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SINTEF Building and Infrastructure

COIN Annual report 2011

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Summary

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 three focus areas are:

- 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

More than 50 various articles and presentations were published in 2011 and one workshop was accomplished. 15 master students had their degrees within COIN, 3 PhD students were achieved their degrees and four more PhD fellows have started. The research of one of the PhD students has leaded to Mapei applying for a patent.

The Consortium has a Board of Directors, three Thematic Advisory Committees TACs, a manager and a management group. The centre is located in Trondheim with SINTEF Building and Infrastructure as host institution. The Board has nine members; seven from the industrial partners, one from NTNU and one from SINTEF. All partners are represented in the TACs.

The consortium partners 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. One new subcontractor joined the centre in 2011.

The accumulated cost in 2011 was NOK 31 831 000.

"We think that COIN is a necessary step doing the Norwegian concrete industry more acknowledged. The concrete development around the start of the Norwegian oil industry was tremendous, but it has since then been weaker. We believe this project will increase the concrete production in Norway"

Trond Hagerud
managing director,
Mapei, Norway

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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 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.

Tallhall – Norwegian Meterological Institute in Oslo – Norway's first office building made of low-carbon concrete, opened June 2011. Architects: Pir II. Photo: SINTEF Building and Infrastructure

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. Innovation potential, image and customers needs, productivity, sustainability, environment and high performance concrete for harsh climate are topics addressed. COIN seeks a more fundamental understanding of the mechanisms in order to bring the development a major leap forward.

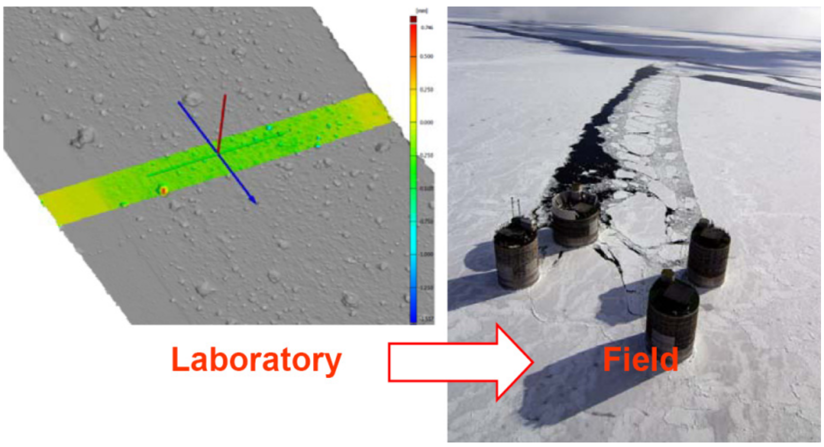
The status discussed in the original project description is still valid, but COIN has turned more in the direction of reducing CO_2-emissions and saving energy and resources. The latter was a driver when COIN reorganised the research tasks to focus on fewer research topics with more research volume. Both nationally and internationally, COIN's three focus areas (see chapter 3.3) are important drivers for research. The first one focus on developing cements with significantly reduced CO_2 emission under production. The second energy focus resulted in implementation of the topic in an EU-project in which COIN was involved, but which was rejected. The third topic of saving resources is manifested in the research on e.g. aggregates.

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 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 results will be verified in test productions and case study constructions by the industry partners.

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.



From research to application; ice abrasion on shafts of the Sakhalin II platform (PhD)

3 Organisation

3.1. The consortium

COIN has 11 partners: SINTEF Building and Infrastructure is host institution, NTNU is research partner and eight industrial partners and one public partner represent the whole value chain of the business sector. In 2011 Reforcetech, which develops, produces and supplies non-metallic reinforcement for concrete, joined as sub-contractor to Kværner Engineering. Spenncon announced their withdrawal (valid from 2012).

The consortium has a Board of Directors and three Technical Advisory Committees, a manager and a management group. The centre's manager reports to the Board. The Board has nine members; seven from corporate partners, one from NTNU and one from SINTEF.

3.2. The center

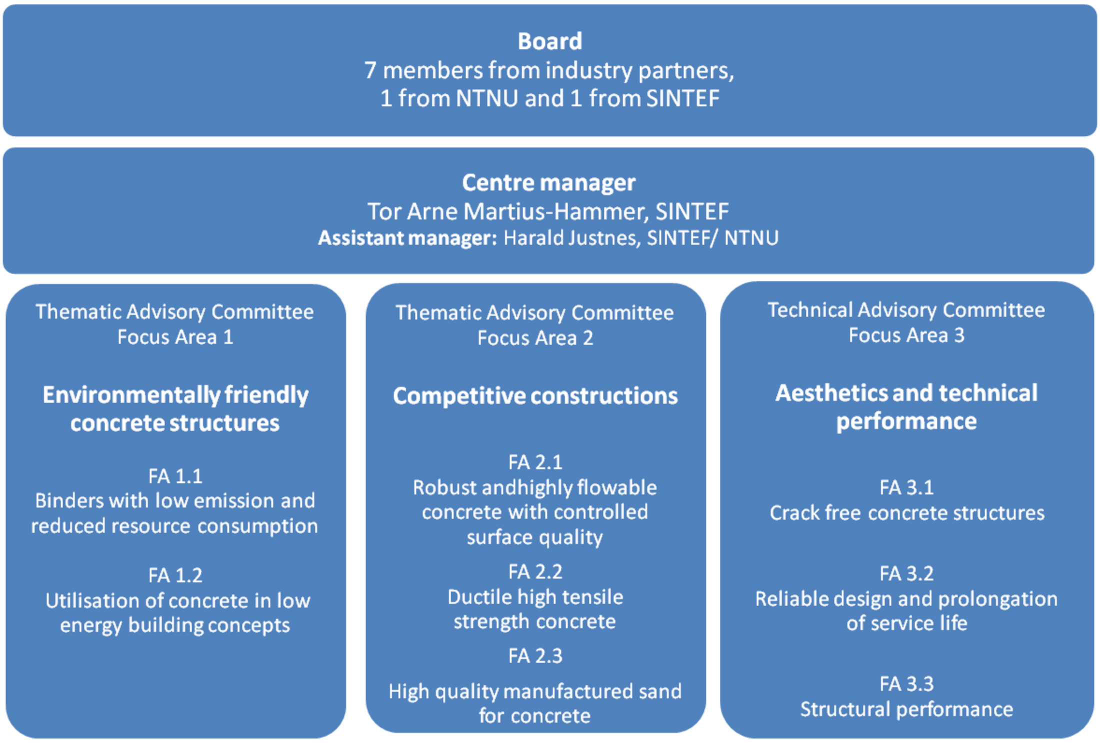
The centre is located in Trondheim with SINTEF Building and Infrastructure as host institution. Senior Scientist Dr. Tor Arne Martius-Hammer is Research Centre Manager and Chief Scientist Professor Harald Justnes is Assistant Centre Manager. The SINTEF employed project managers constitute the management group together with center manager and administrative manager.

3.3. Technical activities

The technical activities are organized in 3 focus areas (FA) with 2-3 projects per FA:

- 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

Each FA has a Thematic Advisory Committee (TAC) with members from the partners, and headed by the centre manager. 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.



COIN organisation chart

3.4. Cooperation within the center

The centre operates in close cooperation with NTNU Faculty of Engineering Science and Technology. Three professors at the Department of Structural Engineering (Kanstad, Jacobsen, and Geiker) are disciplinary responsible for six projects. In addition four adjunct professors at NTNU are strongly involved in COIN: Justnes (SINTEF) is project manager and disciplinary responsible for one project, Kjellsen (Norcem) is project manager and member of thematic advisory committee, Smeplass (Skanska) is engaged in several projects


Full scale testing of SCC in the laboratory; Employees from NTNU and industrial partners.
Photo: Giedrius Zirgulis

and member of thematic advisory committee and Larsen (Norwegian Public Roads Administration) is also member of a technical advisory committee.

The centre uses the laboratory facilities of NTNU and of SINTEF in Trondheim as well as in Oslo. Some of the experiments are also done at the industrial partners' research facilities, both in Norway and abroad.

