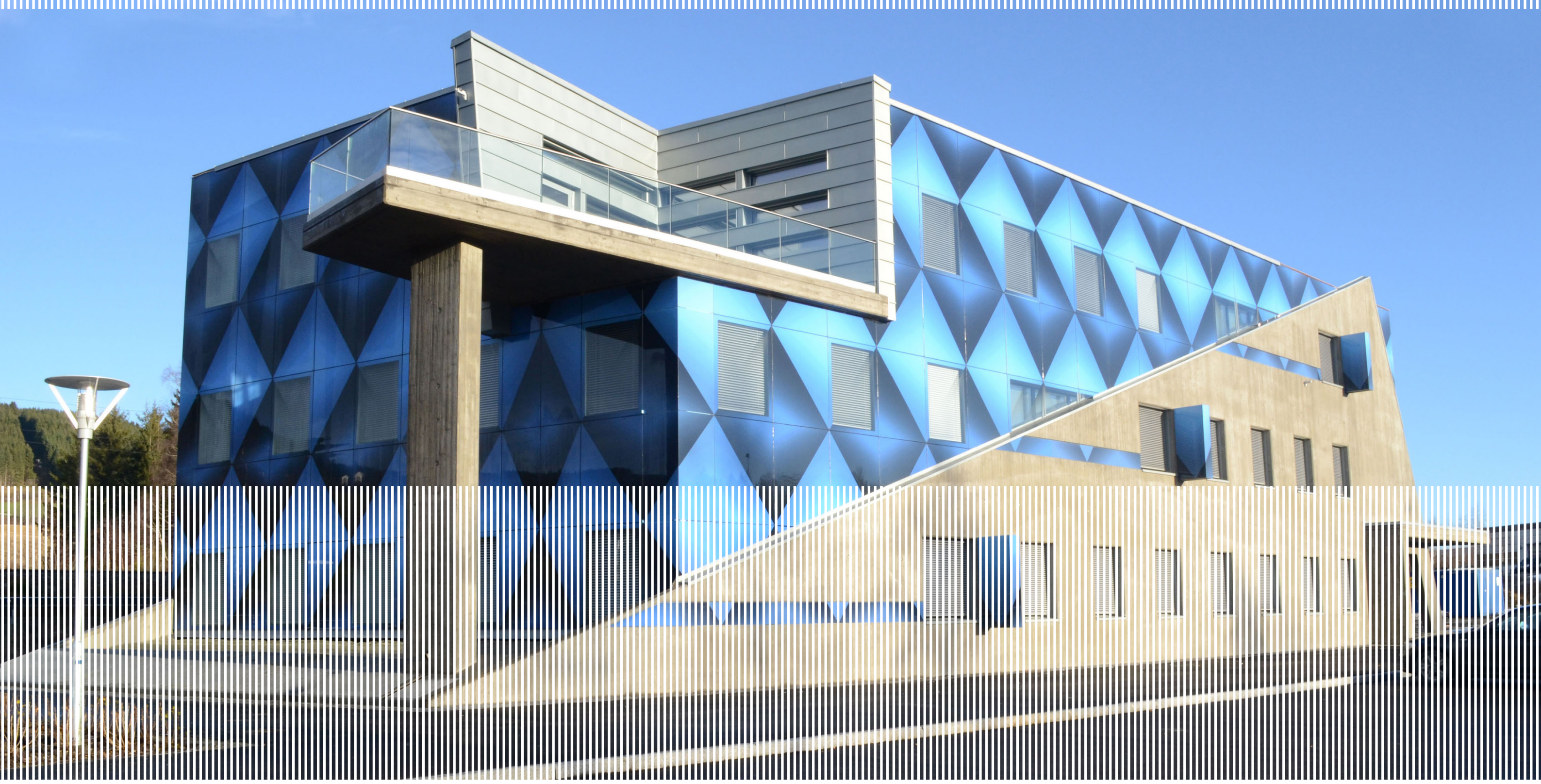
SINTEF Building and Infrastructure

COIN – Annual Report 2013



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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)

Kværner Engineering
Contact: Jan-Diederik Advocaat
Email: Jan-Diederik.Advocaat@kvaerner.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

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

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

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

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

Unicon AS
Contact: Stein Tosterud
Email: stto@unicon.no
Tel: +47 22309035

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

Summary

The vision of COIN is creation of more attractive concrete buildings and constructions. To achieve this, the work is divided into three focus areas

2013 was the seventh of eight years of the centre financed by RCN. More than 50 various articles and presentations were published in 2013 and two workshops were organized. 13 master students completed their degrees within COIN and three PhD students achieved their degrees. COIN is also attractive internationally, and five PhD students / post docs worked in the centre for various periods throughout the year.

The centre is located in Trondheim with SINTEF Building and Infrastructure as host institution The consortium partners and subcontractors represent the value chain of the business sector; Material suppliers, concrete producers, contractors and users. They represent leading multinational companies in the cement and building industry. The partners cooperate through the work in the projects (technical work and joint meetings) and in the TACs.

COIN's first patent was approved: "Hardening accelerator and a method for accelerating the hardening of hydraulic binders and mixtures thereof." Most of the experimental work is now completed, allowing for wide publication and summing up in the last year.

The accumulated cost in 2013 was 31 million NOK.

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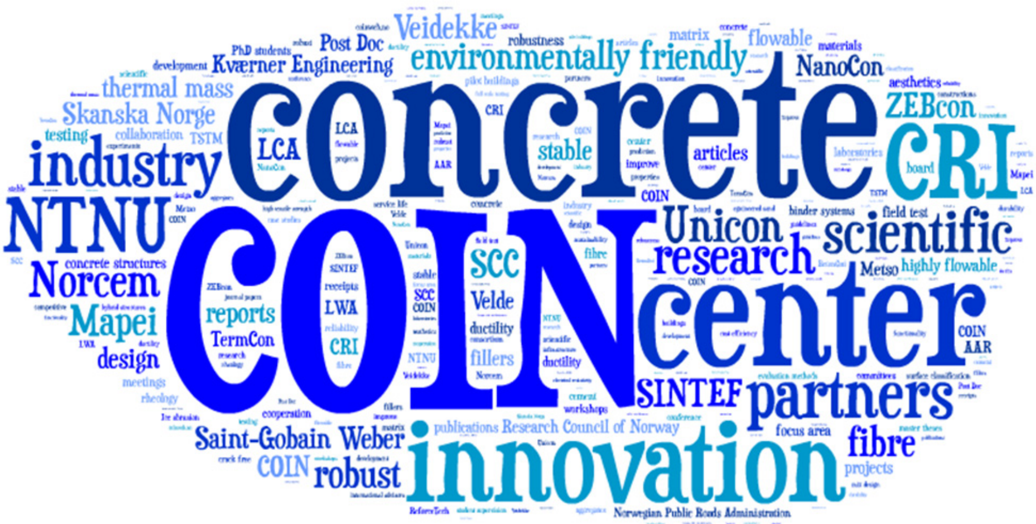
1 Vision and goal

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. COIN aims 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. Secondary goals are:

- To improve the quality of concrete products and to make them and their production even more cost efficient and environmentally friendly.
- To develop more rational production and to increase the level of competence in the concrete business area.
- To develop designs and construction systems for significant reductions in energy consumption for heating and cooling of buildings by adequate utilisation of the high thermal energy of concrete.
- To improve the sustainability through development of technologies for reduced raw material and energy consumption and for low emissions, while maintaining the market share.



2 Research plan

The construction industry is one of Norway’s largest, and concrete is the dominating construction material in buildings and infrastructure. COIN’s research plan is based on the partners' innovation themes as well as the demand from the society. The research tasks are well anchored in the innovation strategies of the partners. Innovation potential, image and customers' needs, productivity, sustainability, environment and high performance concrete for harsh climate are topics addressed.

The status discussed in the original project description is still valid, but COIN has turned more in the direction of reducing CO_2-emissions and saving energy and resources. Both nationally and internationally, COIN's three focus areas (see chapter 4.2) are important drivers for research. The first one focus on developing cements with significantly reduced CO_2 emission under production. The energy focus is addressed in the project Utilisation of concrete in low energy building concepts. The third topic of saving resources is manifested in the research on e.g. aggregates and on securing long service life of structures before they need to be repaired or replaced.

Research methodology
The overall research method, described in the original proposal, is *to achieve practical applications through fundamental understanding*. The methodologies vary between the research tasks. Firstly, the mechanisms underlying the behaviour of cementing materials are of high chemical and physical complexity and are not yet fully understood. Therefore, there is need for investigations on a nano-/micro-scale level. This includes theoretical studies combined with laboratory investigations. The SINTEF group and NTNU together hold the equipment and laboratory facilities required for advanced materials research ranging from nanometre to meters, as well as for advanced research on structural (reinforced) elements. The industrial partners as well as NPRA have research facilities own laboratories, and some of the experiments are also been done in their laboratories, both in Norway and abroad.

Secondly, the present research revealed a lack of reliable and relevant test methods to be an obstacle for innovation (e.g. fibre reinforced concrete and utilisation of aggregate resources because of risk of alkali-silica-reactions). Hence, further development of test methods is an activity in some tasks.

Thirdly, the present research revealed a lack of field data to be an obstacle for innovation (e.g. chloride penetration and energy consumption as well as thermal indoor climate connected to the thermal mass concept). Hence, systematisation of field data versus laboratory data is an activity in some tasks.

Testing from small to full scale: To the left:Scanning Electron Microscope (SEM) image of cement paste with fly ash, In the middle: Thermogravimetric analysis (TGA) and to the right: Delivery from concrete-mixer truck in the laboratory at SINTEF/ NTNU. Photos by Giedrius Zirgulis

3 Organisation

3.1 The consortium

The consortium constitutes an active and close cooperating network. COIN has 11 partners representing the whole value chain of the business sector.

- Host Institution — SINTEF
- Research partner — NTNU
- Industrial partners — Kværner
Saint-Gobain Weber
Norcem
Unicon
Skanska
Mapei
Veidekke
- Public partner — Norwegian Public Roads Administration (NPRA)
- Subcontractors — Velde
Metso
Reforce Tech

The corporate partners are leading multinational companies in the cement and building industry. COIN has attracted more research to Norway from international parent organisations of some partners.

The consortium has a board and three Technical Advisory Committees, one for each of the three focus areas. The TACs have the responsibility to establish the innovation objectives and criteria, prioritizing and reporting. The TACs also break down the overall objectives into manageable and adequate action plan and tasks.

