www.coinweb.no

SINTEF Building and Infrastructure Hedda Vikan, Sindre Sandbakk and Terje Kanstad (NTNU)

Material properties influencing concrete residual bending strength – Experimental study

COIN Project report 28 - 2011

SINTEF Building and Infrastructure

Hedda Vikan, Sindre Sandbakk and Terje Kanstad (NTNU)

Material properties influencing concrete residual bending strength – Experimental study

FA 2 Competitive constructions

SP 2.2 High tensile strength all round concrete

COIN Project report 28 – 2011

COIN Project report no 28
Hedda Vikan, Sindre Sandbakk and Terje Kanstad (NTNU)
Material properties influencing concrete residual bending strength – Experimental study
FA 2 Competitive constructions
SP 2.2 High tensile strength all round concrete

Keywords:
Fibre, residual bending strength, matrix, ductility

Project no.: 3D005920

ISSN 1891–1978 (online)
ISBN 978-82-536-1222-5 (pdf)

Address: Forskningsveien 3 B
POBox 124 Blindern
N-0314 OSLO
Tel: +47 22 96 55 55
Fax: +47 22 69 94 38 and 22 96 55 08

www.sintef.no/byggforsk
www.coinweb.no

Cooperation partners / Consortium Concrete Innovation Centre (COIN)

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

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

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

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

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

SINTEF Building and Infrastructure
Contact: 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

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

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

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

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

Preface

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

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

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

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

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

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

For more information, see www.coinweb.no

Tor Arne Hammer
Centre Manager

Summary

One of COIN's overall targets is to increase the residual bending strength towards 15MPa. A working hypothesis has been that the ductility of fibrous concrete increases with decreasing concrete compressive strength due to lower crack load and also lower maximum loads. The objective of the following study has therefore been to confirm this hypothesis, and to investigate the influence of paste/matrix composition and properties, workability and compressive strength on the ductility of the test-specimen. Influence of fibre type, fibre combinations and fibre dosages have also been studied.

A number of preliminary mixes were tested before selecting two mixes for incorporation of different fibre types, dosages and combinations. Maximum aggregate size was the main parameter separating these two mixes. Both mixes were workable, but not self-compacting.

The proportionality limit was slightly increased with increasing fibre content (0-1volume %). The increase was larger for steel fibres than for synthetic fibres.

The concrete with smaller maximum aggregate size (d_{max}= 8mm) had more promising ductility properties than the concrete with larger aggregates (d_{max} = 16 mm).

The beam specimens cast with d_{max}= 8mm and 0.5% of both steel and synthetic fibres fulfilled the ductility requirements best. The same concrete with 0.5 or 1.0% steel fibres is also promising considering ductility.

The residual bending strength $f_{R,3}$ (crack width = 2.5mm) is 4.5MPa for the 11-5 concrete with 0.5% of both fibre types. Although this is far away from the overall COIN-target of 15 MPa, increased fibre content can easily bring us higher up.

Suggestions for further work include

- further development of the concretes developed within this study
- verification of the ductility-experience of the present investigation in structural elements of larger dimensions
- development of new test method for study of fibre distribution under casting

Table of contents

1 Background

Plain unreinforced cementitious materials are characterized by low tensile strengths and low tensile strain capacities; they are brittle materials. Reinforcement is therefore needed before they can be used as construction materials. Traditionally, this reinforcement has consisted of continuous reinforcing bars which could be placed in the structure at appropriate locations to withstand the imposed tensile and shear stresses. Reinforcing concrete structures after this traditional method is generally a rather expensive and time-consuming process for designers as well as for constructors. The reinforcement design participates with about 50 % in the total design costs, and with around 30 % in the total work costs (Markovic et al. 2003). Fibre reinforcement, on the other hand, has the advantage of being significantly less labour-intensive than rebar reinforcement. A concrete reinforced by fibre would imply increased industrialization of the construction process, improved work environment, and cost efficiency. Fibre reinforcement is therefore a focus area within COIN.

Fibres as opposed to rebars are discontinuous and most commonly randomly distributed throughout the cementitious matrix. They are therefore not as efficient in withstanding tensile stresses as rebars. However, because they tend to be more closely spaced than conventional reinforcing rebars they are better at controlling cracking. Because of these differences fibre reinforcement has been found to perform better than traditional rebars for applications such as:

- Thin sheet components in which traditional reinforcing bars cannot be used
- Components which must withstand locally high loads or deformations such as tunnel linings, blast resistant structures or precast piles which must be hammered into the ground
- Components in which fibres are added primarily to control cracking induced by humidity or temperature variations, such as slabs and pavements (Bentur and Mindess 2007)

The mixture composition of fiber reinforced cementitious materials is a compromise between acceptable workability and improved efficiency in the hardened state. Fibers need to be homogeneously distributed and clustering of fibers must be counteracted in order to optimize the performance of the fiber. Generally, the resistance to flow has been found to increase with increasing fiber factor ($V \cdot l/d$ where V is the fiber volume, l is the length and d the diameter of the fiber), increasing coarse aggregate content and decreasing paste content (Groth 2000, Khayat and Roussel 1999). This is explained by increased internal porosity of the granular skeleton, decreased layer thickness around each particle and increased friction. The critical fiber content is surpassed when a stiff structure of the granular skeleton makes flow under concretes' own weight impossible (Balaguru and Najm 2004, Grünewald 2004).

Self-compacting concrete (SCC) may render benefits in terms of achieving more uniform fibre dispersion. Fibers will, however, reduce the flowability of a SCC due to their long shape and high specific surface compared with aggregate of the same volume. While keeping a stable mixture, the workability of the concrete itself should, therefore, be as high as possible to compensate for the effect of the fibers. A certain yield stress and plastic viscosity of the cement paste is, on the other hand, required in order to obtain a stable mix and avoid segregation (Ferrara et al. 2007, Oh et al 1999, Grünewald and Walraven 2001). Stability of SCC can be achieved in at least three ways: By aid of fines and/or filler, by aid of chemical stabilizer or a mixture of both fines and stabilizer (Takada, et al. 1998, Kim et al. 1996, Corradi et al. 2003). Apart from ensuring stability, environmental concerns are contributing to filler and powder technology (i.e. supplementary cementitious materials (SCM)) becoming an integral part of modern concrete proportioning. The environmental concerns embody both damages caused by the extraction of raw material and CO_2 emissions during cement manufacturing.Work on binder systems which opens for production of allround cements with considerably reduced clinker content and thus correspondingly reduced CO_2 emission from the production is therefore an integral part of COIN (De Weerdt and Justnes 2009, De Weerdt et al. 2008).