The main strategy for knowledge transfer is to have joint activities and to involve many persons from each industry partner. The partners cooperate through the work in the projects (technical work and joint projects meetings). Four partners or more are represented in all projects, and four partners have personnel taking part in the Master of Science education at NTNU.

PhD-students and MsC-students are partly involved in both NTNU and partner.
The partners cooperate through the work in the projects, i.e. technical work and joint projects meetings and in TAC. More than 60 persons from the industrial partners are on the list of personnel involved in COIN work. Four partners have personnel taking part in the Master of Science education at NTNU, and one partner is supervising Master students at Oslo University College.

3.5. Industry partner Mapei’s experiences COIN

Mapei is one of the nine industrial partners in COIN (named Rescon Mapei until October 2011). Mapei is an international corporation with companies in more than 80 countries and one of the world's largest producers of adhesives and chemicals for the construction industry. Mapei's main office in Norway, located in Nord-Odal, is Mapei's cornerstone to the Nordic market, and is also the location of one of their 18 research centers.
We have asked Trond Hagerud, managing director of Mapei, Norway, to tell about their involvement in COIN as a centre.

What are your main interests in COIN?
Mapei’s main interest in COIN is to increase our knowledge on concrete science and develop concrete admixture products based on innovative research. This project will also increase our R&D activity in the Mapei Group.

Mapei was involved when hiring PhD student Kien Hoang within the work of admixtures. Could you tell something about this?
In our laboratory we started screening admixtures which might have an accelerating hardening effect on blended cements. From the first results we saw that this work was quite comprehensive, so we needed a supplement from COIN. When Kien was engaged, we sent our work to him, and together with his supervisors he brought in new ideas which ended in an admixture which had the wanted effect on the hardening development of cement with as much as 30% fly ash.

You have now applied for a patent based on the results of PhD student Hoang. What do you expect from this new product, both regarding Mapei's added value and importance for the concrete industry (in Norway and world wide)?
This product is expected to have an impact on the work of achieving high early strength in concretes with cements with high content of fly ash. This has been a milestone for COIN, and this work has given added R&D value for Mapei. Out in practice the product has until now been tested in smaller volumes. Soon we will get more experience used in bigger volumes. For the industry we believe this product will be an important part for the substitution of CEM I to CEM II with high fly ash content. Such a cement substitution will add to a more sustainable development in the construction business, and accelerators are important to overcome the inherent lower 1 day strength in order to maintain productivity. In the environment point of view, this substitution will decrease the CO2 outlet from the cement production.

Mapei is part of the Mapei Group. Has COIN influenced the Norwegian company's position in the international group, and if so: In what way?
COIN has induced new technology and knowledge to the Mapei Group. Other Mapei R&D groups are quite interested in the work on the hardening accelerators.

How is the cooperation with other industrial partners within COIN?
The cooperation is very valid for Mapei. We have now more knowledge in what challenges and possibilities the concrete industry has; from the cement production to the casted concrete. Together with Norcem, Mapei is developing quality improvers added in the cement production to enhance the 1 day strength in Norcem cements with higher amount of fly ash. We have a cooperation with aggregate suppliers and concrete producers to develop robust self-compacting concretes with normal aggregates and crushed aggregates. Meanwhile we have gained good relationship with the partners.

From Mapei's point of view: What does COIN mean for the Norwegian concrete industry as a whole?
We think that COIN is a necessary step doing the Norwegian concrete industry more acknowledged. The concrete development around the start of the Norwegian oil industry was tremendous, but it has since then been weaker. We believe this project will increase the concrete production in Norway.

4 Scientific activities and results

The activities in COIN are divided into three Focus Areas

- Environmentally friendly concrete
- Economically Competitive Construction
- Technical Performance

4.1 PhD degrees

Three of the PhD students defended their theses in 2011 –and they all got their degrees:

4.1.1 Blended cement with reduced CO_2 emission

Photo: G. Zirgulis

Klaartje De Weerdt did her thesis on "*Blended cement with Reduced CO2 emission – utilizing the fly ash-limestone synergy. The effect of combining fly ash and limestone in blended Portland cements on hydration mechanisms and strength development"*.

During cement production large amounts of CO_2 are emitted, about 1 tonne CO_2 per tonne clinker, if no measures are taken. One way to reduce these emissions on the short term is by replacing part of the clinker with other materials. In this study it was opted to use fly ash and limestone powder, as a beneficial interaction between both materials was expected. Limestone powder interacts with the AFm and AFt hydration phases, leading to the formation carboaluminates on the expense of monosulphate and thereby stabilizing the ettringite. The effect of limestone powder on OPC is restricted due to the limited amount of aluminate hydrates formed by the hydration of OPC. The additional aluminates brought into the system by fly ash during its pozzolanic reaction amplify the mentioned effect of limestone powder. This synergetic effect between limestone powder and fly ash in ternary cements is confirmed in this study and it translates into improved mechanical properties within the period of testing (½ year). Hence, for a similar compressive strength, a larger amount of clinker can be replaced by a combination of fly ash and limestone than when using only one of them, and therefore CO_2 emissions can be reduced.

The doctoral work has been carried out at SINTEF Building and Infrastructure in Trondheim and at EMPA in Dübendorf, Switzerland. Adjunct Professor Knut O. Kjellsen at the Department of Structural Engineering, NTNU, has been main supervisor, and adjunct professor Harald Justnes and prior professor Erik Sellevold (both NTNU) have been co-supervisors.

4.1.2 Chloride induced reinforcement corrosion in concrete

Ueli Angst achieved the degree PhD for his work *"Chloride induced reinforcement corrosion in concrete. Concept of critical chloride content – methods and mechanisms"*. The work has been carried out mainly at NTNU, but a minor part was carried out at ETH, Zwitzerland. Professor Øystein Vennesland at NTNU has been main supervisor, and Bernhard Elsener at ETH and Claus Kenneth Larsen at NTNU have been co-supervisors.

The critical chloride content is a decisive parameter for service life predictions or condition assessment. In general, the variable is nowadays still based on experience dating back to the 1960s–1980s. A thorough literature review has shown that although a lot of research efforts have worldwide been made during the last fifty years, the present state of the art does not allow improving current practice. Moreover, values for the critical chloride contents used by consulting engineers (and scientists) are based on experience with Portland cement; critical chloride contents for modern binder types (compare other activities within COIN and numerous research groups all over the world) are in general unknown. Ueli Angst's experimental work indicated how measuring setups for the critical chloride content can be improved so that the results are more reliable and realistic. On the basis of theoretical, probabilistic considerations he has suggested how laboratory results might be transferred to practice.

4.1.3 Fibre Reinforced concrete

Sindre Sandbakk was awarded the degree PhD for his thesis *"Fibre reinforced concrete Evaluation of test methods and material development.* Professor Terje Kanstad at NTNU has been his supervisor.

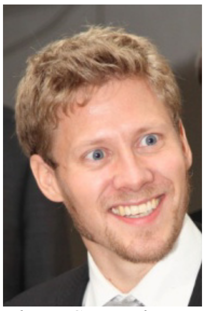


Photo: G. Zirgulis

Concrete is a structural material with excellent properties when subjected to compression, but abilities to resist tensile stresses are rather poor. The concrete's tensile zone is normally reinforced with large continuous steel bars, a combination which ensures an excellent construction material. Placing the re-bars generates many man-hours, which means that the reinforcement work accounts for a considerable part of the total concrete cost. An alternative to the conventional re-bars is fibre reinforced concrete, which is reinforced with small randomly distributed discontinuous fibres.

One working hypothesis that Sandbakk seems to have proven correct through a large number of experiments, is that the behavior of the fibre reinforced concrete can be uniquely described by the fibre slip. A second objective was to show that fibre reinforcement actually has sufficient strength and ductility to be used as a replacement to conventional re-bars in some types of concrete structures. A concrete called ductile high strength all round concrete is developed, and this concrete shows promising properties with regard to shear strength, bending strength and ductility.