Centre manager Tor Arne Martius-Hammer reports to the board and is the head of the centre's management group. Technical work is divided into eight projects, led by project managers from various partners: Harald Justnes, Olafur Wallevik and Klaartje De Weerdt from SINTEF, Terje Kanstad, Mette Geiker and Jan Arve Øverli from NTNU, Børge J. Wigum from Norstone and Knut O. Kjellsen from Norcem. Justnes, Wigum and Kjellsen are also adjunct professors at NTNU.

3.2 Cooperation between the centre's partners

Researchers from all partners are working in the COIN projects. Project groups comprise PhD candidates, researchers from SINTEF, professors at NTNU and personnel from the other partners. The partners cooperate through the work in the projects (technical work, joint projects meetings and publications). Personnel from the industrial partners are also co-supervisors to some of the PhD students.

The main strategy for knowledge transfer is to have joint activities and to involve many persons from each industry partner. Four partners or more are represented in every project.

New collaborations have been created through the joint work which has revealed common interests among partners and cooperation on projects outside COIN:

- Norcem and Mapei: Grinding aid
- Saint-Gobain Weber and SINTEF: Calcined clay
- NPRA and NTNU: Service life modelling
- Norstone and Mapei: New sands and fillers for self-compacting concrete
- Veidekke and ReforceTech: New fibre for fibre reinforced concrete (FRC)

Veidekke's new regional headquarters in Rudshøgda, Hamar. Veidekke received the company's Concrete Prize 2012 for this building. Photo: Veidekke

Veidekke and Reforce Tech are pushing limits with use of FRC, and in two recent projects, traditional reinforcement is to a great extent replaced by basalt fibre reinforced concrete. The two main projects are the final construction stage of the housing development "Chocolate factory" in Oslo and Veidekke's new regional headquarters in Rudshøgda, see photo above. Because basalt fiber does not rust, a reduction in thickness of the concrete cover layer enabled thinner walls. Traditional reinforcement or composite basaltic bars are only used at window and door corners, bigger block outs and wall ends. Benefits summed up by Veidekke and Reforce Tech:

- Reduced outer layer thickness from 80 mm to 40 mm
- Resulted in lower material costs by 65 percent
- Lower logistics and installation costs

4 Scientific activities and results

4.1 Technical activities

The technical activities are organized in 3 focus areas with two/ three projects per focus area:

- Focus area F1) Environmentally friendly concrete structures
  - Binders with low emission and reduced resource consumption
  - Utilisation of concrete in low energy building concepts
- Focus area F2) Economically competitive construction
  - Robust and highly flowable concrete with controlled surface quality
  - Ductile high tensile strength concrete
  - High quality manufactured sand for concrete
- Focus area F3) Aesthetics & technical performance
  - Crack free concrete structures
  - Reliable design and prolongation of service life
  - Structural performance

4.2 Some research results from the projects 2013

4.2.1 Gypsum free concrete

Calcium sulphate (e.g. gypsum) is the common set regulator in Portland cement. It has been shown that ground clinker can be set regulated by other calcium salts than gypsum that has sufficient solubility, in particular calcium acetate, formate, nitrate, nitrite and propionate. Finely divided calcium carbonate, on the other hand, is not sufficiently soluble to act as a replacement for gypsum.

Rheology of paste is improved when gypsum is replaced by the other salts, probably due to less water binding and less needle shaped surface hydration products than ettringite (i.e. AFm type products). This is an important result which implies that concrete can be made with less water using such cement, which contributes to higher strength and improved durability without incerasing the cement content.

For in particular calcium nitrate the cumulative hydration temperature is reduced, which opens up for low-energy cement without changing clinker chemistry. The effect has been documented by curing of mortar under semi-adiabatic conditions and comparing the temperature profile for 3.5 % gypsum and 2.0 % calcium nitrate, respectively, as set retarders for the ground clinker.

Removing calcium sulphate all together may also allow heat curing or evolution of hydration heat in massive structures to exceed 70 ºC without risking delayed ettringite formation (DEF). Mortar based on clinker with 3.5 % gypsum and 2.0 % calcium nitrate, respectively, was heat cured at 80 °C for 3 days. Thereafter linear expansion was monitored as a function of time. The expansion was larger for the mortar with gypsum than for the mortar with calcium nitrate, probably caused by delayed ettringite formation (DEF) in the former.

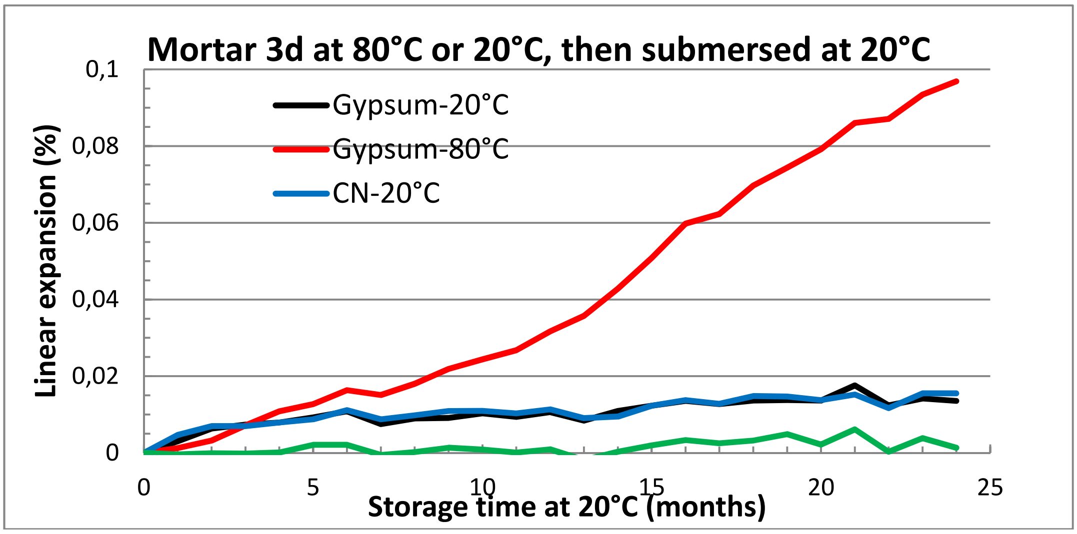


Figure 1: Linear expansion as function of time up to 2 years for mortar prisms based on clinker 1 with 3.5 % gypsum and 2 % calcium nitrate as set regulators, respectively, and cured for 3 days at either 80 or 20°C followed by storage at 20 °C. Note that mortar with gypsum cured initially at 80 °C expands, while mortar where gypsum is replaced with calcium nitrate (CN) is dimensional stable!

4.2.2 Utilisation of concrete in low energy building concepts

The study in project 1.2 Utilisation of concrete in low energy building concepts includes an emissions sensitivity analysis of different types of concrete used in the bearing systems for a zero emission building (ZEB) office concept. Further, the investigation contains an emission comparison of concrete façade elements with three different thicknesses. The results are based on and use of the data extracted from a Revit BIM (Building information model) from a ZEB office concept study presented by ZEB, the Research Centre on Zero Emission Buildings in 2013.

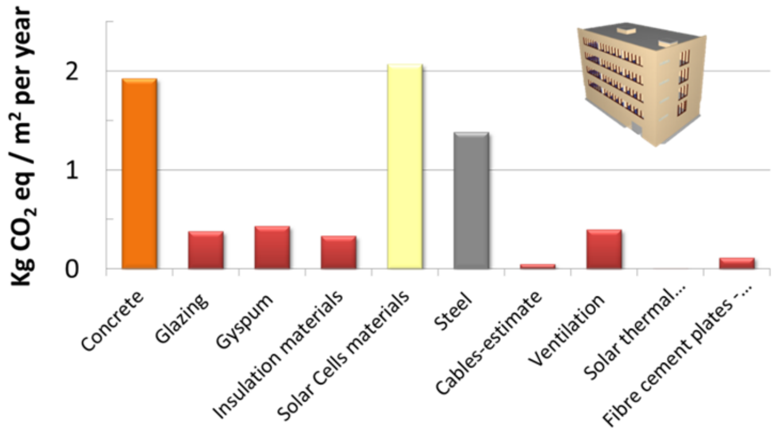


Figure 2: Embodied emission main material contributions (60 year's live time)

In the concept building a total of approximately 875 m^3 of concrete is used. Calculations using seven different emission factors for concrete have been made, using the life cycle analysis tool SimaPro (PRé Consultants, 2012) as well as for three different thicknesses of concrete façade elements. The analysis includes calculations for the use of two types of low carbon concrete and eco-crete. Energy simulations have also been performed with SIMIEN (ProgramByggerne, 2012) to look at differences in thermal comfort and emissions from energy use of the different façade elements. Energy simulations are based on the climatic conditions in Oslo, Norway.

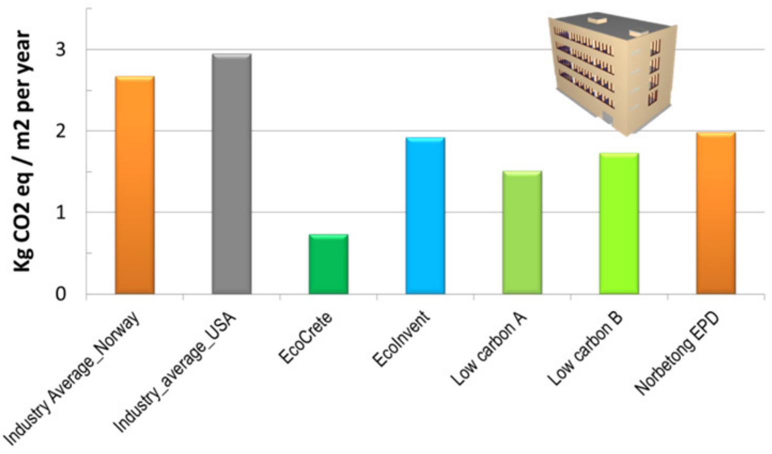


Figure 3: Embodied emission of concrete having various carbon footprint.

The results show that the emissions from the different types of concrete for the office concept vary from 10 to 30 % of the total embodied emissions, which is a significant difference. In addition the different thicknesses of the exterior walls have the effect of stabilizing temperatures in the building, thus increasing thermal comfort.