In 2008 COIN arranged a Creative Forum where the participants were invited to identify ideas that has the potential to innovate concrete as a material and how it is produced. One of the emerging ideas was the development of standard concrete with tensile strength of 15 MPa. The challenge has been taken by COIN's fibre project in which the overall target has been defined into *increasing the residual bending strength towards 15MPa*. One way of ensuring high residual bending strength is to produce a composite with strain hardening behaviour. This implies that upon reaching the first crack during loading (either in tension or bending) additional straining of the composite will require an increase in load (Bentur and Mindess 2007). Strain hardening behaviour has been obtained for high performance composites as illustrated by Figure 1 and Li et al. (2002). Ultra-High Performance Fiber Reinforced Concretes (UHPFRC) are cementitious composites also known as reactive powder concretes which exhibit compressive strength >150 MPa, tensile strength > 8 MPa and strain-hardening behavior under uniaxial tension. The mix design of UHPFRC differs significantly from that of normal and high strength concretes: UHPFRC mix compositions are characterized by high cement, superplasticizer and silica fume contents. Furthermore, the water-binder ratio is lower than 0.20. The size of the coarsest aggregate used in UHPFRC generally lies between 0.5 and 4 mm. Aggregates are thus replaced by crushed quartz and sand in order to improve the compactness and homogeneity of the concrete. Strain-hardening behavior of Ultra-High Performance Fiber Reinforced Concretes has been achieved by incorporating more than 2 vol.% steel fibers (Richard and Cheyrezy 1995). High performance composites such as UHPFRC are expensive and thus special products. A challenge would therefore be to develop an all-round strain hardening composite. The working hypothesis for this project is that the ductility of fibrous concrete increases with decreasing concrete compressive strength due to lower crack load and also lower maximum loads.

Using a single type of fiber may improve the properties of fiber reinforced concrete to a limited level. The concept of hybridization with two different fibers incorporated in a common concrete mix can, however, offer more attractive engineering properties since the presence of one fiber enables the more efficient utilization of the potential properties of the other (Sahmaran et al. 2007, Yao et al. 2003, Kobayashi and Cho 1982). Although not investigated extensively, the use of two or more fiber types in the same concrete mix is considered promising. Banthia and Bindiganavile (2001) found for example that that a blend of macro- and micro-steel fibers lead to a closer fiber-to-fiber spacing, which reduced the micro-cracking and increased the concrete tensile strength.

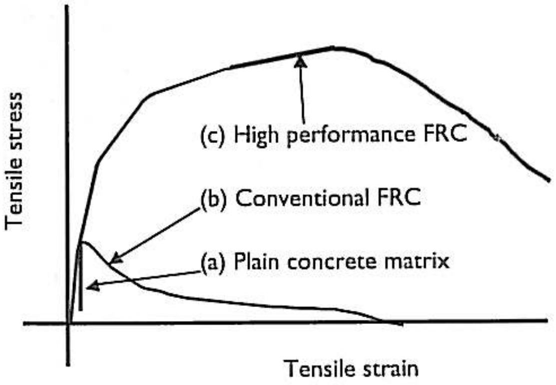


Figure 1: Schematic description of strain softening and strain hardening behavior of fiber reinforced composites (ACI 2005)

2 Objectives of the study

The main objective of the fibre activity within COIN is to produce a composite with residual bending strength towards 15MPa. The concrete should be an all-round product with economical composition.

To ensure even fibre distribution the concrete should be highly workable and should thus be designed after the principles of SCC.

Future all-round cements will probably contain supplementary cementitious materials both due to environmentally concerns and due to the powders' reactive and stabilizing properties. Extensive work on supplementary cementitious materials is currently undertaken in COIN. Chemical synergetic effects have been proven for fly ash and limestone. It has also been proven that ordinary clay can be used as cement replacement when calcined at medium temperature (De Weerdt and Justnes 2009, De Weerdt et al. 2008). This project will thus base the concrete design on materials and material combinations studied within these projects.

A working hypothesis for the study is that the ductility of fibrous concrete increases with decreasing concrete compressive strength due to lower crack load and also lower maximum loads. The project aims therefore to produce concrete with low compressive strength, here defined as approximately 30MPa.

The literature indicates that the critical fiber content is 2 - 4 vol.% for traditional concretes and SCC. Strain-hardening behavior of Ultra-High Performance Fiber Reinforced Concretes has, moreover, been achieved by incorporating more than 2 vol.% steel fibers (Richard and Cheyrezy 1995). Increasing the fiber content above 2 % seems, however, to demand new casting techniques or a change of the fiber reinforced concrete concept as exemplified by SIFCON and textile reinforced concrete (Vikan 2007). This study aimed therefore to produce concretes with a maximum fiber volume of 1% to ensure castability. The final objective of the study was to investigate the effect of hybridization with two different fiber types on the concrete tensile strength.

3 Experimental

The materials selected for the study reflects that the matrix should consist of alternative binder combinations in line with COIN's objective of developing concretes with reduced environmental impact.

The experimental work consisted of two parts: Firstly concrete compositions without fiber additions were designed and tested in order to obtain high degree of workability and compressive strengths of approximately 30 MPa. A selection of concrete mixes was thereafter selected as basis for fiber reinforced concretes. The workability of the final mixes fiber containing was measured before samples were cast, cured and mechanical properties measured.

3.1 Materials

- Cement: CEM I 42.5 R (Norcem Standard), density 3120 kg/m^3, Blaine 370-380 m^2/kg, C_3A 7%
- Limestone powder (Norcem), density 2700 kg/m^3, typical Blaine 360 m^2/kg
- Calcinated clay, "Trial 5" (calcinated 45 min at 750^{o}C) density 2700 kg/m^3
- Silica fume obtained from a ferro-silicon manufacturer consisting of 94.80% SiO_2. Density was 2200 kg/m^3. The specific surface is typically 22,000 m^2/kg.
- Gneiss/Granite aggregates of following fractions were used: Årdal 0/2 mm natur, Årdal 0/8 mm SKB, Årdal 8/16 mm lab. Sieve curves are given in Appendix
- Admixtures
  - Polyacrylic superplasticizer (Dynamon SP130), dry solids 30 ± 1.5%
  - Viscosifyer (Viscostar 3KN), dry solids 2.2 ± 0.5%
- Fibres
  - Steel fibres with hooked ends, Dramix 65/60, length 60 mm, tensile strength 1000 MPa
  - Polyolefin fibres with continuously embossed surface, Barchip Shogun, length 48 mm, tensile strength 550 MPa

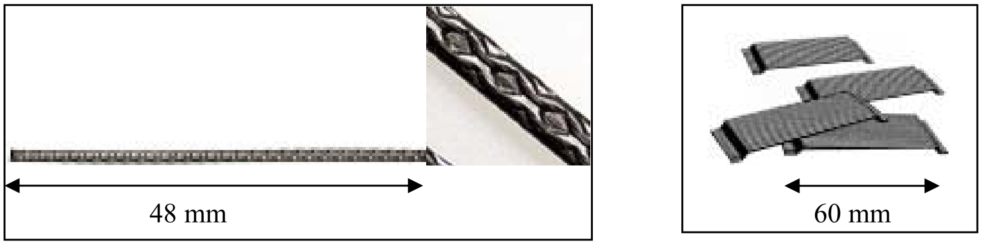


Figure 2: Illustration of plastic fibre with close-up (left) and steel fibre (right)

3.2 Concrete composition

A number of preliminary mixes were tested with regard to workability and compressive strength before selecting mixes for incorporation of different fibre types, dosages and combinations. The particle-matrix model was used for the concrete design (Smeplass and Mørtsell 2001). In this model the matrix phase consists of water, admixtures and solid material with a particle size smaller than 0.125 mm. The particle phase consists of aggregate larger than 0.125 mm. The matrix content of all mixes was 393 l/m^3. Mixture 11 had a maximum particle size of 8 mm, while mix 12-13 had a maximum particle size of 16 mm. Mixture 12-17 explores the effect of replacing 30 volume percent cement with fly ash, limestone powder, calcined clay and silica fume. Unfortunately the water-powder ratios are not kept constant for mix 12-17, but varies within the range 0.76-0.82.