4.2 Patent application

Research within COIN has resulted in a patent application: Mapei has applied for a patent on an admixture for concrete that will improve the strength of concretes with fly ash. The patent is based on the work of PhD student Kien Hoang, his former supervisor Roar Myrdal, present supervisors Harald Justnes and Mette Geiker at NTNU and Espen Rudberg at Mapei. For obvious reasons we cannot describe neither the results nor the product. Kien Hoang has however described his work and the process leading to the patent application.

4.2.1 Accelerator for blended cements

Interview with PhD student Kien Hoang

Photo: G. Zirgulis

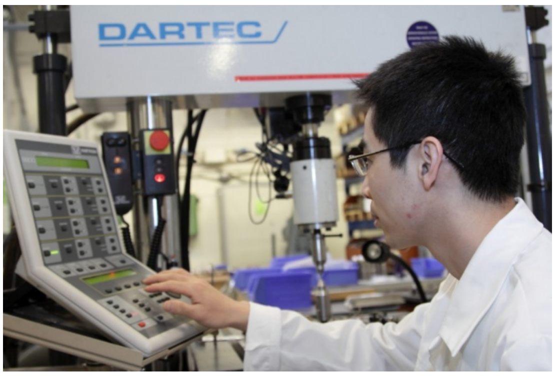
In his PhD study, Kien Hoang focuses on using chemical methods to accelerate the hydration of fly ash blended cement in which 30% of Portland cement is replaced by fly ash, a by-product obtained from thermal-power production. Eventually, the early strength of this fly ash blended cement will be enhanced through the acceleration of its hydration.

In what way are the industrial partners involved in your work?
Industrial partners contributed to my work by supplying materials (e.g. chemicals from Mapei and Portland cement from Norcem). In addition, I also got supports from the industrial partner during the research process, such as doing experiments with concrete in Mapei Norway and analytical experiments in Mapei Italy.

How will the patent application affect your further work?
It is nice to get a patent through this work. It is one way to estimate the efficiency of the project. However, due to the confidentiality during the patent application, the results of my research cannot be disclosed. This costs me time to wait before writing and publishing scientific papers as well as restricting my opportunities to discuss with other people who are not involved in COIN.

Which (if any) advantages do you experience by doing your PhD study within COIN?
COIN is an organization including academic, scientific to industrial partners. Doing PhD study within COIN helps me see the efficient cooperation between science and industry. It shows an 'organic' relationship among them. Scientific research origin from problems occurring in real life and the results obtained from research are applied back to industry to improve productions. I think doing research in this way is a good experience for me.

Why did you come to Norway to start as PhD student in the first place?
I believe that there are two main reasons influencing my decision to go to Norway to study PhD. First is about the topic of this project. I was interested in the topic from the first time I saw the advertisement about it. It is a combination between chemistry and materials, in specific cement based materials in this case. Second is that Norway is a developed country that is good for me to go to study and get further knowledge.



Kien Hoang in the laboratory. Photo: Giedrius Zirgulis

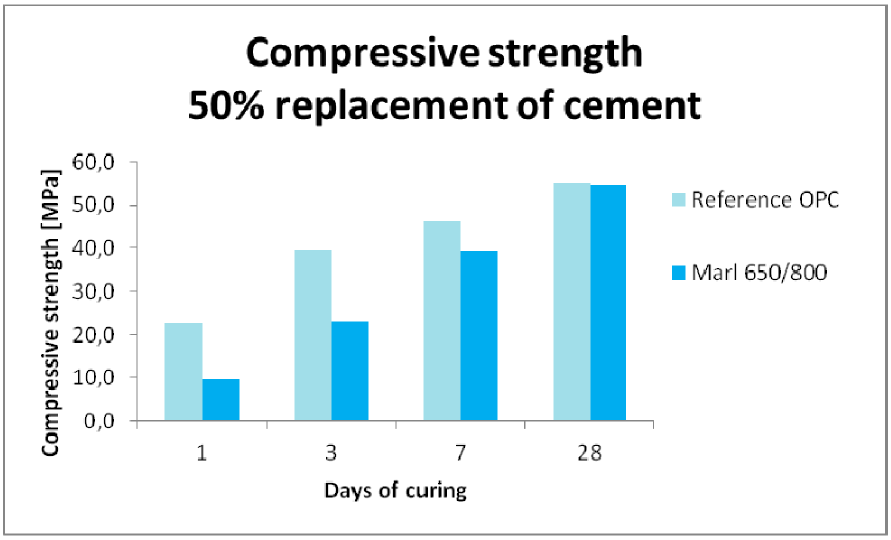
4.3 Some research results from the projects 2011

4.1.1 Calcined marl – the work for more sustainable concrete continues

The search for materials to partly replace cement in concrete continues in COIN FA1.1 *Low-carbon footprint binder systems* in order to minimize the global carbon footprint of concrete. The synergy between limestone and fly ash has already been elucidated in FA1.1 through the PhD of Klaartje De Weerdt with respect to strength (see chapter 4.1.1). The principle behind this; "any supplementary cementing material (SCM) containing more aluminate than cement (e.g. fly ash), and that produces calcium aluminate hydrates (CAH) in their reaction, will increase the reaction degree of limestone filler", was in fact already postulated in the original COIN application. However, a PhD was required to prove that it will happen and also to find the magnitude this would have on macro properties like strength.

Availability of good quality fly ash may however be limited in certain areas (Norway import it) and slag as alternative is already put into good use as cement replacement. When looking for an alternative that was widely enough spread to serve the concrete industry as a whole, even world-wide, marl came up as an idea since it consist of clay minerals contaminated with limestone. This contamination makes marl unsuitable for the clay industry and thus an unexploited resource. Calcined clay is known to be an SCM producing CAH, and with limestone present, this was thought to be an "egg of Columbus".

The first tests of carefully calcined marl was very promising showing that 50% cement could be replaced in mortar while obtaining the same strength as reference mortar with 100% cement and sufficient strength (about 10 MPa) for demoulding of e.g. concrete. The last year, marl calcined in real rotary kilns (i.e. industrial process) has been tested in mortars where 0, 20, 35, 50 and 65% cement has been replaced with calcined marl at different curing times up to 90 days. Cement replacements of 20, 35, and 50% gave higher or equal strength to the reference at the crucial 28 days age, but only 20 and 35% replacements gave higher strength than reference at 90 days. 1 year strength will be tested in due time.

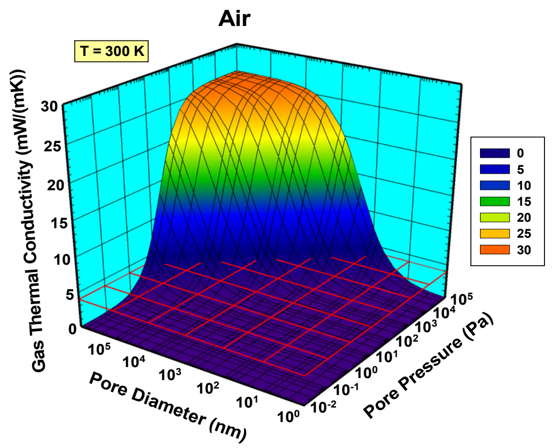


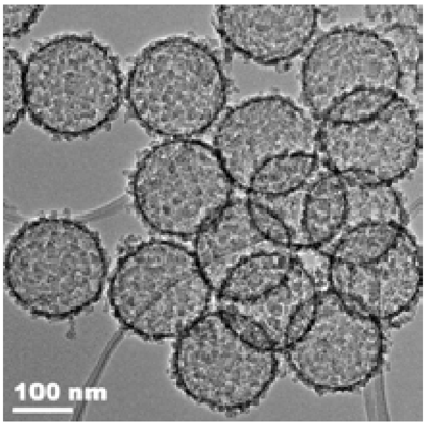
Compressive strength of test samples 1, 3, 7 and 28 days after casting: Comparison between mortar mixed with Portland cement and mortar where half of the cement is replaced with calcined marl.