NanoCon
A novel approach in the project named NanoCon, is to have thermally insulating structural concrete, incorporated aerogel as insulation. Aerogel are nanoparticles from about 100 nm or less, are hollow spheres and represents the State-of-Art on thermal insulation with thermal conductivity between 12 to 20 mW/(mK) at ambient pressure. The gel is relatively strong, but as concrete, low in tensile strength. Results, both with normal and ultra high strength concrete (having water/binder-ratio as low as 0.2) show that aerogel can be incorporated successfully.

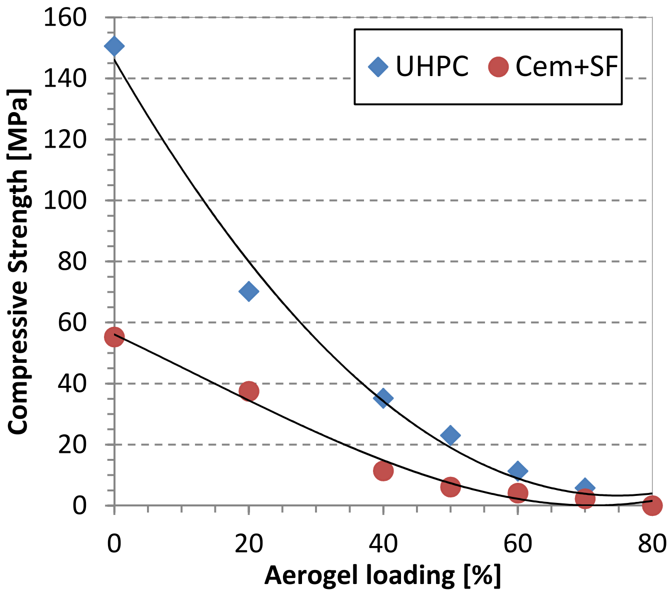


Figure 4: Compressive strengths versus aerogel loading of mixes with w/b-ratio of 0.2 (UHPC) and 0.6 (Cem+SF) respectively

4.2.3 BetongGUI – Concrete surface classification software

There is a need for an objective concrete surface classification system for the Norwegian building industry in order to avoid disputes between architects, construction companies, concrete producers and owners. This is also a hot topic internationally, as this one of the main focuses of the Fib 8.9 task group on Aesthetics of Concrete Surfaces.

Within the COIN project, a surface classification tool consisting of an image taking procedure together with a Matlab based image analysis software called BetongGUI has been developed. The work is a collaboration between the concrete department at SINTEF Building and Infrastructure and the department for optical measurement systems and data analysis at SINTEF ICT. The aim is to provide a user friendly, objective and semi-automatic tool for classification of concrete surfaces by analyzing the amount and size of pores and the grey scale level and variations.

In cooperation with Skanska and Unicon the COIN project has tested the robustness of the classification tool and the software on pores and pore classes according to Eide and Hegseth's master theses. A large number of tests to evaluate the performance and limitations of the classification tool and the system have been performed during 2013 and continuing in 2014.

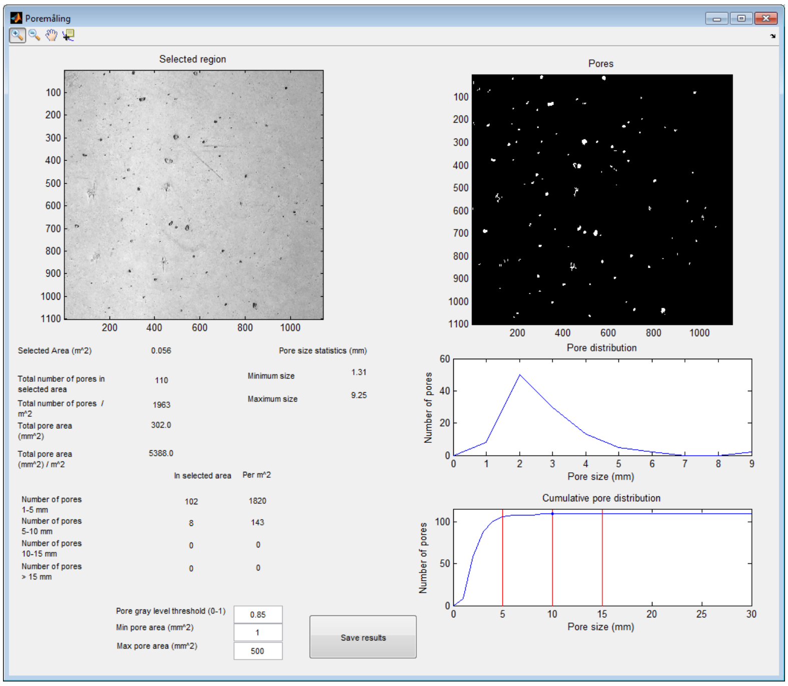


Figure 5: Example of the BetongGUI software on pore meassurements

For pores BetongGUI gives promising results for the images tested so far. There is good visual agreement between the output from the automatic pore analysis and the pores that are visible in the original image of the wall. Images with flash from two angles (45 degrees left and right) are used for the automatic counting of pores with BetongGUI. The program (example given in Figure 5) gives statistics on the distribution of pores based on the classes of pores recommended in the before named master theses. The classes are: 1–5 mm, –10 mm and 10–15 mm. Larger pores are counted as concrete casting flaws.

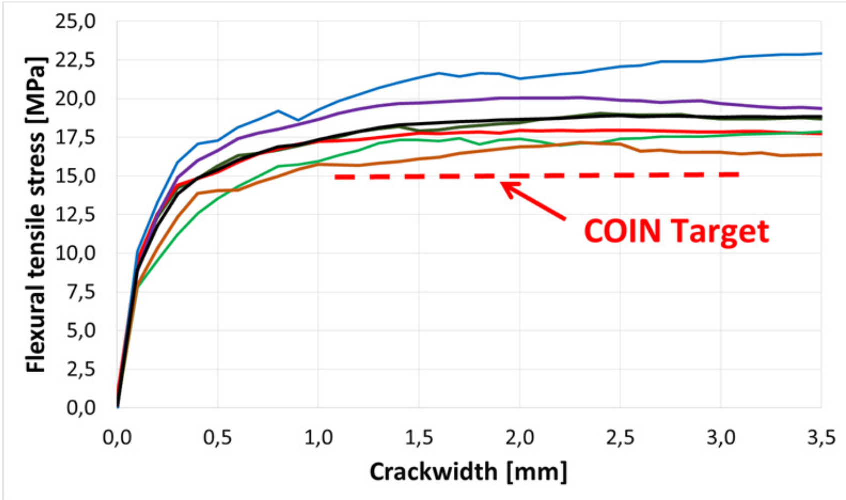
Accurate measurement of the grey level variation of concrete from the image of the surface is only possible if there is a grey scale calibration object present in the image. It has been challenging to find a grey scale calibration object that has a uniform reflection regardless of viewing angle. Uneven reflection of the flash results in wrong grey level calibration values in the software. We are currently working on evaluation of different grey scale calibration sheets.

The next step is to test the pore classification system on different building sites. A testing program in collaboration with potential users is being planned for 2014.

4.2.4 Focus area 2.2 Ductile High Tensile Strength Concrete (Fibre Reinforced Concrete)

Through the entire project period the main objectives have been due to development of an economically competitive concrete with a residual flexural strength target of 15MPa and to do R&D work which stimulates and makes use of fibres possible in load carrying structures. Considering the first objective, some of the recent results are illustrated in Figure 6 below. The performance has been gradually improved as the proportioning method and the understanding of the major influencing parameters have been developing. To handle the main problem, which is to combine high residual strength with flowability, the most successful approach seems to be to design a superflowable and stable SCC without fibres, which to a certain extent, results in a reasonably good flowability also after the fibres are added.

a)



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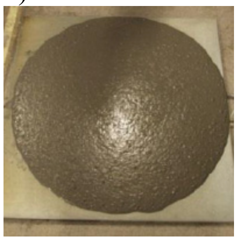


c)

Figure 6: Selected results from the materials development process, w/b=0,35, 2% (160kg/m^3) 60mm steel fibres

Considering the understanding of fibre orientation there was a breakthrough in 2012, and good agreement was achieved between flow simulations, computer tomography (CT-) scans, image analyses of sawn sections and mechanical test results. In 2013 the work has continued by studying the effect of formwork surface and reinforcement on the fibre orientation in slabs. Figure 7 shows a CT-scanned beam from a slab with bottom reinforcement in one direction. It is clearly seen that the reinforcement has influenced both the distribution and the orientation of the fibres. Furthermore, the flow and fibre orientation in vertically cast wall elements have been investigated, and some confusing results on fibre distribution from the period 2003–2005 have been verified and fully understood.

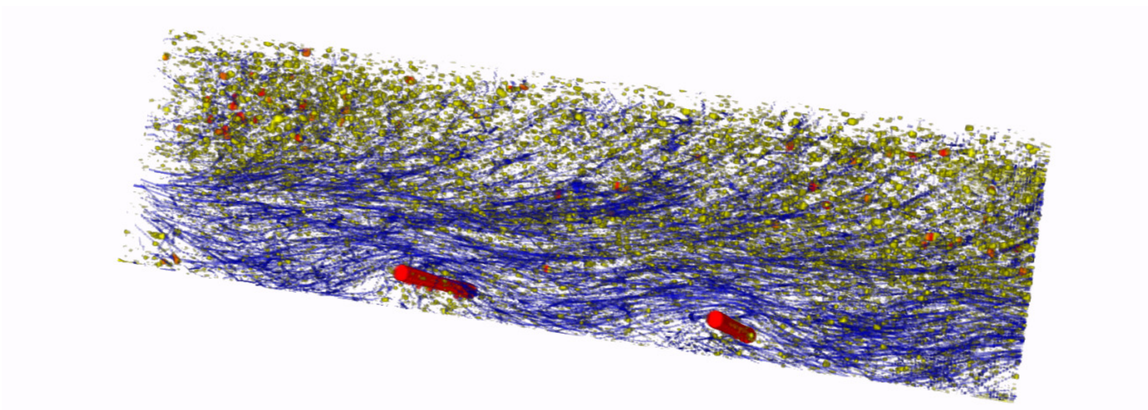
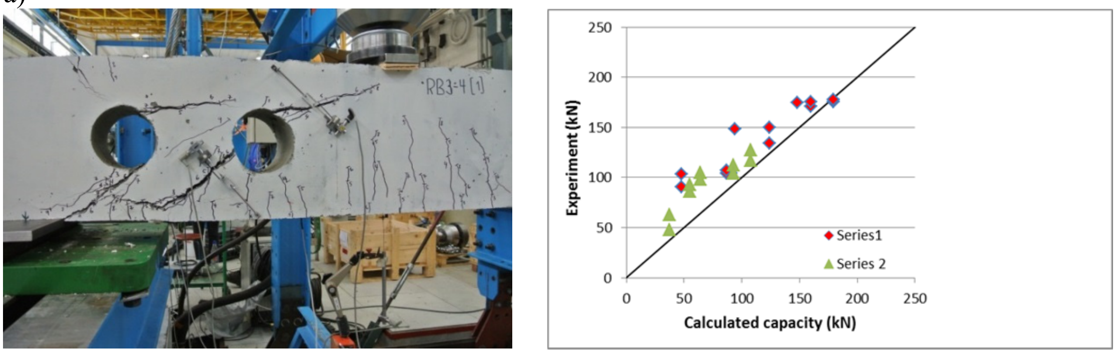


Figure 7: CT scanned beam cut from a slab with bottom reinforcement in one direction.