Concrete compositions are given in Table 1 and Table 2. Applied admixture dosages are given in Table 3.

Generally, the resistance to flow has been found to increase with increasing fiber factor (V·l/d where V is the fiber volume, l is the length and d the diameter of the fiber), increasing coarse aggregate content and decreasing paste content (Groth 2000, Khayat and Roussel 1999). This is explained by increased internal porosity of the granular skeleton, decreased layer thickness around each particle and increased friction.

Mixture 12 was chosen as basis for further experiments with different fibre combinations since it obtained a 28 days compressive strength of approximately 30 MPa. Mixture 11 was chosen as basis for the second test series in order to investigate the effect of maximum aggregate size. Applied fibre dosages of mixture series 11 and 12 are given in Table 4. Admixture dosages are kept constant within each series to be able to study the effect of fibre addition on castability.

Table 1: Concrete mix proportions

Mix no.	**D_{max}**	**Paste (l/m^3)**	**Matrix (l/m^3)**	**Cement, (vol%)**	**Fly ash (vol%)**	**Limestone powder (vol%)**	**Clay (vol%)**	**Silica fume (vol%)**	**w/p**
11	8 mm	346	393	80		20			0.66
12	16 mm	339		100					0.76
13		339		70		30			0.79
14		339		70	20	10			0.82
15		339		70		10	20		0.79
16				70		20	10		0.79
17				70		20		10	0.80

Table 2: Concrete mix design. All units are given in kg/m^3

Mix no.	**Cement**	**Water**	**Fly Ash**	**Lime-stone**	**Clay**	**Silica fume**	**0-2 mm**	**0-8 mm**	**8-16 mm**
11	291	235		58			254	1142	
12	319	242					480	600	634
13	223			83			480	600	634
14	223		45	27.6			480	600	634
15	223			27.6	55.2		480	600	634
16	223			55.2	27.6		480	600	634
17	223			55.2		22.5	480	600	634

Table 3: Admixture dosages given as percentage of the cementitious powders cement, fly ash, limestone powder, clay and silica fume.

Mix no.	**Superplasticizer (wt% of powder)**	**Stabiliser (wt% of powder)**
11	1.0	0.4
12	0.2	1.3
13	0.2	1.3
14	0.2	1.4
15	0.2	1.3
16	0.2	1.3
17	0.2	1.3

Table 4: Fibre dosages of concrete mixture 11-ref to 11-5 and 12-ref to 12-5

Concrete mix no	Plastic fibre		Steel fibre	
	Vol%	kg/m^3	Vol%	kg/m^3
11-ref, 12-ref	-	-	-	-
11-1, 12-1	0.5	4.6	-	-
11-2, 12-2	1.0	9.1	-	-
11-3, 12,3			0.5	39.0
11-4, 12-4			1.0	78.0
11-5, 12-5	0.5	4.6	0.5	39.0

3.3 Mixing procedure

A forced pan mixer with a volume of 50 litres from Eirich was used to prepare the concretes. The volume of the concretes batches was approximately 48 litres. The mixing procedure was as follows:

- 1-2 minute dry mixing of powders, aggregates and fibres
- 2 minutes while adding mixing water and half the amount of superplasticizer (previously intermixed with the water) and retarder
- 2 minutes pause
- 1 minute addition of remaining superplasticizer until aimed slump flow value was reached
- 1 minute mixing

The concrete used for the BML run was remixed together with the rest of the concrete and used for casting samples.

3.4 Measurement of fresh properties

Measurement of slump, slump flow, air content and fresh density was measured directly after mixing.

The rheological properties of the mortars were measured directly after mixing with a BML concentric viscometer with inner and outer diameter of 200 and 400 mm respectively. The rheometer measures the toque (T) produced on the stationary inner cylinder while the outer cylinder is rotation at various speeds. The Bingham model is thereafter applied by the software with the relationship:

$$\text{Torque} = G + H \cdot \text{Speed} \qquad [\text{Nm}] \qquad (1)$$

were

G is a measure of the fore necessary to start a movement of the concrete [Nm]
H is is a measure of the resistance of the concrete against flow [Nm·s]

The computer software uses the Riner-Rivlin equation to convert the measured constants (G and H) to the Bingham parameters yield stress (τ_y) and plastic viscosity (μ_p). The Bingham equation is:

$$\tau = \tau_y + \mu_p \cdot \dot{\gamma} \qquad (2)$$

were

τ is the shear stress [Pa]
τ_y is the yield stress [Pa]
μ_p is the plastic viscosity [Pa·s]
$\dot{\gamma}$ is the shear rate [s^{-1}]

The rheological properties of the concrete were measured by using following set-up test set-up:

Maximum rotational speed: 0.3 rps (rounds per second)
Minimum rotational speed: 0.05 rps
T/N points: 7 (number of rotational speed steps)

Transient time: 0 sec (time between each step)
Sampling interval: 4sec
Number of sampling points: 150
Total duration of the measurement: 64 seconds

The measuring procedure is illustrated in Figure 3. The segregation coefficient (Seg) is defined according this procedure as the relative change of the slope of the flow curve (plastic viscosity) due to a sudden increase in the rotational speed, and is calculated as follows:

$$Seg = \frac{H - H^{'}}{H} \cdot 100\% \qquad (3)$$

$H^{'}$ is measured at the segregation point for which the rotational speed is 2/3 of maximum (i.e. 0.20 rps).

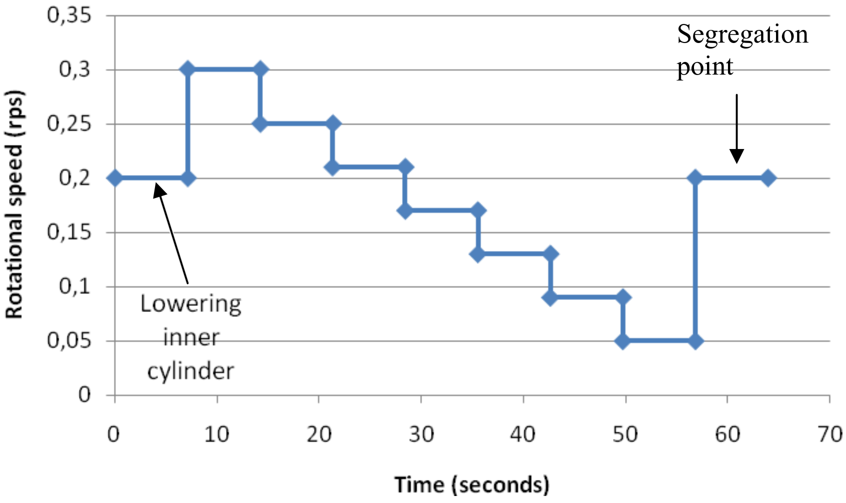


Figure 3: Measurement set-up of the BML viscometer

3.5 Casting

Cubes (100x100x100mm) were cast for determination of compressive strength. The cubes were all cast in one pour without compaction or vibration in order to avoid fibre segregation and fibre alignement. A trowel was used along the form sides and edges to ensure filling of corners. The forms were covered with plastic and cured in laboratory atmosphere for 24 hours. The samples were thereafter demoulded and cured in water bath until time of testing.