The industrial like production of calcined marl gave us sufficient quantity of material to cast large batches of mortar so we could make a number of specimens for durability tests. The plan for 2012 is to test mortars where 0, 20, 35, 50 and 65% cement has been replaced with calcined marl with respect to chloride ingress, carbonation and sulphate attack at both 5 and 20 °C. The microstructure of the binder in the mortars will also be tested by scanning electron microscopy, so "stay tuned" for future interesting result…

4.1.2 Nanotechnology utilized for increasing the thermal resistance of concrete: Research paths from concept to experimental studies

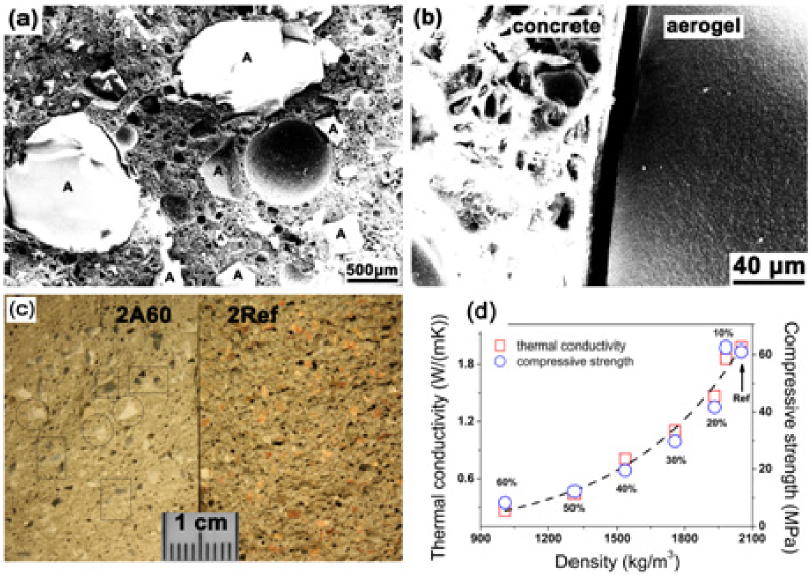
Nanotechnology is utilized for increasing the thermal resistance of concrete, i.e. decreasing the thermal conductivity. Starting from theoretical concepts involving e.g. the Knudsen effect for reducing the gas thermal conductivity in nano porous materials, the first experimental attempts have been made to manufacture nano insulation materials (NIM) based on hollow silica nano spheres, see figure below.





Theoretical concepts depicting the gas thermal conductivity vs. pore diameter and pressure (left) and first experimental attempts to make NIMs based on hollow silica nano spheres (right).

As an initial start to improve the thermal resistance of concrete by applying nanotechnology, aerogel has been incorporated in concrete. Miscellaneous experimental results as scanning electron microscope (SEM) studies and thermal conductivity and compressive strength as a function of mass density and aerogel content have been depicted in below. A decrease in thermal conductivity from 1.8 W/(mK) for standard concrete to 0.26 W/(mK) for aerogel (60 vol%) incorporated concrete is observed. Forthcoming investigations will include incorporation of tailor-made NIMs and mechanical strenghtening remidies like e.g. various carbon nano tubes (CNT). Appurtenant life cycle analyses (LCA) will be performed on the different concrete and nano material combinations.



Incorporating aerogel in concrete as an initial start to improve the thermal resistance of concrete by applying nanotechnology. (a) and (b) SEM photos of aerogel incorporated in concrete, (c) photo comparing concrete with (60 vol%) and without aerogel, and (d) thermal conductivity and compressive strength as a function of mass density and aerogel content in vol%.

4.3.1 Concrete Surface Classification

To this date, no Norwegian tool for describing concrete surfaces with respect to the aesthetic expression exists. An architect must instead refer to existing projects or order a trial casting in order to describe what type of surface he or she wants. Subjective descriptions and misunderstandings can therefore often lead to time-consuming and expensive conflicts for owners, architects and construction companies. One of the main goals of COIN FA 2.1 *Robust highly flowable concrete* is to develop a classification tool in order to describe smooth formed concrete surfaces objectively.

A smooth formed concrete surface ready to be classified.

To this date, no Norwegian tool for describing concrete surfaces with respect to the aesthetic expression exists. An architect must instead refer to existing projects or order a trial casting in order to describe what type of surface he or she wants. Subjective descriptions and misunderstandings can therefore often lead to time-consuming and expensive conflicts for owners, architects and construction companies. One of the main goals of COIN FA 2.1 is to develop a classification tool in order to describe smooth formed concrete surfaces **objectively**.

In the suggested classification system, greyscale variations and pore size and distribution are the major classification parameters. Prior studies have indicated that these two parameters govern the perception of the surface quality. Both parameters will be classified separately, which implies two separate systems. Each system will include four classes with requirements, which will be illustrated with pictorial examples. In addition, a project specific class will be included for which requirements can be made specifically for a given project, and a class without any requirement.

In order to set criteria for the classification system, methods for determining greyscale variations, and size and distribution of pores must be in place. The following work has been performed in 2009-2011:

- A procedure for taking pictures of concrete surfaces has been developed. The procedure is different when assessing colour evenness and when evaluating the pores.
- SINTEF Building and Infrastructure has in cooperation with SINTEF ICT developed a Matlab-based software, called BetongGUI. The software has two separate functions; one to evaluate pores and another to evaluate the greyscale variations. The procedure developed for taking the pictures gives the necessary input for the software.

Currently, work is undertaken to test and calibrate the picture-taking procedure and the software. The aim is to create a solid basis for the criteria of the classification system. This will be used as input for the Norwegian Concrete Surface Specification NB9, for which the project was granted financial support (250 kNOK) from the Norwegian Concrete Association. The work will also provide an objective tool to assess smooth formed concrete surfaces as a combination of picture-taking procedures and robust user-friendly image analysis software.

The need for a concrete surface classification system is not solely a challenge for the Norwegian building industry. Several European countries are currently developing national classification systems, e.g. Belgium and Spain. International driving forces within this field are gathered in the fib TG 8.9 “Aesthetics of Concrete Surfaces”, in which COIN FA 2.1 takes part. The fib committee is composing a technical report on exposed concrete, on which national systems can be based or to which they can refer.

4.3.2 Ductile high tensile strength concrete

The objective of the project is to establish the basis for developing all-round concrete with 15 MPa tensile strength as well as the basis for structural design with this concrete. Three activities from this focus-area in 2011 are high-lighted:

The mile-stone this year was Sindre Sandbakk’s PhD-thesis finalization, which was held according to the planned time schedule. One red line through the thesis is due to the test method investigations, which were a central part of the work. It has been shown that comparable stress-crack-width relations have been determined from different types of beam and panel tests. Such relations are the main fibre-concrete material properties, and the different geometry and crack patterns occurring in the different test specimens, require comprehensive analytical considerations to obtain the stress crack-width relations. The main implication from the test method investigation is that corresponding input data to structural analysis and design can be obtained from either circular slabs with different support conditions or standard beams exposed to three or four point bending. Furthermore has the investigation contributed to better understanding of the test methods and their input, which is very important when fibre reinforced concrete is approaching standardization. Another valuable experience from the test method investigation is that combinations of various fibre and concrete types can be evaluated based on simple pullout-tests of single fibres.