Within the last part of the project, field and fullscale testing of fibre reinforced concrete structures, the composite basaltic fibres made by Reforce Tech (Minibars) were used in the 5 floors high inner walls of the "Chocolate factory – project" in Oslo where Veidekke was the contractor. Some other examples of structures which have been tested and evaluated in the project are shown in Figure 8a: first beam elements with circular openings followed by a diagram which shows the achieved agreement between experiments and calculation models. These results showed that the vertical and horizontal additional detailing reinforcement around the openings can be replaced by fibres without loss of strength and ductility. Figure 8b shows the Leonardo daVinci bridge which was made of UHPFRC in 2008, and the measured load deflection curves. The test has been carried out by a master student and presently they are under evaluation by means of nonlinear finite element analysis. However, the preliminary evaluation shows that the concrete had a residual flexural strength on about 18 MPa which is comparable to the concrete presented in Figure 6 above. Finally Figure 8c) below shows a picture from the casting of a post-tensioned and fibre reinforced flat-slab which was tested in Spjelkavik in the spring term. The measured load-deflection curve is also shown. The main conclusions are that the ductility was sufficient, and that the calculated moment capacity was considerably on the safe side if the moment distribution is determined from the conventional methods based on elastic theory. The results from the structural testing described above are being used in the ongoing standardization work towards CEN's Eurocode 2 committee on fibre concrete, and the work on Norwegian fibre concrete guidelines within the Norwegian concrete association.

a)



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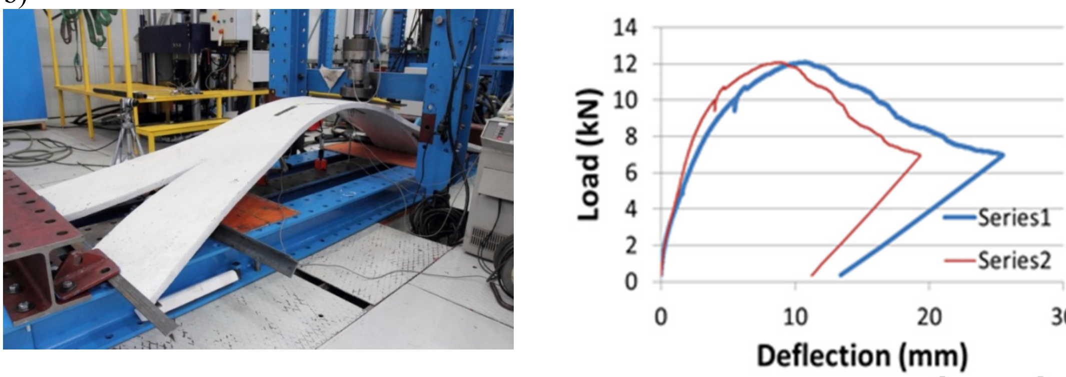

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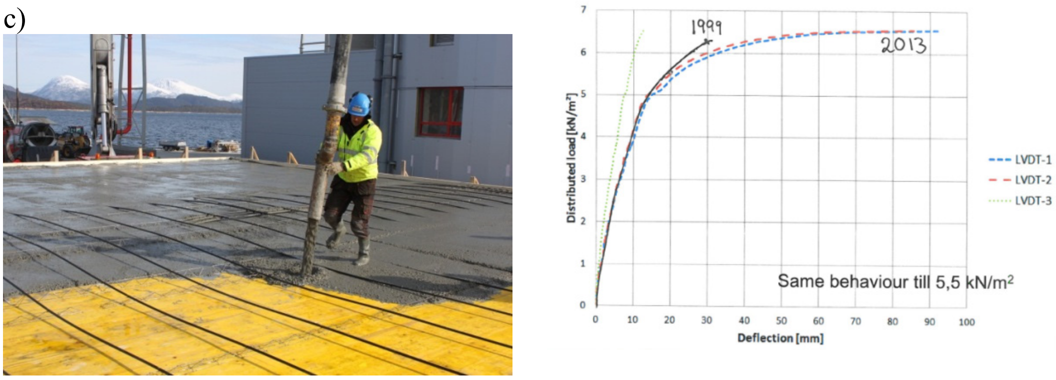


Figure 8: Examples of fibre reinforced concrete structures which have been tested and evaluated. (a) Beam elements with circular openings and a diagram which shows agreement between experiments and calculation models, (b) The Leonardo daVinci bridge which was made of UHPFRC in 2008, and the measured load deflection curves, (c) Casting of the post-tensioned and fibre reinforced flatslab which were tested in Spjelkavik and the measured load-deflection curve.

4.2.5 Improving the quality of crushed fine aggregates

The goal of project 2.3 High quality manufactured sand for concrete is to be a driving force in enhancing the future of concrete mix design technology, with focus towards development of better crushed fine aggregates (Manufactured sand) for the society. Among which, it was found in previous investigations that properties of the fillers (fine parts of crushed sand) are crucial parameters that could have the most effect on the fresh concrete rheology. For this, extensive work has been done and is still ongoing to characterize these materials, including investigation on the applicability of PM model in predicting the rheological performance of concrete possessing different types and grades of fillers through experimental investigations of the matrix.

In general, the rheology of concrete can be governed by at least two factors: (1) by fillers addition and (2) through the introduction of chemical admixtures such as superplasticizers. The effect of fillers is thus twofold, by first exerting its effect as a mineral additive, and secondly impacting the behavior of admixtures through effective surface adsorption. Fillers are considered part of the matrix in the PM model, owing to their size which is less than 0.125µm. Due to the resulting high surface areas, fillers can exert an influence on the added chemical admixtures in the polyelectrolyte rich medium, thus altering their impact on the rheology of concrete. Therefore, a subtopic in FA2.3 was created to understand this colloidal nature of the interaction between fillers and admixtures.

In some preliminary studies on the zeta potential of very diluted matrix systems in 2013, it was shown that fillers of different mineralogy and types (manufactured or natural) possessed different surface charges (Table 1), which can be attributed to the degree of compression of the stern layer around the fillers as a result of for example, their innate charges [Figure 1]. This, by default signified that the affinity and thus influence on admixtures depending on the type and grade of fillers present.

Table 1. Zeta potential of different fillers measured with Zetasizer (diluted system)

Material	Zeta potential [mV]
Årdal natural sand	-18
Årdal manufactured sand	-11
Limestone	-10

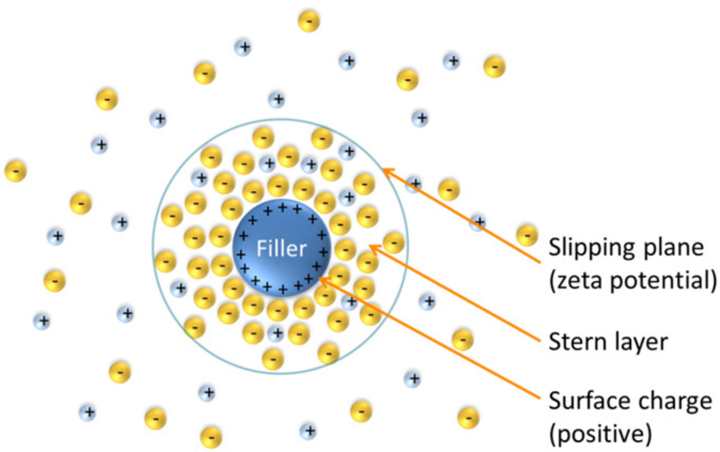


Figure 9: Schematic illustration of the electric double layer and zeta potential of a filler particle

Zeta potential is dependent on the ionic characteristic of the medium, the innate surface charge of the particle and incoming materials that can adsorb onto the surface. Further investigations are ongoing this year to further clarify the impact of fillers on admixtures. The main highlight in 2014 for this research is that it will be conducted in concentrated media, where a suitable w/c of 0.5 will be utilized. Thus, direct correlation to actual conditions in concrete is expected and a better understanding of the working mechanism can thus be achieved.

4.2.6 Crackfree concrete structures

The most important results in 2013 are from testing of the time-dependent material property development of the more environmentally friendly low-heat concretes used today, and in particular the effect of flyash (FA) content. This is needed for reliable crack risk assessment of early age concrete, and the time-dependence of the following properties have been investigated for varying FA-content: Hydration heat, compressive strength, tensile strength, E-modulus, and autogenous shrinkage. Theoretical work with material models which describe the property development is important and has been carried out, and the materials data base is continuously updated. The systems for measurement of volume changes, i.e. shrinkage and thermal dilation under various temperature histories has been improved, and the accuracy is now sufficient both for isothermal and realistic temperature histories. Much effort is also spent on quality control and improvement of the Temperature-stress-testing-machine (TSTM) list.