Three 150x150x550 mm beams were cast for each of mixture within series 11 and 12. Method of casting and curing was identical as described above for cubes. Visual observations indicated that the fibres were evenly distributed without alignment into any given direction or formation of balls.

3.6 Measurement of hardened concrete properties

Compressive strength of the cubes were measured according to NS-EN 12390-3:2009.

Flexural tensile strength tests were carried out on 150x150x550 mm beams according to NS-EN 14651: 2007: Test method for concrete with metallic fibres – Measurement of bending strength, see

Figure 4. Equivalent bending strengths at the proportionality limit (1st crack) and at 4 different predefined crack widths ($CMOD_1$-$CMOD_4$) as shown in Figure 5 were determined for all the fibre reinforced beams and the corresponding reference beams without fibres of series 11 and 12.

Notations:

$\mathbf{f_{ct,L}}$ =Bending strength corresponding to 1st crack (proportionality limit), or at maximum crackwidth=0,05 mm if strain hardening occurs.
$\mathbf{f_{R,1}}$ = Residual bending strength corresponding to 0,5 mm crackwidth
$\mathbf{f_{R,2}}$ = Residual bending strength corresponding to 1,5 mm crackwidth
$\mathbf{f_{R,3}}$ = Residual bending strength corresponding to 2,5 mm crackwidth
$\mathbf{f_{R,4}}$ = Residual bending strength corresponding to 3,5 mm crackwidth

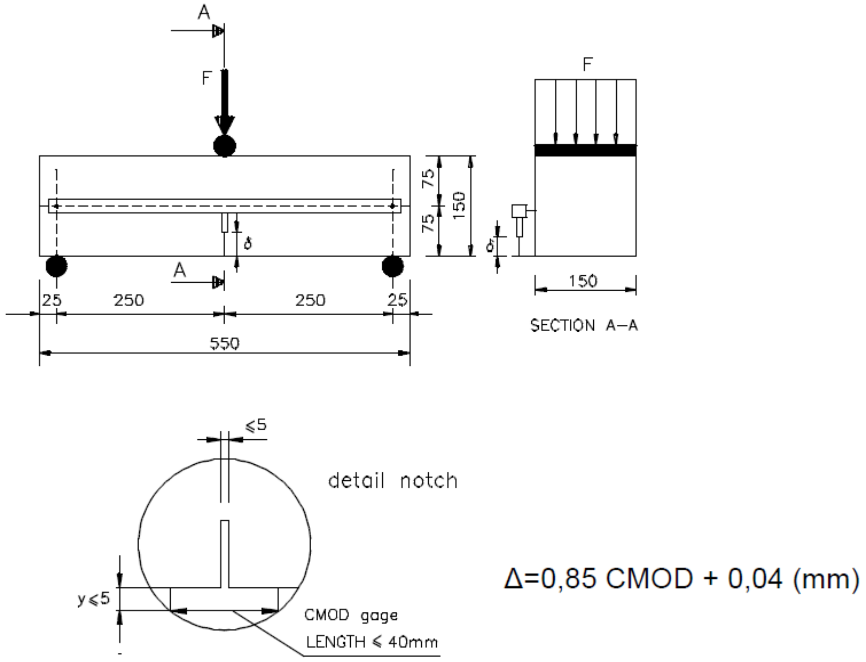


Figure 4: Principle of beam test according to NS-EN 14651: 2007

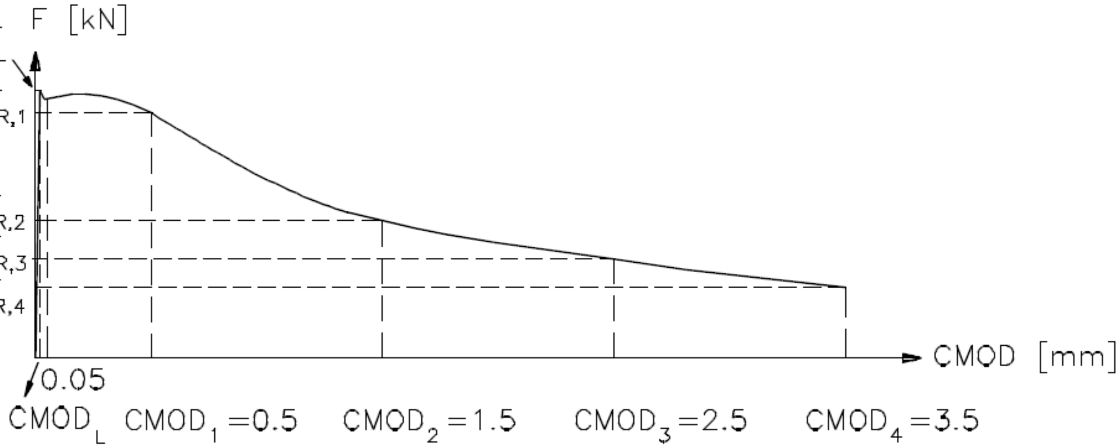


Figure 5: Principle for determination of proportionality limit (1st crack) and the predefined crack widths ($CMOD_1$-$CMOD_4$)

4 Results and discussion

4.1 Fresh concrete properties

Fresh and rheological properties of concretes without fibre are given in Table 5 and Table 6. The BML software calculates yield stress and plastic viscosity by aid of the Bingham model. Note the high segregation coefficient of mixture 11 and 12. Fresh properties obtained for these mixes will thus not be discussed for these mixes.

Addition of fibres increases the water demand of concrete. This effect in line with remixing of the concretes directly before casting, ensured that the cured samples were not inhomogeneous due to segregation and bleeding.

Note that mixture 11 has maximum particle size 8 mm, while the other mixtures are concretes with maximum diameter 16 mm. Water-powder ratio and admixture dosages deviates also markedly from the other mixtures. Wallevik (2003) showed that a good correlation between the measured yield stress of concrete and mortar. No such relationship could however be found for plastic viscosity. Direct comparison of mixture 11 with mixture 12-17 will thus be speculative. Mixture 11 will, however, give indications of the effect of maximum particle size on the flexural tensile strength of the composites.

The high air content of mixture 11 is caused by the smaller aggregate size compared to the other mixtures. This effect is also seen by the results given in Table 7. Increased air content has been reported to reduce the plastic viscosity while having little or no effect on the yield stress. The relative impact of increased air content is, however, difficult to predict (Wallevik 2003).