Also Sandbakk’s contribution to the ductile high tensile strength concrete development is important, and the results obtained so far are promising, see the post-cracking strength curves in the figure below. The replacement of cement by limestone and flyash, the reduction of dmax from 16 to 8mm, and combination of steel and synthetic fibres are important elements in this work. For further development and verification of the materials, some of these materials have been used in structural elements, and in addition to Sandbakk PhD-candidate Giedrius Zirgulis and 5 master students were involved. The work included

fresh concrete testing (aggregate segregation vs flow length), and effects of the flow process on the fibre orientation and residual tensile strength in addition to the structural behaviour.
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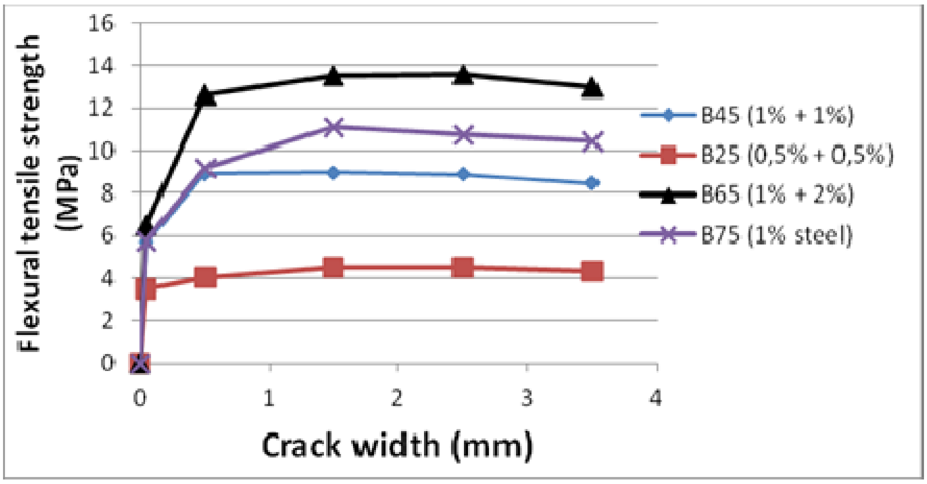
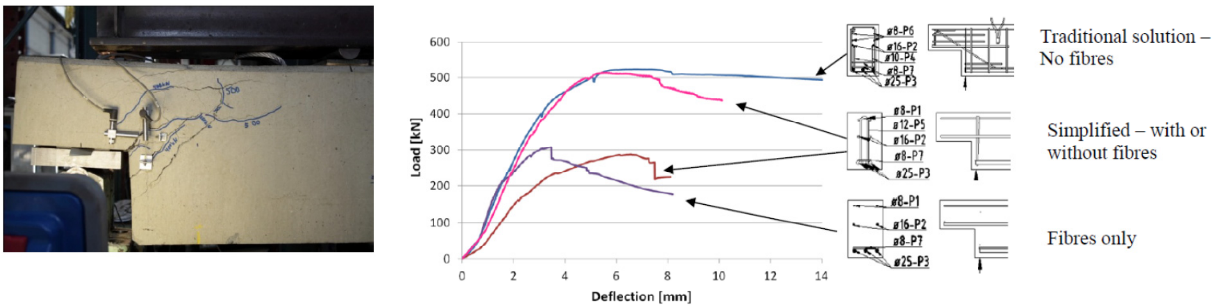


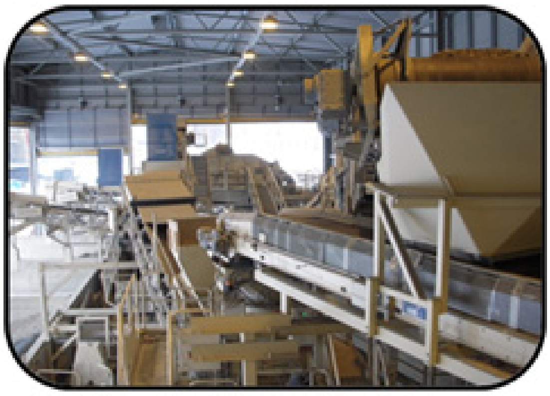
Figure: Residual bending strength vs crack width for different concretes. Different concrete strength and varying fibre volumes (48mm long synthetic fibres and 60mm long steel

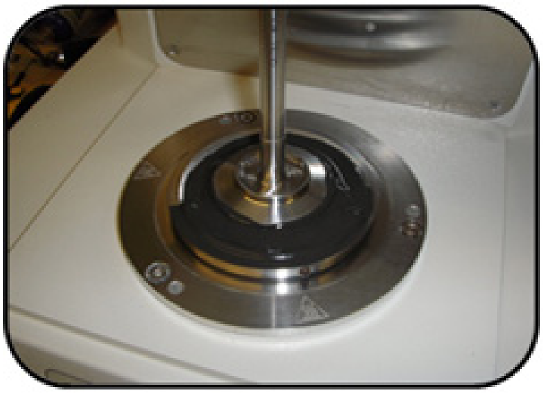
The second milestone in 2011 is the publishing of the proposal for guidelines for design and execution as a COIN- report. The report has been submitted to the Norwegian Concrete Association, and a committee for further consideration of the report is established. The work covers the topics: Material documentation, test methods, verification and execution, design methods, and reinforcing rules.

The third activity to be high-lighted is the experience with flow simulations, which are carried out in cooperation with DTU and the Danish Steelfibre consortium. These results are very promising and will probably contribute considerably towards the final goals of our project. Simulations of the flow in slabs, walls and beams have been carried out and the results of the simulations are being verified by fibre counting on sawn or drilled parts of the structures. The latter methods are quite cumbersome and labour intensive to conduct, and an activity on CT-scanning have therefore been established. Figure 2 below shows results from a series of corbel-end beams made by Spenncon/Consolis as part of the PhD work of Giedrius Zirgulis. It has been shown by means of fibre counting that the fibre orientation in the critical part of the beams is about isotropic. However recent simulations show that an alternative casting procedure may lead to a considerably more optimal fibre orientation, which will lead to both increased strength and improved ductility.



Prefabricated corbel end beams, Solution with fibres and alternative reinforcement configurations.





4.3.3 Improving the quality of crushed fine aggregates

The ultimate goal of COIN FA 2.3 *High quality manufactured sand for concrete* is to develop a technology for 100 % use of manufactured aggregate in concrete. Lots of issues ranging from economic, industrial and environmental problems, understandable by most of the people, i.e. the society, to very specific scientific ones need to be solved to accomplish this complicated task.

One of the main research directions, with a direct link to industry and society, would then be developing a crushing and processing technique that would allow improving the quality of crushed fine aggregates. In 2011 this subject was addressed by studying how the crushing process parameters, from the key pieces of machinery when processing manufactured sand, influence the fresh state properties (rheology) of the main end product for crushed fine aggregate – Portland cement concrete. The results revealed the principal differences between different types of crushers used. It was also possible to map out some crushing process parameters that can have crucial effect on the end product with respect to the fresh concrete rheology. An economical study revealed the influence of varying some of these parameters to the total costs of the production operations.

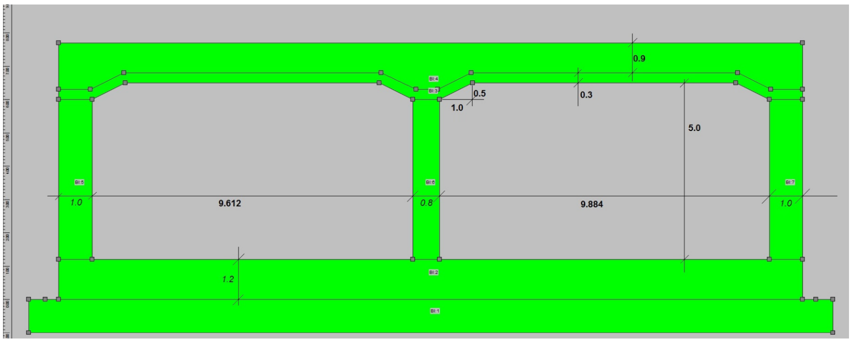
Those results are of a direct implication to all of the Norwegian aggregate producers who supplied their crushed aggregates for the study – NorStone AS, Norsk Stein AS and Hokksund Pukkverk AS, however, not limited to only those manufacturers. The research demonstrated the potential of improving their products by use of the state-of-the-art crushing technology available at the moment. Direct recommendations for the quarries were prepared as part of Cepuritis' master thesis *Effects of Concrete Aggregate Crushing on Rheological Properties of Concrete and Matrix*.