The material data base is adapted to the new special purpose early age concrete calculation program, Crack-TestCOIN (developed in 2012), and the use of this program among the COIN-partners is now increasing, within both research and education as well as practical construction projects. Through the Erasmus-program a researcher from Graz in Austria stayed at NTNU for a couple of months, and a new activity on calculation of stresses

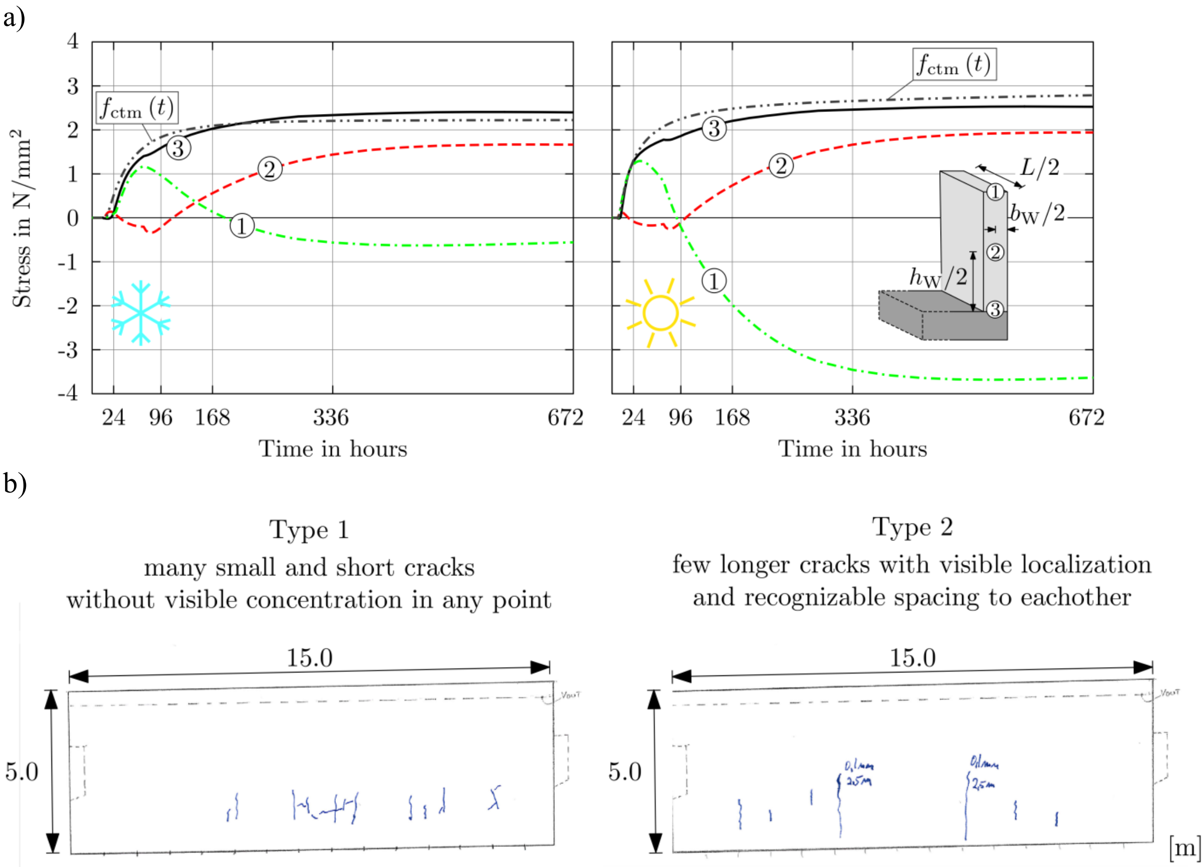


Figure 10: (a) Calculated stress and strength development for a representative structural system of the Møllenberg tunnel. (b) Observed types of crack patterns on the inner surface of the outer wall.

and crackwidths was started. The purpose of the new activity is to couple the early age crack assessment, which traditionally is used only for materials design and construction planning, with the crack-width design which usually is decisive for the reinforcement design in mass concrete structures with strict requirements due to durability and water tightness. Figure 10 above shows calculated stress development for the Møllenberg tunnel under summer and winter conditions, and typical crack pattern observed on site. The amount cracking and the crack-widths are reasonably well described.

4.2.7 Prediction of reinforcement corrosion in concrete structures

Collaborative projects take place between NTNU, Norcem, SINTEF, Skanska and NPRA to establish improved tools for prediction of reinforcement corrosion in concrete structures. Such tools will facilitate the assessment of existing structures and support the design of new reinforced concrete structures.

Much emphasis is placed on means of ensuring a long service life of reinforced concrete structures. Improved durability leads to increased structural reliability, less maintenance and repair, and overall increased sustainability. Possible solutions improving service life and/or sustainability, however, are difficult to evaluate, since current service life models are not based on detailed descriptions of the processes. Collaborative projects take place with the support from COIN to establish improved methods for compliance testing of aggregates for concrete and improved tools for prediction of reinforcement corrosion in concrete structures. Ongoing research related to reinforcement corrosion within COIN FA 3.2 focus at

- The combined impact of exposure and binder composition on the time dependency of chloride ingress
- The impact of the electrical resistivity of the concrete on the rate of reinforcement corrosion
- The impact of reinforcement corrosion on the structural performance of reinforced concrete structures.

Resent results on the structural impact of reinforcement corrosion are summarized in the following.

Structural impact of reinforcement corrosion

In current guidelines (Du, et al., 2005) the impact of corrosion is modelled via empirical relations for stiffness, strength and ductility of the corroded reinforcement bars. Localized corrosion is usually treated as uniform corrosion with larger impact coefficients (Hanjari, et al., 2011). The mechanisms resulting from localized corrosion have received limited attention.

Work at NTNU focuses on the impact of localized corrosion (pitting) on the carrying capacity of under-reinforced concrete beams. To allow for investigations of the possible interference of pits on adjacent rebars a 3D numerical model was established.

An idealized case was selected in which two adjacent rebars each have one local corrosion pit. From the results of numerical simulation on one configuration of an under-reinforced RC beam it was found that pits only interfere within a critical distance. Interference of pits reduces gradually for increasing distances between the pits along the rebars ("lp", see Figures 11 and 12). For the investigated beam with 80 mm (c-c) between tensile bars the critical distance was 100 mm; i.e. for higher ratios of longitudinal pit distance to rebar distance than 100/80=1.25 no interference was observed.

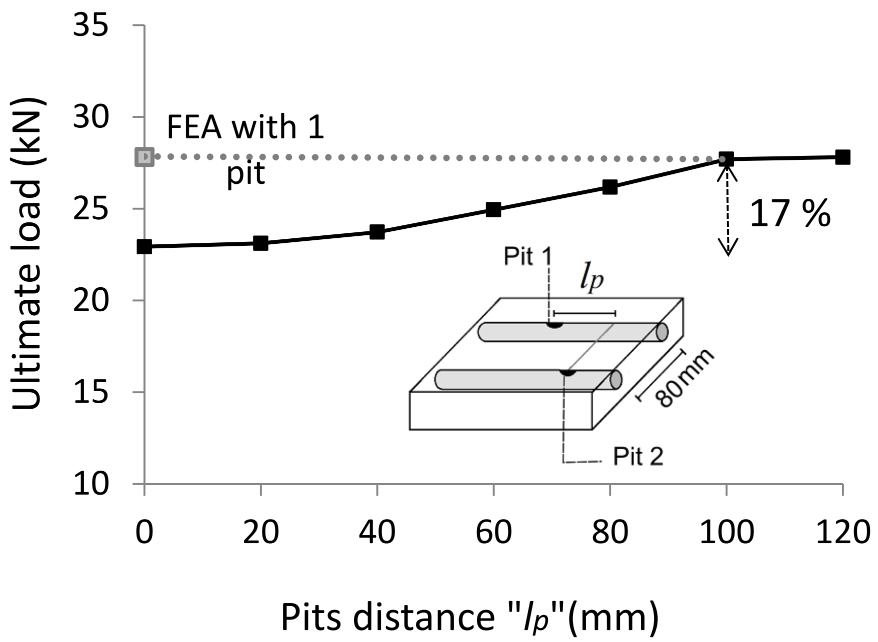


Figure 11 - Effect on ultimate capacity of varying pit distance on adjacent bars (c-c 80 mm) in longitudinal direction. For each bar 14% uniform plus 13% localised steel cross-section loss was assumed. (Kioumarsi, et al., 2014a)

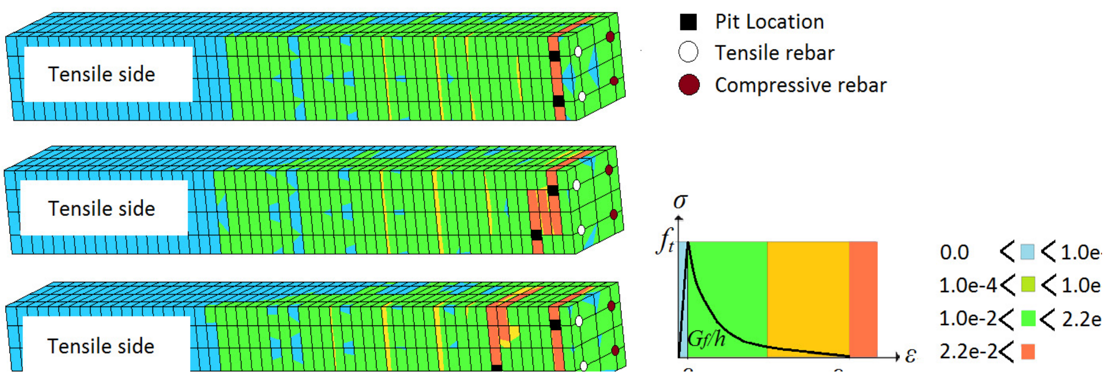


Figure 12 - Crack patterns in terms of maximum principle tensile strains from 3D numerical analyses, pit distance in longitudinal direction on adjacent bars a) 0 mm, b) 40 mm and c) 120 mm. (Kioumarsi, et al., 2014a)

A parametric study of the combined impact of pit size and pit locations suggests that the possible interference can be described by a factor, see equation 1.

$$\sum A_{res} = 2A_0 - (2A_{uni} + A_{pit} + \beta A_{pit}) \quad (1)$$

$$\beta = \beta(l_p/l_r)$$

Where $\sum A_{res}$ is a modified total residual area of two rebars after uniform and localized corrosion, A_0 is the area of a non-corroded rebar, A_{uni} is the uniformly corroded area of one rebar and A_{pit} is the corrosion pit area of one rebar. The interference is introduced by factor β which is a function of the ratio of longitudinal pit distance to rebar distance, l_p/l_r. Based on numerical simulations the factor was found to vary according to Figure 3.

It is suggested that equation (1) can be used to quantify the possible interference of localized corrosion in connection with reassessment of corroded reinforced concrete structures.