Table 5: Fresh properties of concrete mixes without fibre addition

Mix no.	Plastic/steel fibre (vol%)	Slump (mm)	Slump flow (mm)	Air (%)	Density (kg/m^3)
11	-	240	460	5.0	2225
12	-	260	550	1.0	2330
13	-	270	570	0.9	2320
14	-	275	610	0.6	2305
15	-	250	465	0.9	2315
16	-	250	486	1.0	2310
17	-	250	490	1.4	2290

Table 6: Rheological properties measured by the BML viscometer on concrete mixes without fibre additions. The measurements were not repeated. Note the high segregation coefficients for mixture 11 and 12.

Mix no.	Yield Stress (Pa)	Plastic Viscosity (Pa*s)	R^2	Segregation coefficient
11	6.7	43.2	0.98	38.1
12	4.9	9.4	0.99	24.1
13	56.9	12.4	0.99	10.4
14	33.5	10.0	0.98	9.1
15	145.1	13.2	0.96	6.3
16	110.8	16.3	0.97	13.9
17	91.0	14.9	0.99	9.3

4.1.1 Influence of cementitious replacement

Figure 6 illustrates the effect of replacing 30 volume% cement with pure limestone powder or a mixture of limestone powder and fly ash or calcined clay. The paste volume and matrix content is constant within the test series. Mixture 12 and 13 illustrate that workability is somewhat increased as 30 volume% cement is replaced by limestone powder. The surface fineness of the two materials are similar (370-380 kg/m^2 for cement and 360 kg/m^2 for limestone powder). The increased workability flow is probably caused by reduced water demand since limestone is an inert material which does not consume water in order to form hydration products. Limestone will, moreover, pack between the cement grains and disperse them. Finally, the superplasticizer saturation dosage of limestone is lower than cement's (Vikan 2005, Vikan and Justnes (2007), Vikan and Kjellsen (2008). Cement will consume superplasticizer during hydration, meaning that adsorbed superplasticizer molecules will be embedded by the cement hydration products. Limestone being a non-hydrating material will not consume superplasticizer in a similar way and will thus leave more superplasticizer to actively disperse the cement particles.

The results show that adding fly ash together with limestone powder increased the workability. The water reducing effect of fly ash has been attributable to three mechanisms. First, fine particles of fly ash get adsorbed on the oppositely-charged surfaces of cement particles and prevent them from flocculation. Secondly, the spherical shape and the smooth surface of fly ash particles help to reduce the inter-particle friction in a concrete mixture and thus facilitate mobility. Thirdly, the "particle packing effect" is responsible for reduced volume of cement paste needed to plasticize the system (Malhotra and Metha 2005).

Calcined clay reduced workability particularly by increasing the yield stress. Porosity and high fineness of the clay particles might be reasons for the increased water demand (Noor-ul-Amin 2010).

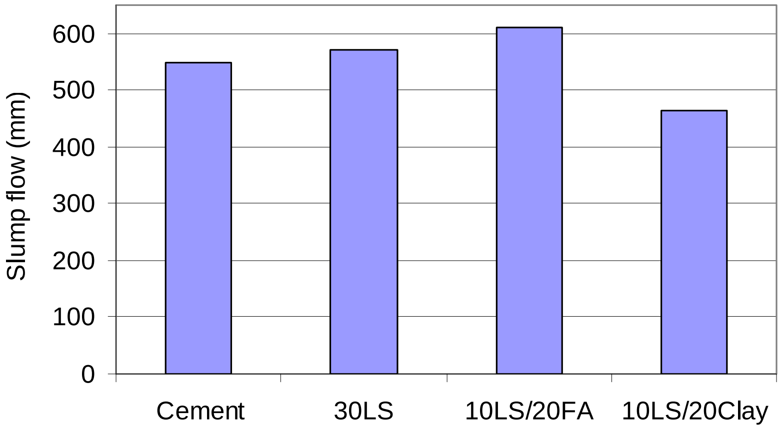


Figure 6: Effect of limestone (LS) in combination with fly ash (FA) or clay on concrete slump flow

Figure 7 illustrates how the yield stress increases (and castability decreases) as the content of calcined clay increases on the behalf of limestone powder.

Mixture 15-17 contains limestone powder together with calcinated clay or silica fume as cement replacement. Silica fume at the given dosage reduced workability in line with previous findings (Vikan and Justnes 2007). Similar workability reduction was found for calcined clay when the replacement ratio was kept constant at 10%.

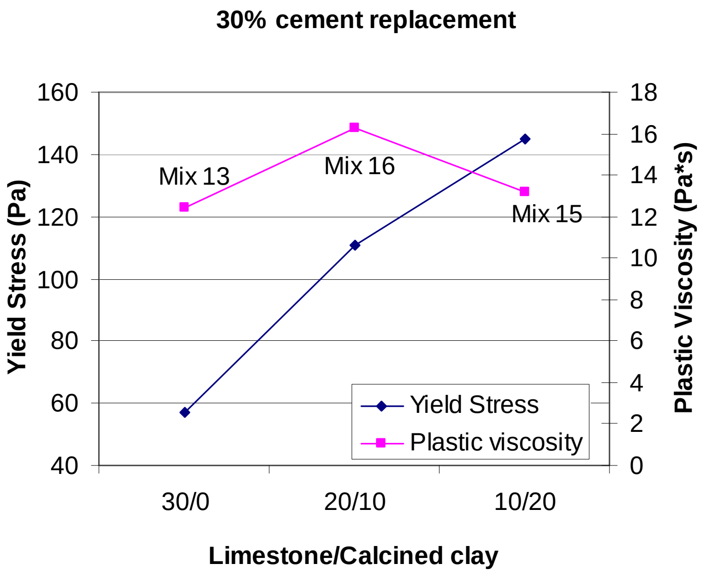


Figure 7: Influence of calcined clay on the Bingham parameters of fresh concrete.

4.1.2 Influence of fibre type and dosage

Fresh properties of concretes with fibre additions, series 11 and 12, are given in Table 7. Mixture 12 had a 90 mm larger slump flow than mixture 11 as given by Table 5. Mixture 12 is exactly within the lower end of self-compactivity with a slump flow level of 550 mm. Mixture 11 is on the other hand not self-compacting.

Table 7: Fresh properties of concrete series 11 and 12

Mix no.	Plastic/steel fibre (vol%)	Slump (mm)	Slump flow (mm)	Air (%)	Density (kg/m^3)
11	-	240	460	5.0	2225
11-1	0.5/-	250	510	4.3	2225
11-2	1.0/-	235	460	4.0	2215
11-3	-/0.5	250	535	6.7	2205
11-4	-/1.0	250	535	8.4	2195
11-5	0.5/0.5	240	515	6.9	2195
12	-	260	550	1.0	2330
12-1	0.5/-	240	435	1.9	2305
12-2	1.0/-	205	425	2.1	2290
12-3	-/0.5	240	485	2.2	2315
12-4	-/1.0	215	470	3.3	2300
12-5	0.5/0.5	220	465	3.0	2300

The slump flow value of mixture 11 is maintained or even increased by the addition of fibre. This indicates that some of the surplus water responsible for segregation tendencies is adsorbed by the fibre surface. The slump flow of mixture 12 is on the other hand reduced by fibre addition.

Workability is found to be higher for mixtures with steel than plastic fibres. This is surprising considering the polymer fibre being shorter than the steel fibres. The relative high surface of the polymer fibre adsorbing water might be one reason for the reduced workability. Relative high flexibility of the polymer fibre compared to the relative stiff steel fibre might be another.