Furthermore, the master thesis also revealed that the properties of the filler (fine) part of crushed sand are the parameter that could have the most crucial effect on the fresh concrete rheology. That is a very good input for further development regarding the aggregate production process. More attention will now be paid to study the air-classification and washing processes that allow modifying the properties of the filler part. This research will be continued within the work group of FA 2.3 as well as by one of the industrial partners Metso Minerals Oy (a subcontractor to Norcem AS) in close co-operation with the quarries (pilot plants) mentioned above. Metso is a world leading manufacturer of crushers and other equipment to the mining and aggregate industry. Their extensive expertise in the field of crushing technology and air-classification gives a very good interaction with the quarrying professionals and academic people from the research institutions, i.e. SINTEF and NTNU. COIN FA 2.3 has so far served as a valuable hub that brings all those experts together – a thing that would be unlikely to happen anywhere else!

4.3.4 Crack free concrete structures

The most important results from FA 3.1 *Crack free concrete structures* in 2011 are due to testing of low-heat concretes, and especially the effect of flyash (FA) content on the time-dependent material property development in general.

The connections to practical applications are close in this focus-area due to use of the material properties in the calculation program *Crack-Test COIN*. This is an originally Swedish program which, based on initiative and arrangements by COIN and the Swedish corporate partners, now is especially adapted to Norwegian practice and concrete technology. The focus-area has also close relations to construction works and application of low-heat concrete in several large ongoing infrastructure projects, amongst others the works at E6-east in Trondheim (Møllenberg tunnel illustrated below) and the new train-terminal at Værnes airport, where the active COIN-partners Norwegian Public Roads Administration and Skanska have central roles.

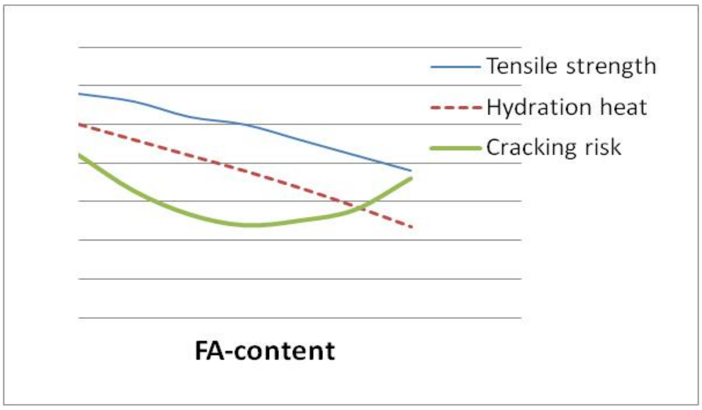


Cross section of Møllenberg tunnel, Trondheim

The use of low-heat concrete in these projects is favourable for sustainability reasons, but in the mentioned cases this kind of concrete is mainly being used because it may contribute to lower risks of cracking and thereby better quality of the structures. The main reason is that FA-addition in general gives lower hydration heat and therefore lower temperature differences between hardening and hardened structural elements. So far it seems like the optimum FA content, as illustrated in principle in the figure below, lies around one third of the total binder content. When higher FA dosages are being used, the negative effect of the loss in tensile strength seems to be larger than the positive effect of reduced hydration heat. However, in general this can be questioned because it is related to many factors, and it will be further investigated for the most relevant concrete recipes.

Timedependent development of the following properties has been investigated for varying FA-content: Hydration heat, compressive strength, tensile strength, E-modulus, autogenous shrinkage, drying shrinkage, and stress development under restrained conditions (TSTM-machine).

Four MSc-students wrote their thesis related to this focus area in 2011.



”In principle”-relations between tensile strength, hydration heat, cracking risk and flyash-content. The presence of the optimum FA content is not generally verified.

4.3.5 How to use alkali-reactive aggregates safely

In Norway, a lot of bridges and dams have Alkali-silica reactions (ASR); In moist environments, some siliceous aggregates (called alkali-reactive aggregates) are partly dissolved due to the high pH in the concrete. The dissolved silica (SiO2) reacts chemically with alkalis in the concrete and forms alkali-silica gel that expands when it sucks up water. Thus, the concrete expands and cracks. This might lead to structural damages. Additionally, ASR can "open up" the concrete for other deterioration mechanisms (rebar corrosion and freeze/thaw damage).

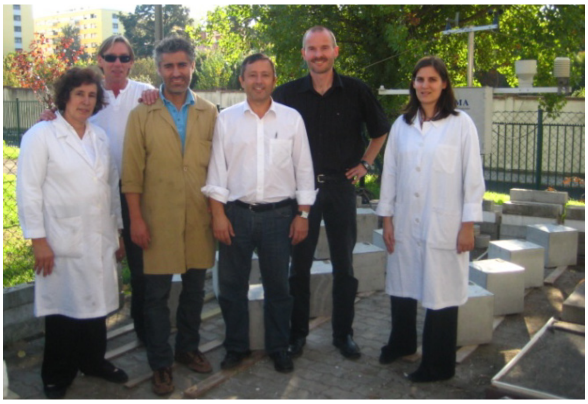
Alkali-silica reactions were recognised as a concrete durability problem more than 70 years ago. Several comprehensive research projects have focused on test methods for determining the alkali reactivity of aggregates and corresponding acceptance criteria. In the early 90'ties, we discovered that alkali-reactive aggregates are present in most parts of Norway. However, to be able to utilise these aggregates for production of durable concrete, and thus avoid costly and non-environmentally friendly transport of non-reactive aggregates, the effects of various actions must correctly be identified by accelerated laboratory performance tests. Internationally, the most frequently used measures are use of low-alkali cements or incorporation of supplementary cementing materials (e.g. silica fume, fly ash or ground granulated blast furnace slag). Alternatively, the effect of various mitigating actions can be documented from relevant long term field experiences. However, such experiences are naturally lacking for new materials.

The PhD study of Jan Lindgård (2007-2012) has aimed to evaluate whether concrete prism tests (CPTs) developed for assessment of alkali-silica reactivity of aggregates might be suitable for general ASR performance testing of concrete. In addition to review the literature thoroughly, the effects of several parameters important for development of ASR have been studied in a comprehensive laboratory test program. Focus has been on the internal moisture state in the test prisms and extent of alkalis leaching out from the prisms during the ASR exposure.

Several performance test methods have been used worldwide for at least 15 years, but most of them are developed for aggregate testing, and thus lack documentation with respect to reliability for performance testing. Additionally, the test conditions differ from one test method to another. As a consequence, the results and conclusions from different test methods may vary widely. In order to calibrate the accelerated methods used in laboratories, Lindgård has established field stations with larger concrete cubes exposed outdoors in Trondheim

(Norway) and Lisbon (Portugal). This work will be followed up through another project within COIN (2012-2014).

Field station in Trondheim, Norway:
Erik and Stig from the SINTEF Laboratory



Field station in Lisbon, Portugal:
PhD student Jan Lindgård in black shirt.

The PhD study has continuously given (the main) input to the work in the international committee RILEM TC-219 ACS-P (2007-2012), where the objective is to develop a reliable performance testing concept. This work is led by the leader of the COIN industrial board, Terje F. Rønning, assisted by the PhD student. Three of the five CPTs assessed are draft RILEM aggregate test methods, developed 10-15 years ago. Based on preliminary results (2010) on impact of alkali leaching on ASR expansion, the RILEM committee immediately withdrew two of the three RILEM methods.

The study is performed in close co-operation with Norcem (Heidelberg). It is crucial for them to document that the blended cements they produce, e.g. fly ash cements for the Norwegian market, safely can be used to hinder development of ASR in combination with different alkali-reactive aggregates in the various countries in which the cements are used. To make agreement internationally on a reliable performance testing concept is thus of high importance.

The findings in the PhD study will be published in international journals. Today, three of five planned papers have been published, two of them in Cement and Concrete Research and one in Nordic Concrete Research. Additionally, preliminary results are published on international conferences (see list of publications in Appendix 2).