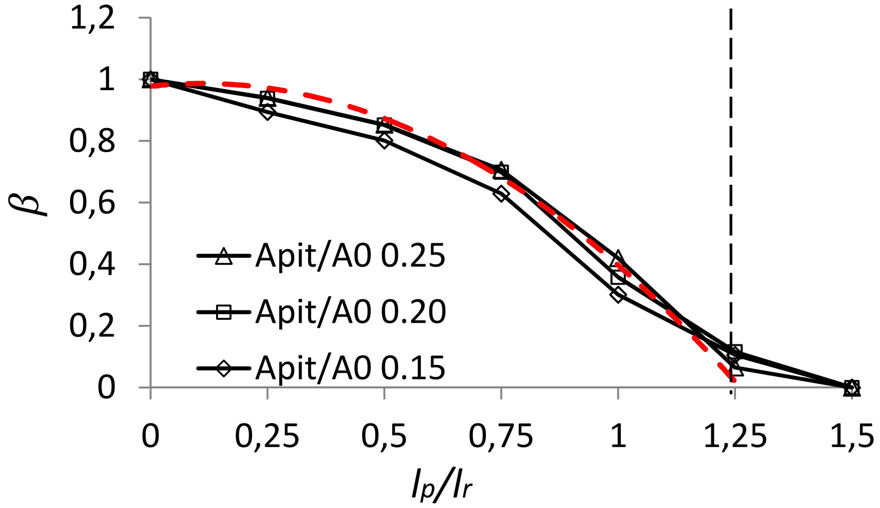


Figure 13 - Pit interference factor β as a function of the ratio of longitudinal pit distance to rebar distance, l_p/l_r. (Kioumarsi et al 2014b).

References

Du, Y. G., Clark, L. A. & Chan, A. H. C. 2005. Residual capacity of corroded reinforcing bars. Magazine of Concrete Research, 57, 135-147.

Hanjari, K. Z., Kettil, P. & Lundgren, K. 2011. Analysis of mechanical behavior of corroded reinforced concrete structures. ACI Structural Journal, 108, 532-541

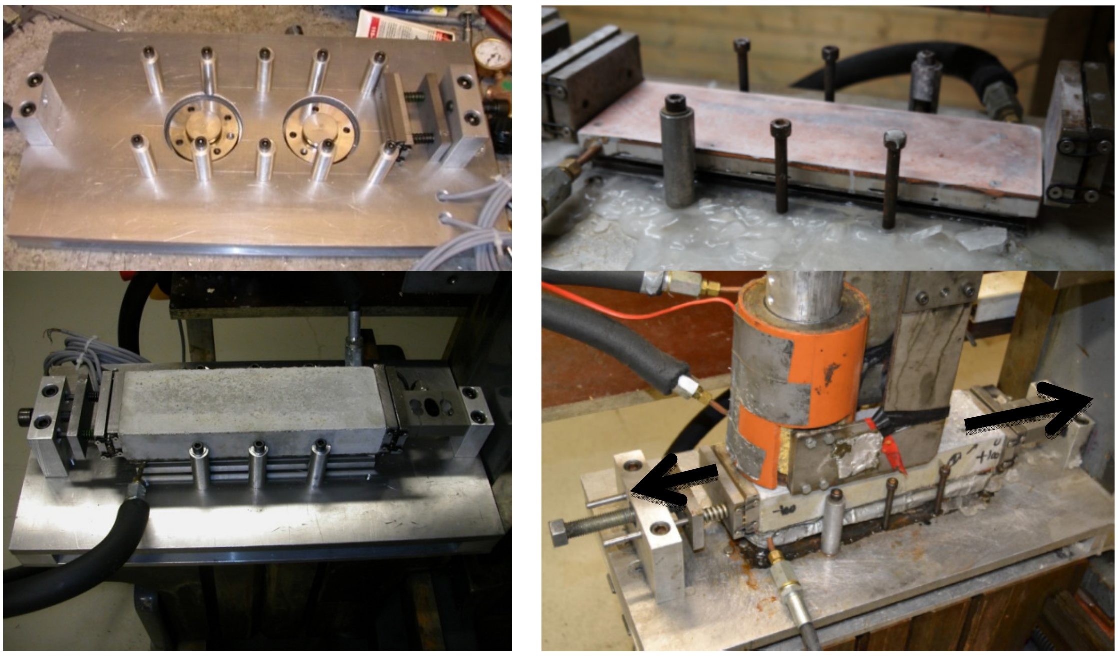
Kioumarsi M., Geiker M., Hendriks A., Interference of localized corrosion in adjacent reinforcement bar of a beam in bending, Concrete innovation conference, CIC, 2014, Oslo, Norway (Kioumarsi, et al., 2014a).

Mahdi Kioumarsi, Max A.N. Hendriks and Mette Geiker: Quantification of the interference of localised corrosion on adjacent reinforcement bars of a beam in bending. Submitted to Nordic Concrete Research (Kioumarsi, et al., 2014b).

4.2.8 Structural performance

Ice abrasion

Ice abrasion has been an ongoing topic for several years with Kværner as the industrial partner. PhD student Egil Møen will finish his work in 2014. Of great importance in this project has been and still is the development of a laboratory for simulation of the severe abrasion caused by ice movement on concrete structures. A circular ice surface moves horizontally back and forth while forced on a fixed concrete specimen. The concrete specimen is in a holder with roller bearings, thermal control and horizontal and vertical load cells measuring reaction forces (friction) and temperature during ice movement. During 2013 the laboratory has been rebuilt and improved. Also effort has been made to control the quality of the ice in cooperation with another Centre for Research based Innovation; SAMCOT / Professor Høiland. Together with Kværner an experimental program has been set up to investigate concrete ice abrasion on repair materials and the effect of steel fibre and concrete strength on the abrasion.



Concrete specimen holder with load cells (upper left), copper-epoxy-steel coiled support and heat transfer plate (upper right), concrete specimen and horizontal load cell (lower left) and in operation with ice moving (lower right) (Photos by Egil Møen, Joakim R. Kirkhaug and Nicolai S. Greaker)

During an experiment the abrasion is measured with a digital indicator for movement in x and y direction and/or scanning with structured light. A lot of work has been done using scanning with structured light with a lens adapted to the size of the specimen and analysing the data for abrasion calculation and surface roughness analysis. This technology allows much more detailing of the wear but for the time being the accuracy is somewhat reduced compared to the digital indicator. Work on friction studies by an improved sample holder and new hard- and software for improved test control and increased friction sampling rate has started. Finally, modelling the abrasion by combining tribology, mechanics, ice- and materials science has started.

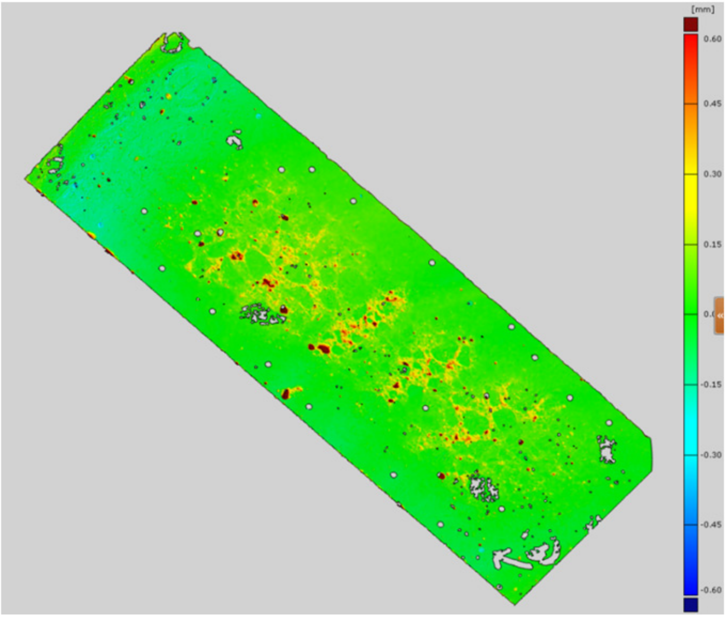


Figure 14: Concrete-ice abrasion by 3D scan of a cut concrete surface of a B60 normal density concrete after 2,5 km ice abrasion at -10 °C, 1 MPa average ice pressure, 0.25 m/s average sliding speed. (Data by Joakim R. Kirkhaug and Kristian Sætre, NTNU, Trondheim)

Mechanical properties related to porosity of LWAC

Light weight aggregate concrete (LWAC) used as construction material is of large public interest because of the combination of low weight, reasonable mechanical properties, good durability and better thermal conductivity than normal density concrete (NDA). To achieve lower concrete density, constituents with lower density than traditional aggregates or binder are added. Normal density aggregate may be replaced by lower density aggregate like expanded clay or shale, expanded glass EPS or other. All aggregates share the same philosophy; lightness by introduction of porosity in one or another form. The cementitious binder may be made lighter by the addition of fine air bubbles by air entrainers or specialised foams. In general it can be claimed that lower density concrete is concrete were air bubble is introduced with one or several measures creating a porous structure. Consequently, a LWAC with specific pre-decided density can be made low density by adding LWA, air bubbles in the paste or a combination of the two methods. This study focuses on the effect of pore size distribution on the mechanical properties. An experimental program has been carried out in cooperation with Saint-Gobain Weber as the industrial partner, where porosity is introduced by foam, EPS and aggregate. Preliminary results indicate that light aggregate contributes to highest strength to density ratio of the concrete, and that cement paste with EPS has a higher ratio than paste with foam. However, new experiments will be carried out to verify the results.

Ductility of reinforced LWAC structures

Finding ways to improve the ductility of LWAC in structural elements has been a subject in COIN since the beginning. A pilot study was initiated in 2012, with Kværner as the industrial partner, showing that addition of steel fibres is an efficient way of increasing the ductility of LWAC elements to the same level as an equivalent normal weight concrete. The work continued in 2013 with new experiments of the effect of fibres on the compressive ductility in LWAC structures. Four MSc-students wrote their thesis related to the project. In addition the focus in 2013 has been reporting results.

4.3 PhD degrees achieved

Three of the PhD students defended and achieved their theses in 2013:

4.3.1 Development of high performance lightweight aggregates

Markus Bernhardt defended his thesis on *"Development of high performance lightweight aggregates"*. The work has been performed at NTNU, Department of Materials Science and Engineering and the concrete laboratories at NTNU and SINTEF with a close cooperation with COIN industrial partner Saint-Gobain Weber. Laboratory experiments are carried out at NTNU, Saint-Gobain Weber in Lillestrøm, Norway, and at TU Bergakademie Freiberg, Germany.