4.2 Hardened concrete properties

4.2.1 Compressive strength

The compressive strength of mixture 11 increased with the addition of fibre (see Table 8). The plain mixture without fibre addition was unstable and had a segregation coefficient of 38.1. Addition of fibre increased the stability of the mixture. Increased stability combined with thorough mixing ensured that homogenous samples of mixture 11-1 to 11-5 were cast. Increased compressive strength with the addition of fibre might thus be an effect of improved stability by fibre addition. No effect of fibre inclusion can be found for mixtures within series 12.

Compressive strength of concrete is reduced as 30 volume% cement is replaced the supplementary materials limestone powder, fly ash, calcined clay and silica fume. The highest reduction of compressive strength was found replacement with 30% limestone powder (compare mixture 12 and 13). The compressive strength is higher for mixtures were cement is replaced with a combination of limestone powder and a pozzolan as seen by comparing mixture 13 with 14-17. There is no marked effect of pozzolans after 6 days of curing. The compressive strength is, however, clearly higher for mixtures with pozzolans after 28 and 91 days of curing. Note that altering the there ratio between limestone powder and pozzolan from 1:2 to 2:1 did not have any marked effect on compressive strength (see mixture 14 and 15 versus 16 and 17).

Table 8: Compressive strengths. Abbreviations: C = cement, L = Limestone, FA = Fly ash, SF = Silica fume

Mix no.	**Matrix composition (vol.%)**	**Plastic/steel fibre (vol%)**	**Compressive Strength (MPa)**		
			6 days	**28 days**	**91 days**
11	80C-20L	-	14.4	23.1	-
11-1	80C-20L	0.5/-	23.1	29.2	-
11-2	80C-20L	1.0/-	-	27.2	-
11-3	80C-20L	-/0.5	-	25.3	-
11-4	80C-20L	-/1.0	-	25.2	-
11-5	80C-20L	0.5/0.5	-	25.3	-
12	100C	-	25.1	32.9	38.5
12-1	100C	0.5/-	-	32.8	-
12-2	100C	1.0/-	-	32.4	-
12-3	100C	-/0.5	-	32.7	-
12-4	100C	-/1.0	-	29.7	-
12-5	100C	0.5/0.5	-	31.4	-
13	70C-30L	-	14.1	18.6	23.2
14	70C-20FA-10L	-	14.6	19.9	28.5
15	70C-10L-20Clay	-	16.4	27.1	31.7
16	70C-20L-10Clay	-	14.8	23.2	28.1
17	70C-20L-10SF	-	14.4	23.2	29.0

4.2.2 Load – Deflection

Figure 9 presents the measured load-deflection curves for the bending tests of the mixes in series 11 and 12. Each curve represents an average of three similar beams. The corresponding results in terms of the bending strength parameters according to NS-EN 14651 are presented in Table 9 and Figure 8.

Table 9: Measured bending strengths

Mix no.	Synth/ steel fibre	$f_{ct,L}$	$f_{R,1}$	$f_{R,2}$	$f_{R,3}$	$f_{R,4}$
11	-/-	2,90	0,2	0	0	0
11-1	0.5/-	3,2	1,3	1,5	1,6	1,5
11-2	1.0/-	3,3	1,8	2,4	2,5	2,5
11-3	-/0.5	3,2	2,9	3,3	3,4	3,5
11-4	-/1.0	4,1	5,0	5,3	5,2	5,0
11-5	0.5/0.5	3,5	4,0	4,5	4,5	4,3
12	-	3,2	0,2	0	0	0
12-1	0.5/-	3,7	1,1	1,2	1,4	1,3
12-2	1.0/-	3,7	2,4	2,9	3,0	2,9
12-3	-/0.5	4,2	2,9	3,5	3,8	3,8
12-4	-/1.0	4,5	5,5	5,9	5,4	5,3
12-5	0.5/0.5	3,9	3,4	4,1	4,3	4,2

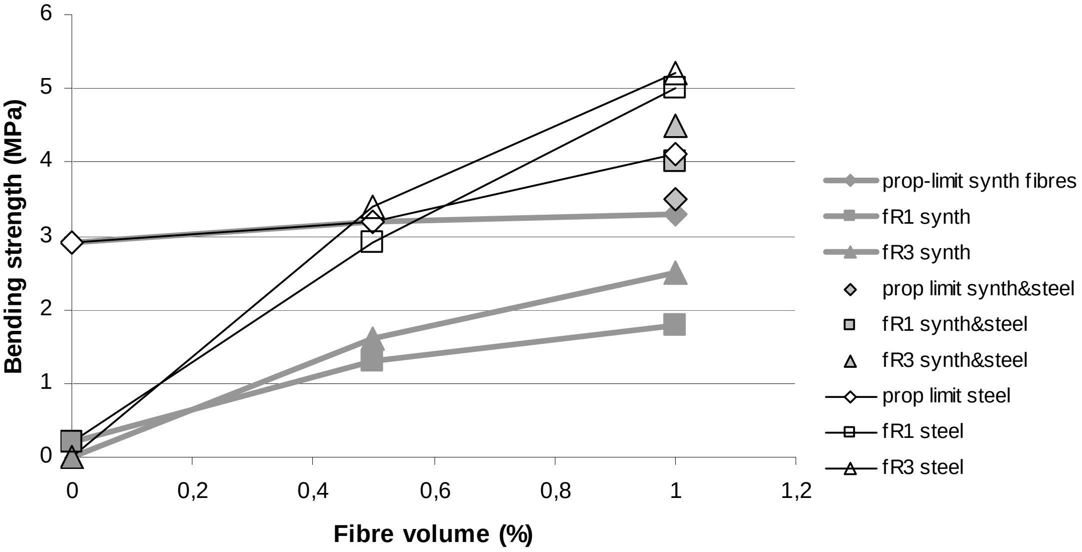


Figure 8: Different bending strength values according to NS-EN 14651 versus fibre volume for mixture series 11 (proportionality limits and residual bending strengths).

The following observations can be made:

The proportionality limit (1st crack strength) is in general between 0.3 and 1.0 MPa larger for the mixes in series 12 (d_{max}=16) than for the corresponding mixes in series 11 (d_{max}=8). Addition of steel fibres leads to a larger increase in the proportionality limit than synthetic fibres do.

Considering the residual bending strength values in the range between 0.5 and 3.5mm crack width, which are interesting for design both in service limit states and ultimate limit states, it is seen that they increase nearly linearly with increasing fibre volume for both synthetic and steel fibres. This is illustrated by curves for f_{R1} and f_{R3} in Figure 6.

To fulfil the minimum reinforcement rules for load carrying structures mainly exposed to bending, as beams and slabs, without reinforcing bars, the residual bending strength, $f_{R,3}$, should be larger than the proportionality limit, $f_{ct,L}$, for the concrete without fibres: Monotonous increase of the load-deflection curve after occurrence of the first crack (i.e. limit of proportionality) indicates formation of a number of small cracks. Marked drop of the load-deflection curve after the proportionality limit is on the other hand indication of a large crack/fissure developing at the notch of the beam. The principle of higher residual bending strengths than the proportionality limit, $f_{ct,L}$, for the concrete without fibres is only fulfilled for the concretes with 0.5 or 1.0% steel fibres and the concrete with 0.5% of both fibre types. However, the concretes with 1% synthetic fibres have residual bending strengths, $f_{R,3}$ rather close to this.