4.3.6 Structural performance

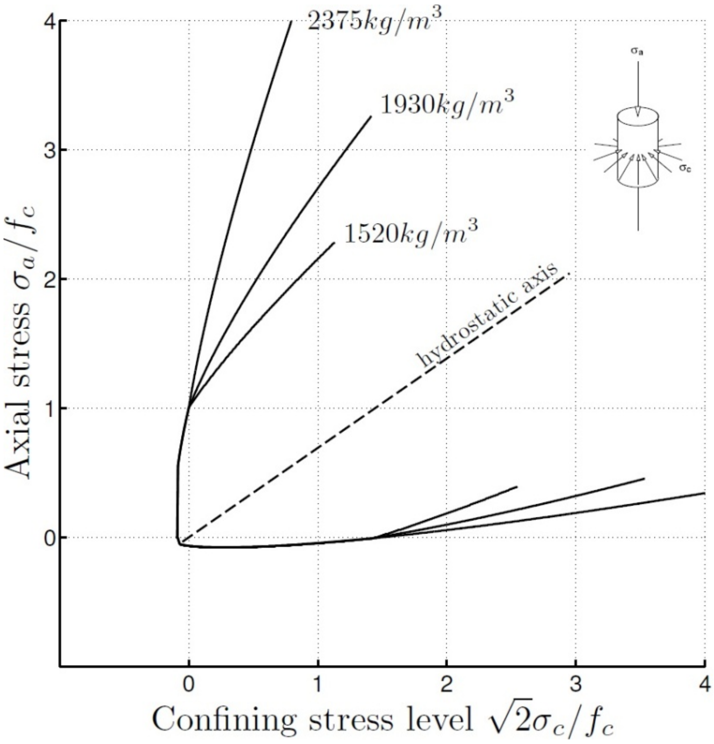
The main objective of Focus area 3.3 is to develop and utilize new concrete material combinations and applications. Activities (sub-projects) in 2011 were:

- PhD on super LWA development, see interview with Markus Bernhardt, chapter 5.1
- PhD on material modeling with focus on LWAC, see brief description below
- PhD on ice abrasion, see brief description below
- Ultra high performance concrete (mainly literature study)
- PhD on hybrid structures (layered slab elements)
- Preparation of project description for a new activity on ductility of reinforced light weight aggregate concrete structures (project start-up January 2012)

<u>Some research achievements in 2011:</u>

Material modeling:
The focus in PhD Håvard Nedrelid's work is on the understanding of the ultimate behaviour of lightweight aggregate concrete (LWAC) in compression and bending. This work is used

as a starting point on the new COIN activity on how to achieve ductility of LWAC. There is a general scepticism regarding the use of LWAC for structural applications. This is mainly due to the more brittle post-peak material behaviour and smoother crack surfaces of these concretes compared to normal weight concrete (NWC). However, in his work,–the main hypothesis is that the two key material characteristics generally dictating the ultimate response of concrete structures are: the large effect small secondary stresses have on the compressive strength and the large increase of the transverse deformation at a stage close to the peak stress level. As a consequence of these features, the strength and especially the ductility of structural concrete members depend on local multiaxial stress conditions that develop within the compressive zone prior to failure.



Failure envelopes for concretes of varying mass densities under axisymmetric triaxial stress.
Note the large effect of even small secondary stresses on the load-carrying capacity in the axial direction.

Ice abrasion

FA 3.3 is active in research and development of concrete technology for the Arctic. PhD Egil Møen focus in his work on developing solutions to handle ice abrasion on offshore concrete structures. During his work a purpose-built test rig to simulate the effect of ice sliding against concrete surfaces has been developed. The rig allows variation in different parameters such as ice-pressure, temperature, velocity and material qualities. The laboratory is used to measure abrasion resistance for different concrete mixes. The lab allows operating temperatures down to -20 °C and is calibrated with field samples from offshore concrete structures that have been subjected to ice exposure for several decades. By exposing new materials for the same test conditions as materials collected from structures with long-term field exposure, we can estimate the expected design lifetime for the new materials.

Taking core samples for testing in laboratory.

As part of the ongoing PhD project, there has been carried out experiments on various concrete mixes that are intended for use in the splash zone in one of the concrete offshore projects to Kværner Engineering that is one of our industrial partners in COIN. The performed testing comprise more than 500 hours of laboratory testing at NTNU of various concretes and repair mortars. The results from these experiments have been helpful in the process of designing the exposed ice zone of the offshore concrete shafts. This shows that our industrial partners' R&D investments may pay off directly in ongoing projects and contribute to improve solutions.

5 International cooperation

5.1 Interview with PhD student Markus Bernhard

Can you shortly describe your PhD work?

My PhD work is about the development of a clay based high performance lightweight aggregate. Lightweight aggregates (LWA) are used in many applications in the construction industry, mainly as an aggregate in concrete. In this project we try improve the mechanical properties of LWA without compromising the density. If this succeeds new application fields could be encountered. In particular we try to fiber-reinforce this porous clay spheres or change the mircostructure with special heat treatments or additives to make the aggregate stronger.

Lightweight aggregates (LWA)

You have stayed some months at Freiberg University in Germany. What is the reason for this, and what have you been doing at Freiberg?

I spent 5 month in the glass-group of the department of "Glas, Keramik und Baustoffe" at TU Bergakademie Freiberg. The matrix of my LWA samples consists of 70-90 % of glassy phase since the clay melts partly during the production process and stays in an amorphous state during cooling. The idea was to strengthen the LWA with techniques that are used for toughening ordinary glass. Freiberg is one of the leading Universities when it comes to glass technology and with the help of Prof. Hessenkemper and his group I learned a lot about the possibilities to strengthen and handle glass. I produced a lot of new samples there including different additives for LWA and heat treatments. Testing of the mechanical strength and density was also executed in Freiberg.

How will you follow up when you are back in Norway?

In Freiberg we got promising results with a special heat treatment. We observed a strength increase of around 70 % for the same density compared to a reference LWA. Now that I'm back in Norway the main focus is to figure out the mechanisms behind this increased strength.

The next step will then be to execute a pilot scale production, which means burning bigger amounts of that special heat treated LWA in a rotary kiln. If this succeeds we will be able to produce concrete specimens including that special LWA and we are able to test a possible strength increase in concrete blocks. The amounts of LWA produced in the laboratory are not sufficient to perform this kind of application test.

In what way are the industrial partners involved in your work?
My industry partner St.-Gobain Weber is quite deeply involved in my work. I have monthly meetings with Hilde Tellesbø, my co-supervisor from St.-Gobain Weber and additionally I always stay in touch with her by phone calls or email. We discuss all the new results and plan the next steps in my work together. This project benefits from a long experience of LWA production from the industry side. I also attend internal meetings of the research group of St.-Gobain Weber to exchange knowledge.

Why did you come to Norway to start as PhD student in the first place?
I came to NTNU because it is one of the most renowned universities in Europe and the facilities I can use and the support I get is just as good as it could possibly be. I also wanted to stay abroad to improve my language skills and experience a different culture and working conditions. Additionally mid Norway is one of the best places to be when it comes to free time activities like snowboarding, fishing or generally experience fascinating, wild nature. All things I'm very excited about. Hence Norway provides best working conditions and best free time activities that balance the stressful PhD live.

Which (if any) advantages do you experience by doing your PhD study within COIN?
Doing my PhD within COIN, provides the close contact to the industry which is beneficial for us and the industry. Coin also provides a deep knowledge of concrete technology with is a big part of my work. I had a lot of useful discussions with different people about different topics and problems. I am really thankful that I got the opportunity to do my PhD within COIN in Norway.

Markus Bernhard at work in the laboratory.

5.2 Nanocem

Nanocem is a consortium of presently 33 academic and industrial partners from all over Europe, all interested in fundamental research in the nanoscale science of cement and concrete. From 2011, NTNU replaced SINTEF as member of Nanocem on behalf of COIN. Professors Justnes and Geiker our representatives usually attending the two annual meetings, but others may attend depending on the topic.