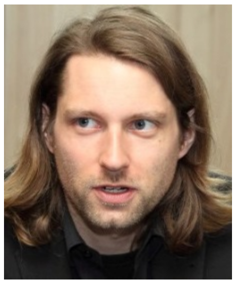


Photo: G. Zirgulis

Artificial lightweight aggregates (LWA) find their application as aggregates in lightweight aggregate concrete (LWAC), LWAC structures, foundation in road construction and houses, insulation material, in geotechnical applications or as material or water filtration. The mechanical properties of LWA play an important role in most of the mentioned fields. In his PhD thesis, Bernhardt investigated artificial LWA with the aim of improving the mechanical properties of the material without compromising other properties, weight in particular. Four strategies were used approach the problem:

- Improved knowledge of the mechanical properties
- Reinforcement with carbon fibres
- Toughening through heat treatments
- Modification of the raw material through additives

The experiments and results are summed up in the thesis and in four journal articles, see list of publications. Professor Kjell Wiik, NTNU, has been the main supervisor. Adjunct professor Harald Justnes, NTNU, has been co-supervisor and Hilde Tellesbø, Saint-Gobain Weber has been industry-co-supervisor.

4.3.2 Experimental and Numerical Study of Hybrid Concrete Structures

Linn Grepstad Nes achieved her PhD degree for her work *"Experimental and Numerical Study of Hybrid Concrete Structures – Optimised Structural Performance with Fibre Reinforced Lightweight and Normal Concrete "*. The doctoral work has been carried out at the Department of Structural Engineering, where associate professor Jan Arve Øverli, Department of structural engineering has been the candidate's supervisor. Dr. Helge Brå, SINTEF, was co-supervisor until 2011.

Photo: G. Zirgulis

Nes investigated beams composed by layers of different types of concrete to investigate the structural behaviour. Normal density concrete (NC) was used as top (and bottom) layer combined with a layer of fibre reinforced lightweight concrete (FRLWC). Hence, the beams had low weight and the NC layer fulfilled requirements for ductility in compression. Steel fibres were added to improve the performance of LWC.

This study shows that the concept of combining NC and FRLWC in one cross-section is working well. No problem with the bond between the layers of concrete was registered. Important aspects for ensuring satisfactory bond were curing conditions and a rough and clean surface for the substrate. Efficient interaction between the materials was ensured as the overlay of stronger normal concrete attracts external forces and governs the behaviour of the hybrid specimen.

Nes' work was divided into an experimental study and a numerical verification. Small-scale tests constitute the basis for obtaining design parameters used in the design of the larger hybrid beams. The PhD project shows that the concept of hybrid concrete beams is a promising approach for a new type of structure. The concept provides low self-weight of the structure, practical solutions in the construction phase and good premises for more efficient building.

4.3.3 Alkali-silica reaction (ASR) – Performance testing

Jan Lindgård defended his PhD work on the topic *Alkali-silica reaction (ASR) – Performance testing"*. The work has been performed in co-operation with the "performance testing" task group of RILEM TC 219-ACS. The doctoral work has been carried out at NTNU, Department of Materials Science and Engineering, where adjunct professor Harald Justnes has been the candidate's supervisor. Erik Johan Sellevold, Department of Structural Engineering, NTNU, and Michael Thomas, University of New Brunswick has been co-supervisors.

Alkali-silica reaction (ASR) is a common deterioration mechanism for concrete structures, both in Norway and worldwide. The damage is caused by a chemical reaction where so-called alkali-reactive aggregates react in the high pH environment in concrete. This leads to expansion and cracking of the concrete. Such aggregates are present in most regions in Norway. For environmental and economic reasons, it is important to exploit these resources in concrete. This can be done by using new, more environmental friendly cement types or additions in the concrete.

The capability of these new cementing materials to prevent ASR must be documented by accelerated performance testing. Several such test methods are in use worldwide. Unfortunately, many sources of errors exist. The results clearly show that parameters of importance for the development of ASR are significantly influenced by the specimen "pre-treatment", "ASR exposure conditions" and prism cross-section. Most test conditions included are representative test procedures used in various "commercial" concrete prism tests. The extent of the impact depends on the concrete quality, i.e. w/cm ratio and cement type. Consequently, the conclusion from a concrete performance test will differ depending on the test procedure used. In his PhD thesis Lindgård gives several recommendations for improvement of existing test methods.

4.4 COIN's first patent

Photo: G. Zirgulis

Patent #WO2013066192 (A1) "Hardening accelerator and a method for accelerating the hardening of hydraulic binders and mixtures thereof." The patent is on a new mixture of admixtures in cement that makes concrete harden more rapidly in cold climate. It is especially beneficial when a great share of the cement is replaced with fly ash. The fly ash replacement makes the concrete more environmentally friendly than traditional concrete, but also slower hardening, and the patented accelerator ensures a quicker building process.

Mapei is the owner of the patent, and Kien Hoang is inventor. As a PhD candidate, Kien Hoang did the neccessary experiments, both in NTNU's laboratory and in Mapei's labs in Norway and Italy. Supervisors Harald Justnes and Mette Geiker, prior supervisor Roar Myrdal (SINTEF/ NTNU) and Mapei's representative Espen Rudberg have made important contributions and are co-inventors. The work is part of COIN's project 1.1: Binders with low emission and reduced resource consumption. Kien Hoang was awarded Norwegian Concrete Association's Research Prize 2013 for this work.

5 International cooperation

5.1 International advisors

COIN's international advisors serve as International Experts in order to support COIN to work with the right topics regarding the need from industry and society. Their task is to survey the work performed in COIN in order to strengthen the quality of the research and ensure that the work is in line with International state-of-the-art and trends. The way this is practiced varies, and in 2013 they participated in project meetings and discussions, contributed in workshops and comment reports before publishing.

Thematically, the activities in COIN cover a wide area. To cover the whole range of topics, COIN has seven international advisors:

- Fred Glasser, University of Aberdeen: Focus area 1.1 Binder systems with low emission and reduced energy consumption
- Otto During, CBI: Focus area 1.2 Utilisation of concrete in low energy building concepts
- Olafur Wallevik, ICI Rheocenter: Focus Areas 2.1 Robust highly flowable concrete and 2.3 High quality manufactured sand for concrete
- Steffen Grünewald, TU Delft: Focus area 2.2 Ductile high tensile strength concrete and focus area 3.3 Structural performance
- Jan Erik Jonasson, Luleå TU: Focus area 3.1 Crackfree concrete structures
- Mike Thomas, New Brunswick University: Focus area 3.2 Reliable design and prolongation of service life (AAR)
- Bernhard Elsener, ETH: Focus area 3.2 Reliable design and prolongation of service life (chloride corrosion)

5.2 International networks and committees

Nanocem is a consortium of 22 academic partners and 11 industry partners from all over Europe, all interested in fundamental research in the nanoscale science of cement and concrete. NTNU is member of Nanocem on behalf of COIN. Professors Justnes and Geiker are our representatives usually attending the two annual meetings. The spring meeting 2013 was hosted by NTNU, and more than 70 delegates attended the seminars and meetings. In 2013 the PhD study of Jan Lindgård was COIN's project contribution in the consortium, see chapter 4.3.3.

COIN FA 3.2 benefits from collaboration with several international researchers. Especially, Dr Alexander Michel from Technical University of Denmark (DTU) has become a regular guest. Michel visited NTNU in October 2011 to February 2012 as PhD student on leave from DTU and in July to August 2013 as Post Doc. Again in 2014 we expect to have his visit for a few months. Michel brings a numerical model for prediction of reinforcement corrosion, and the ongoing work in COIN FA 3.2 provides improved understanding of mechanisms and experimental data for testing of the model.

Photo: G. Zirgulis

Geiker is since 2010 working together with Professor Henrik Stang, DTU, and Assistant Professor Mike Lepech, Stanford University linking service life modelling and sustainability assessment. After his PhD Michel joined this group and further work is undertaking to enable multi scale modelling of deteriorating reinforced concrete structures.

The PhD student Arnaud Müller, EPFL, working in the Marie Curie Initial Training Network TRANSCEND visited NTNU this summer. He participated in in-situ inspections summer 2013. Other visitors were PhD students Denisa Orsakova from University of Brno, Albertas

Klovas, Kaunas University, Svec Oldrich, DTU and Dirk Schlicke, Graz University of Technology. Schlicke was funded by the ERASMUS programme

Both academic employees of SINTEF and NTNU as well as employees of the other COIN partners are members of international committees. Among others COIN personnel was engaged in two fib and four RILEM committees in 2013.

6 Recruitment

6.1 Graduated students

13 students at NTNU took their master's degree with in cooperation with COIN. The master theses are linked to three COIN projects: Structural performance, Ductile high tensile strength concrete and Reliable design and prolongation of service life. Two of the students are female.

Three PhD students achieved their degrees in 2013 (see chapter 4.3.3). Lindgård is a senior scientist at SINTEF, and Bernhardt is now project manager at Norcem. As the financial period from the Research Council of Norway runs out in 2014, no new candidates have been recruited.

6.2 Post doc

Klaartje De Weerdt has been engaged as a Post Doc at NTNU on Improved service life modelling of reinforced concrete structures. The activity focuses on mechanisms and model parameters for the prediction of chloride induced corrosion. The objective of the study is to obtain a better understanding of the underlying mechanisms for changes over time in the surface concentration and diffusion coefficient regarding chloride ingress in concrete from sea water. As master student Alessia Colombo assisted in laboratory testing of chloride binding.

6.3 Interdisciplinary teamwork in the master programme

Experts in Teamwork (EiT) is a compulsory course at NTNU in which students apply their academic competence in interdisciplinary project work to learn teamwork skills**.** The students are free to choose amongst 70 various topics. In 2013 there were 24 students from 8 different studies which signed up for COIN's topic: Concrete Innovation, supervised by Håvard Nedrelid (NTNU). The students formed four groups which looked into

- Architectural and structural design of a landmark diving tower constructed with a hollow cylinder concrete core.
- Architectural and structural design of a robust cycle stand/sitting bench made of fibre-reinforced concrete.
- Architectural and structural design of a modular bus stop made of reinforced concrete. A small prototype made of polypropylene-reinforced concrete was also made.
- Development of a concrete table which glows in the dark by the use of exposed luminous aggregates.

Some snapshots from the final products are shown on the next page.

Figure 15: Snapshots from the various student projects in the course TKT 4851 Experts in Teamwork – Concrete Innovation, given by the Department of structural engineering at NTNU autumn 2013.

7 Communication and dissemination activities

7.1 Scientific publications

COIN emphasizes international scientific publication, and traditionally international conferences are the preferred channel, as this also gives opportunities to get feedback from and discussions with like-minded from around the world. A brief account of 2013 shows 30 conference papers, 13 journal articles and five reports.