In general the best ductility is achieved if the load is increasing monotonically with increasing crack width. This is not achieved for the concretes with synthetic fibres only which all have sudden drops in load just after the proportionality limit. The steel fibre concretes in series 12 also have sudden drops in load capacity just after cracking (0.5%) and around 1.0 mm crack width (1.0%) which might lead to crack localization and failure. The mixes in series 11 are considerably more promising. This is probably due to the effect of d_{max} in the crack initiating phase as discussed by (Li et al 2003).

The concrete which seems to be most promising considering ductility is the 11-5 concrete with d_{max}=8mm and 0.5% of both steel and synthetic fibres. The steel fibres prevent the drop in load just after the proportionality limit which is a major problem for the mixtures with synthetic fibres only. On the other hand this concrete also utilizes that the synthetic fibres are relatively more beneficial than steel fibres at larger crack widths and therefore results in improved ductility compared to the concretes with steel fibres only.

The residual bending strength $f_{R,3}$ which refers to a crack width of 2.5mm, is 4.5MPa for the 11-5 concrete with 0.5% of both fibre types. This is still quite a distance away from the overall COIN-target of 15 MPa, anyway increased fibre amount and further optimization of this concrete can easily increase this value.

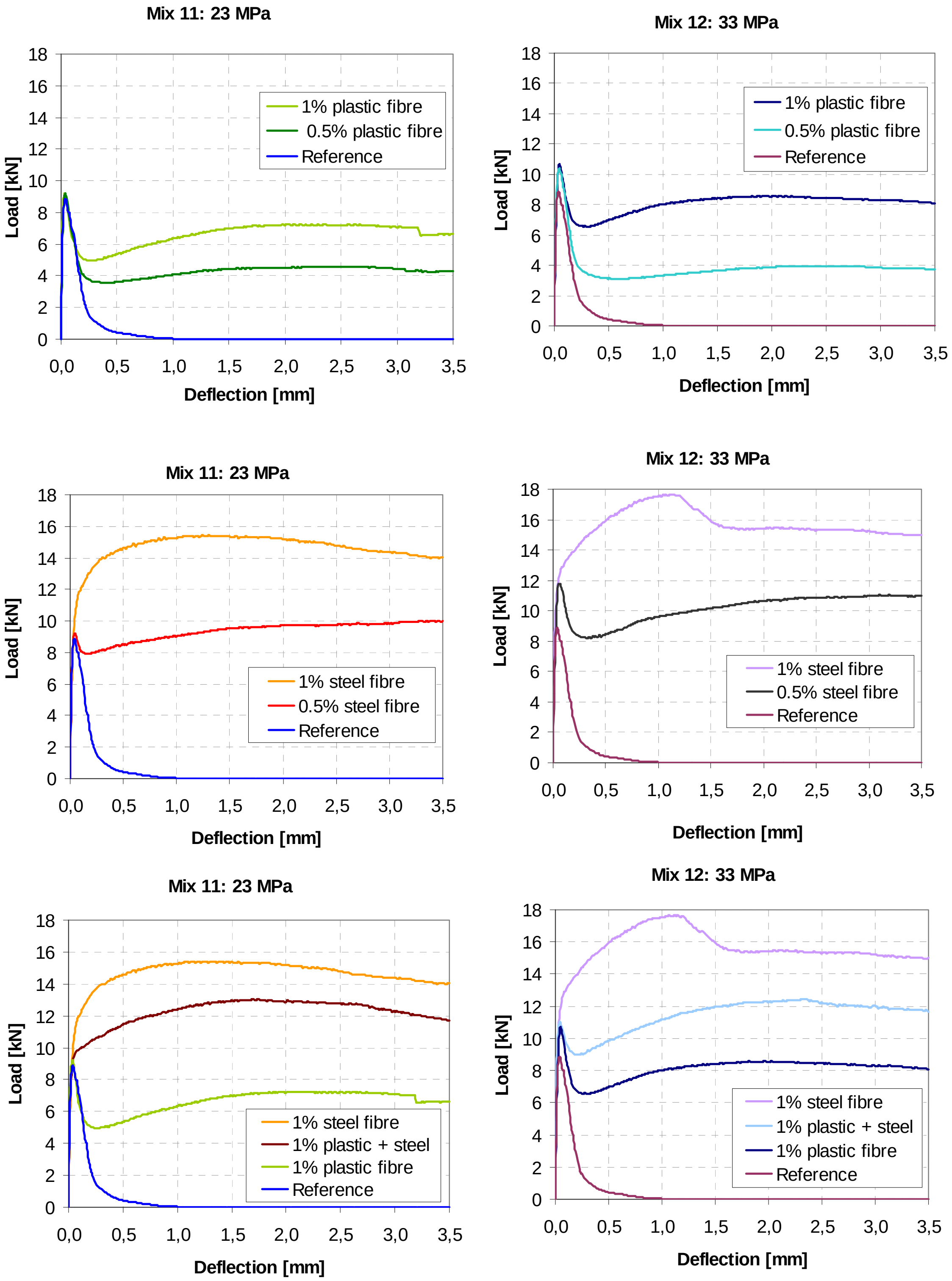


Figure 9: Load-deflection curves for the bending tests of mixes in series 11 and 12

5 Conclusions

5.1 Fresh properties - Castability

5.1.1 Mix design

A working hypothesis for the study is that it is easier to achieve sufficient ductility of fibrous concrete with decreasing concrete compressive strength due to lower crack load and also lower maximum loads. The project aims therefore to produce concrete with low compressive strength, here defined as below 30MPa.

Future all-round cements will probably contain supplementary cementitious materials both due to environmental concerns and due to the powders' reactive and stabilizing properties. Extensive work on supplementary cementitious materials is currently undertaken in COIN. This project has thus based the concrete design on materials and material combinations studied within these projects. A number of preliminary mixes, denoted mixture 11-17, were tested with regard to workability and compressive strength before selecting mixes for incorporation of different fibre types, dosages and combinations. Mixture 11 had a maximum particle size of 8 mm, while mix 12-13 had a maximum particle size of 16 mm. Mixture 12-17 explores the effect of replacing 30 volume percent cement with fly ash, limestone powder, calcined clay and silica fume.

Mixture 12 was chosen as basis for concretes with fibre additions since it obtained a 28 days compressive strength of approximately 30 MPa which was aimed for. Mixture 11 was chosen as basis for the second test series in order to investigate the influence of maximum aggregate size.

To ensure even fibre distribution the concrete should be highly workable. Mixture 12 was just within the lower end of self-compactivity with a slump flow level of 550 mm. Mixture 11 was on the other hand not per definition self-compacting.

Reference mixture 11 and 12, not containing any fibre additions, were segregating. Addition of fibres increases the water demand of concrete. This effect in line with remixing of the concretes directly before casting, ensured that the cured samples were not inhomogeneous due to segregation and bleeding.