The PhD thesis of De Weerdt and Angst were COIN's projects in the consortium. As they both completed their degrees in 2011, two new projects are chosen as COIN's contribution: The PhD study of Jan Lindgård on Alkali-silica reactions (see chapter 4.3.5) and that of Balamurugan Loganathan: *"Improved service life modelling of reinforced concrete structures"*. The latter is focusing on mechanisms and model parameters for prediction of chloride induced corrosion. Angst's PhD thesis and a parallel activity have provided information on prediction of chloride induced corrosion; however there are significant differences in the model parameter proposed used for the time dependence of diffusion. In addition, the impact of cracks on ingress and corrosion has not been dealt with. De Weerdt is also working on the subject as post doc.

5.3 Guest researchers

Unexpected opportunities resulted in the visit from Madeleine Flint, PhD student from Stanford from July to December 2011 and a five month employment by Alexander Michel, PhD student on leave from DTU from October 2011. (Michel stayed until February 2012). Both were working on service life modelling; Michel brought in a numerical model for prediction of reinforcement corrosion. Flint was working out a probabilistic framework for performance-based durability engineering, which is used for sustainability modelling of Norwegian bridge repairs. The two have been working closely together.

5.4 EU-funded projects

5.4.1 Health and corrosion monitoring structural

SINTEF is participating in a EU project headed by Leibniz Universität Hannover (Prof. Steffen Marx): *Health and corrosion monitoring structural*. The main objective of the project is to continually gather structural information of bridges over a period of two years by means of a monitoring system. Long term data as temperature, humidity, and joint-displacements will be recorded every hour. Short term data influenced by crossing traffic or by wind are observed with a sampling rate of 1000 Hz.

The system is installed on one Norwegian bridge, and the collected information will be used as input in ongoing activities within COIN's focus area 3.2 *Reliable design and prolongnation of service life.*

5.4.2 Low Enercrete

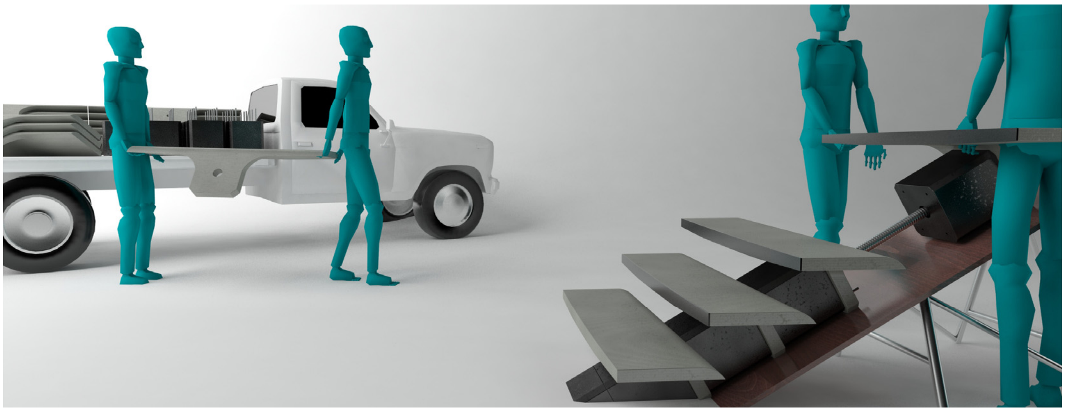
The Spanish company AIDICO initiated an EU-project proposal (within FP7-2011-NMP-ENV-ENERGY-ICT-EeB) *"Product development and application of cementitious building materials with low embodied energy for a sustainable construction- Low Enercrete"* where SINTEF was to lead one package. The application was however rejected.

6 Recruitment

6.1 Master students

COIN is involved in the education of master students in science at the Norwegian education institutions NTNU, UMB and Oslo University College. In 2011 15 students have written ten master theses within the centre. Three master students from foreign institutions have stayed at NTNU to work with their master thesis within COIN. The industrial partners are also involved in supervision of master students, and personnel in both Veidekke and Saint-Gobain Weber have been supervisors to the master students.

COIN is involved in several levels of the master programme at NTNU. The compulsory course “Experts in Teamwork” intends to provide students in their fourth year with practical skills in interdisciplinary teams. In 2011 28 students from several different disciplines signed up for COIN’s village “Concrete Innovation. Mari Bøhnsdalen Eide (SINTEF) was responsible for the village. The students had various ideas for innovative use of concrete, and use new information channels to spread their thoughts – see animation of the modular stairs illustrated below on http://www.youtube.com/watch?v=M446zJiM90E



"Constep" – modular stairs by Group 4 in Experts in Teamwork's village Concrete Innovation 2011.

6.2 PhD students

Three PhD students achieved their degrees in 2011 and were replaced with four new PhD students:

- Elena Vidal Sarmiento will be working with Structural properties of flowable concrete/ fibre concrete
- Balamurugan Loganathan will be working with Improved service life modelling of concrete structures
- PhD student Mahdi Kiumarsi started his studies in August 2011 focusing on the structural impact of reinforcement corrosion.
- Rolands Cepuritis, who did his master thesis at NTNU within COIN 2011, started his PhD study on different types of cement in combination with industrially produced aggregates

Both Spenncon/ Consolis, Saint-Gobain Weber and Norcem have increased their financing of COIN to support laboratory work of the PhD fellows. PhD student Cepuritis is employed at Norstone (subcontractor to Norcem) as industrial PhD with support from RCN.

7 Communication and dissemination activities

COIN seminar 2011. Photo: Klaartje De Weerdt

7.1 COIN seminar 2011

Once every year all partners are invited to a in-house seminar to spread information and results from the research. The venue in 2011 was SINTEF and NTNU's laboratories in Trondheim, where the PhD students presented their work. Two external presenters, Katharina Th. Bramslev from Norwegian Green Building Council and Barbara Lothenbach from EMPA brought new knowledge to the participants.

7.2 Workshop on SCC and manufactured sand

In October 35 Nordic experts within SCC and manufactured sand met at a workshop in Trondheim. The idea was to give an insight on today's ongoing research and experiences in the field of concrete rheology in the Nordic countries.

Klaartje De Weerdt, Bård Pedersen and Børge J. Wigum, project managers within respectively FA 2.1 Robust highly flowable concrete and FA 2.3 High quality manufactured sand, hosted the workshop. Themes like manufactured sand, SCC stability, rheology, SCC field experiences and modeling was thoroughly presented. The mix of scientists and practitioners from the industry resulted in many fruitful discussions. The abstracts from the workshop are collected COIN Report 35 2012 *Nordic Concrete Rheology Workshop*.

7.3 Scientific publication

COIN has published more than 40 scientific papers in 2011. Amongst these are 6 articles in journals with referees, one key-note lecture, three PhD theses, conference presentations and COIN reports. Both PhD students and research staff at SINTEF and NTNU as well as employees in the industrial partners have published conference papers and reports. At Nordic Concrete Research Symposium in Finland in May/ June, COIN contributed strongly with 16 presentations.

7.4 Dissemination to the industry

COIN puts effort in informing the Norwegian building industry of its research and results. At Norwegian Concrete Day and SINTEF/ NTNU's Concrete Information day in October, six of the presentations were related to COIN. Professor Kanstad also gave a presentation at Danish Concrete Day in Denmark in November.

Participants at workshop on SCC and Manufactured sand, October 2011. Photo: Giedrius Zirgulis

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Annual accounts COIN 2011

(All figures in 1000 NOK)

Funding

The Research Council	9.608
The Host Institution SINTEF	163
Research Partner NTNU	8.328
Kværner Engineering	467
Saint-Gobain Weber	1.266
Norcem	5.056
Mapei	1.614
Skanska	1.053
Spenncon	1.028
Norwegian Public Roads Administration	1.637
Unicon	834
Veidekke	777
	31.831

Costs

SINTEF Building and Infrastructure	11.436
NTNU	11.872
Kværner Engineering	177
Mapei	1.440
Norcem	2.931
Saint-Gobain Weber	825
Skanska	608
Spenncon	471
Norwegian Public Roads Administration	1040
Unicon	254
Veidekke	777
	31.831

COIN Publications 2011

Articles in journals

1. Lindgård et. Al: "Alkali-silica reactions (ASP): Literature review on parameters influencing laboratory performance testing", Cement and Concrete Research
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