7.2 CIC 2014: Concrete Innovation Conference

An international "Concrete Innovation" conference will be COIN's "grand finale" and the first in a series of conferences. The conference will be in Oslo 11-14 June 2014, and the papers will be peer-reviewed. Approximately 200 abstracts have been submitted, among these many from COIN projects. There will also be an innovation contest and an exhibition in connection to the conference. Centre manager Tor Arne Martius-Hammer is chair of the organizing committee, assisting centre manager Harald Justnes is head of the scientific committee.

7.3 COIN seminar 2013

The annual gathering of COIN colleagues was held in Trondheim in conjunction with Nanocem's spring meeting. There were therefor also academics from outside the centre present. In addition to presentation of our own results, Karen Scrivener presented Nanocem. The seminar is also a brilliant opportunity for networking, allowing PhD students and researchers time to discuss with the industrial people.

7.4 Workshop: Understanding the fundamental properties of concrete

Celebrating the 75th anniversary of Professor Erik Sellevold, NTNU organized a workshop "Understanding the fundamental properties of concrete". The workshop was held in Trondheim 25 and 26 April 2013 in Trondheim. 36 participants from 9 countries discussed topics such as pore structure, durability and cement.

7.5 Workshop: Future concrete buildings

In November COIN and the Norwegian project "Miljøhandlingsplanen for betong" invited to a workshop on the use of concrete in low energy buildings. Thermal mass, recycling and LCA were on the schedule. More than 30 contractors, architects, property owners and researchers participated. Input from the discussions is used in the further work of COIN's project 1.2 Utilisation of concrete in low energy building concepts.

7.6 Dissemination to the industry

COIN puts effort in informing the Norwegian building industry of its research and results. Nearly all COIN reports are available for free downloading at the website www.coinweb.no. On SINTEF/ NTNU's Concrete Information Day, COIN contributed with five presentations. Three presentations were given in Norwegian Concrete Association meetings and one presentation of main achievements from COIN at the Norwegian ready-mixed association FABEKO's conference. On NPRA's Technology Days, COIN held one presentation.

The trade journal Byggeindustrien is the preferred media to reach the industry. Three articles gave COIN attention. Two press releases were also replicated in this magazine as well as in Norwegian newspapers.

COIN Annual accounts 2013

Funding

	Amount
The Research Council	9 500
SINTEF (host institution)	785
NTNU (research partner)	8 269
Enterprise partners	11 749
NPRA (public partner)	1 103
	31 406

Costs

	Amount
SINTEF (host institution)	9 005
NTNU (research partner)	11 503
Enterprise partners	8 545
NPRA (public partner)	603
Equipment	1 750
	31 406

All figures in 1000 NOK

Key personnel

Centre manager
Tor Arne Martius-Hammer, SINTEF
Phone: +47 930 58 686
e-mail: tor.hammer@sintef.no

Assistant centre manager
Harald Justnes, SINTEF
Phone: +47 930 58 688
e-mail: harald.justnes@sintef.no

Project managers
Harald Justnes, SINTEF
Phone: +47 930 58 688
e-mail: harald.justnes@sintef.no

Olafur Wallevik
Phone: +354 860 7650
e-mail: olafurw@ru.is

Klaartje De Weerdt, SINTEF
Phone: +47 99 60 43 30
e-mail: klaartje.de.weerdt@sintef.no

Terje Kanstad, NTNU
Phone: 47 73 59 45 19
e-mail: terje.kanstad@ntnu.no

Børge J. Wigum, Norstone AS
Phone: +47 476 44 675
e-mail:borge.wigum@norstone.no

Knut O. Kjellsen, Norcem AS
Phone: +47 97 56 95 02
e-mail: knut.kjellsen@norcem.no

Mette R. Geiker, NTNU
Phone: +47 73 59 45 29
e-mail: mette.geiker@ntnu.no

Jan Arve Øverli, NTNU
Phone: +47 73 59 45 13
e-mail: jan.overli@ntnu.no

Administrative manager
Randi I. Henriksen, SINTEF
Phone: +47 997 34 533
e-mail: randi.henriksen@sintef.no

Disciplinary responsible
Stefan Jacobsen, NTNU
Terje Kanstad, NTNU
Mette R. Geiker, NTNU
Harald Justnes, NTNU

PhD
Anja B. E. Klausen, NTNU
anja.klausen@sintef.no

Elena Vidal Sarmiento, NTNU
elena.sarmiento@ntnu.no

Giedrius Zirgulis, NTNU
giedrius.zirgulis@ntnu.no

Ya Peng, NTNU
ya.peng@ntnu.no

Egil Møen, NTNU
egil.moen@ntnu.no

Rolands Cepuritis, NTNU/ Norcem
rolands.cepuritis@ntnu.no

Karla Hornbostel, NTNU
karla.hornbostel@ntnu.no

Mahdi Kioumarsi, NTNU
mohammad.kioumarsi@ntnu.no

Post Doc
Klaartje De Weerdt, NTNU
klaartje.d.weerdt@ntnu.no

Board
Terje F. Rønning, Heidelberg Cement, *chairman*
Jan-Diederik Advocaat, Kvaerner
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Terje Kanstad, NTNU
Trond Hagerud, Mapei
Berit Laanke, SINTEF
Sverre Smeplass, Skanska Norge AS
Stein Tosterud, Unicon

Key researchers

Name	Institution	Main research area
Bjøntegaard, Øyvind	NPRA	FA 3.1: Crackfree concrete
De Weerdt, Klaartje	SINTEF	FA 2.1: Improved construction technology
Geiker, Mette	NTNU	FA 1.1 and 3.2
Jacobsen, Stefan	NTNU	FA 2: Improved construction technology
Jelle, Bjørn Petter	SINTEF	FA 1.2: Energy preserving and insulating concrete
Jensen, Tore Myrland	SINTEF	FA 3.3: Innovative construction concepts
Justnes, Harald	SINTEF	FA 1.1: Advanced materials and admixtures
Kanstad, Terje	NTNU	FA 2.2: Innovative construction concepts
Kaspersen, Kristin	SINTEF	FA 2.1: Robust highly flowable concrete
Kjellmark, Gunrid	SINTEF	FA 3.1: Crackfree concrete
Kjellsen, Knut O.	Norcem	FA 3.1: Crackfree concrete
Kristjansdottir, Torhildur	SINTEF	FA 1.2: Energy preserving and insulating concrete
Maltha, Mette Maren	SINTEF	FA 1.2: Energy preserving and insulating concrete
Martius-Hammer, Tor Arne	SINTEF	FA 2.1: Robust highly flowable concrete
Nedrelid, Håvard	NTNU	FA 2.2: Ductile high tensile strength concrete
Ng, Serina	SINTEF	FA 1.1, 1.2 og 2.3
Smeplass, Sverre	Skanska	FA 2.1, 2.3 and 3.1
Wigum, Børge Johannes	NTNU/ NorStone	FA 2.3: High quality manufactured sand for concrete
Østnor, Tone Anita	SINTEF	FA 1.1: Advanced materials and admixtures
Øverli, Jan Arve	NTNU	FA 3.3: Innovative construction concepts

Visiting Researchers

Name	Affiliation	Nationality	Sex	Topic
Alexander Michel	DTU	German	M	Service life: Moisture measurement
Schlicke, Dirk	Graz University of Technology	Austrian	M	Fibre concrete and crackfree concrete structures

Postdoctoral researchers with financial support from COIN

Name	Nationality	Period	Sex	Topic
De Weerdt, Klaartje	Belgian	2012-2013	F	Improved service life modelling of reinforced concrete structures

PhD students 2013 with financial support from COIN

Name	Nationality	Period	Sex	Topic
Bernhard, Markus	German	2010-2013	M	Development of super LWA
Hornbostel, Karla	German	2009-2013	F	Electrical resistivity
Møen, Egil	Norwegian	2007-2012	M	Ice abrasion
Lindgård, Jan	Norwegian	2007-2011	M	AAR: Lab. testing vs field performance

PhD students working on projects in the centre in 2013 with financial support from other sources

Name	Funding	Nationality	Period	Sex	Topic
Grepstad, Linn	NTNU	Norwegian	2007-2013	F	Hybrid structures
Klausen, Anja B. E.	NTNU	Norwegian	2009-2015	F	Young concrete
Kioumarsi, Mahdi	Private	Iranian	2011-2015	M	Structural effects on reinforcement corrosion
Zirgulis, Giedrius	NTNU	Lithuanian	2010-2014	M	Fibre concrete
Peng, Ya	NTNU	Chinese	2010-2014	F	Rheology of fresh concrete
Sarmiento, Elena	NTNU	Spanish	2011-2015	F	Flowable/ fibre concrete
Cepuritis, Rolands	Norcem	Latvian	2011-2015	M	Crushed aggregates for concrete
Denisa Orsakova	University of Brno	Czhec	Jan-Sept 2013	F	Improved service life modelling of reinforced concrete structures
Arnaud Müller	EPFL	French	Apr-Jun 2013	M	Service life - Moisture measurement
Albertas Klovas	Kaunas University	Lithuanian		M	Concrete surfaces
Oldrich, Svec	DTU		May-Jun 2013	M	Simulation of fibre concrete casting

Master degrees 2013

Name	Sex	Topic
Aspås, Øyvind	M	Testing of Fibre Reinforced Concrete Structures. Shear Capacity of Beams with Openings
Colombo, Alessia	F	Chloride ingress and binding
Hallberg, Malin	F	Posttensioned fibre reinforced flatslabs
Hanssen, Håvard E	M	Posttensioned fibre reinforced flatslabs
Hoff, Stian	M	Duktilitet av lettbetong
Moreno, Angel Arcadi Sorni	M	Improvement in the ductility of lightweight aggregate concrete
Nesse, John Nordseth	M	Testing of fibre reinforced concrete: Shear capacity of I beams
Oskarsson, Johann Helgi	M	The effect of fibres on the compressive ductility if Lightweight aggregate concrete
Roca, Miguel Boix	M	Fibre Reinforced Concrete: Optimization of fibre content and capacity of dapped-end beams shear
Rød, Anders	M	Testing of Fibre Reinforced Concrete Structures. Shear Capacity of Beams with Openings
Seljen, Andreas	M	Testing of fibre reinforced concrete: Shear capacity of I beams
Steen, Torgeir	M	Duktilitet av lettbetong
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Justnes: "Properties of Gypsum-free Portland Cement", 8th International Symposium on Cement and Concrete (ISCC), 20-23 Sept 2013, Nanjing, China

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