5.1.2 Addition of fibre

The slump flow value of mixture 11 was maintained or even increased by the addition of fibre indicating that surplus water responsible for segregation tendencies was adsorbed by the fibre surface. The slump flow of mixture 12 was on the other hand reduced by fibre addition.

Workability is found to be higher for mixtures with steel than plastic fibres.

5.2 Hardened concrete properties

The proportionality limit is slightly increasing with increasing fibre content. The increase is larger for steel fibres than for synthetic fibres.

The concrete with d_{max}= 8mm has more promising ductility properties than the concrete with 16 mm d_{max}.

The beam specimens cast with d_{max}= 8mm and 0.5% of both steel and synthetic fibres fulfilled the ductility requirements best. The same concrete with 0.5 or 1.0% steel fibres is also promising considering ductility.

The residual bending strength $f_{R,3}$ (crack width = 2.5mm) is 4.5MPa for the 11-5 concrete with 0.5% of both fibre types. Although this is far away from the overall COIN-target of 15 MPa, increased fibre content can easily bring us higher up.

An objective of the study was to investigate the effect of hybridization with two different fibre types on the concrete tensile strength, and the combination of long end hooked steel fibres and macro synthetic fibres with embossed surface seems promising considering the residual bending strength - crackwidth relation.

6 Suggestion for further work

Development of a new simple test method where the fresh concrete's ability to keep the fibres homogenously distributed under casting and transportation should be given priority.

Further development of the concrete used in the 11-series with d_{max}=8mm considering alternative cement replacement materials such as fly ash, limestone filler and calcined clay as used in mixture 13-17.

Investigate mixture 11, or similar mixes with increased fibre content and other combinations of synthetic and steel fibres, for instance 0.5% steel and 1.0% synthetic or 1% of both to increase the residual bending strength towards the overall COIN-target of 15MPa.

Verify the ductility-experience of the present investigation in structural elements of larger dimensions, for instance beams planned for moment- or shear failure.

References

ACI Committee 544, *State of the Art Report on Synthetic Fiber-Reinforced Concrete*, American Concrete Institute, Farmington Hills , MI, 2005

ACI 544.3R-93 Guide for specifying, proportioning, mixing, placing and finishing steel fibre reinforced concrete, (1998)

Balaguru P., Najm H., High-Performance Fiber-reinforced Concrete Mixture Proportions with High Fiber Volume Fractions, *ACI Materials Journal,* **101** (2004) 281-286

Banthia N., Bindiganavile V., repairing with Hybrid-Fiber-reinforced Concrete, *Concr. Int.* June (2001) 29-32

Bentur A., Mindess S., Fibre Reinforced Cementitious Composites, 2nd ed. Modern Concrete Technology 15, Taylor & Francis, London and New York 2007

Corradi, M., Khurana, R., Magarotto, R., "User friendly self-compacting concrete in precast production", The Third International RILEM Symposium on Self-Compacting Concrete, Reykjavik 2003, s. 457

De Weerdt K., Justnes H., Synergic Reactions in Triple Blended Cements, 11th NCB International Seminar on Cement and Building Materials, 17-20 November 2009, New Delhi, India : Proceedings, Special Lectures and Extended Abstracts, pp. 257-261

De Weerdt K., Østnor T., Justnes H., Pozzolanic activity of sintered clay and interaction with limestone powder, Extended Abstracts Cement and Concrete Science, Manchester, UK (2008) pp. 15-18,

Ferrara L., Park Y.-D., Shah S.P., A method for mix-design of fiber-reinforced self-compacting concrete", *Cem. Concr. Res.* **37** (2007) 957-971

Groth P., Fibre reinforced concrete – Fracture mechanics methods applied on self-compacting concrete and energetically modified binders, PhD-thesis, Department of Civil and Mining Engineering, Luleå University of Technology (2000)

Grünewald S., Performance-based design of self-compacting fibre reinforced concrete, PhD thesis 2004, DUP Science, Delft, ISBN 90-407-2487-3

Grünewald S., Walraven J.C., Maximum content of steel fibres in self-compacting concrete, The Second International Symposium on Self-Compacting Concrete, Tokyo (2001) 137-146

Khayat K.H., Roussel Y., Testing and performance of fiber-reinforced self-consolidating concrete, First International RILEM symposium on self-compacting concrete, Stockholm, Sweden, (1999) 509-521

Kim, J.K., Han, S.H., Park, Y.D., Noh, J.H., Park, C.L., "Experimental research on the Material Properties of Super Flowing Concrete", Proceedings of the International RILEM Conference o Production and Workability Methods of Concrete, Paisley, June 3-5, 1996, s. 271-284

Li, V.C., Wu C., Wang, S., Ogawa, A., Saito,T.(2002): Interface tailoring for strain-hardening polyvinyl alcohol-engineered cementitious composite (PVA-ECC), ACI Material Journal, September-October 2002.

Malhotra V.M., Metha P.K., High-performance, High-volume fly ash concrete: Materials, Mixture Proportioning, properties, Construction Practice, and Case Histories, 2nd addition, Supplementary Cementing Materials for Sustainable Development Inc., Ottawa, Canada, 2005

Markovic I., Walraven J.C., van Mier J.G.M., Self-compacting hybrid-fibre concrete – mix design, workability and mechanical properties, 3rd International Symposium on Self-Compacting Concrete, Reykjavik, Iceland (2003) 763-775

Naaman A.E., Strain hardening and defelection hardening fibre reinforced cement composites, in A.E. Naaman and H.W. Reinhardt (eds.) Fourth International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC 4) RILEM Publications, Bagneux, France (2003) 95-113

Noor-ul-Amin, Use of clay as a pozzolona in high strength Portland cement and its thermal activation, *Chin.J.Geochem*. (2010) **29**143–145

Oh S. G., Noguchi T., Tomosawa F., Towards mix design for Rheology of self-compacting concrete, 1st International Symposium on SCC, Stockholm (1999) 361-372

Richard P., Cheyrezy M., Composition of reactive powder concretes, *Cem. Concr. Res.,* **25** (1995) 1501-1511

Sahmaran M., Yaman I.O., Hybrid fiber reinforced self compacting concrete with a high volume of fly ash, *Construct. Build. Mater.* **21** (2007) 150-156

Smeplass S., Mørtsell E., “The Particle Matrix Model applied on SCC”, In Proceedings of the Second International symposium on Self-Compacting Concrete, 23-25 October 2001, Tokyo, Japan, 267-276

Takada, K., Pelova, G.I., Walraven, J.C., ”Self-Compacting Concrete Produced by Japanese Method with Dutch Materials”, Proceedings of the 12th European Ready Mixed Concrete Congress, 23-26 June 1998, Lisbon, Vol. 2 s.775-785

Yao W., Li J., Wu K., Mechanical properties of hybrid fibre reinforced concrete at low fibre volume fraction, *Cem. Concr. Res.* **33** (2003) 27-30

Vikan, H., “Rheology and reactivity of cementitious binders with plasticizers”, Doctoral Theses at NTNU 2005:189, Chapter 10, Also available at http://www.diva-portal.org/ntnu/theses/abstract.xsql?dbid=689

Vikan H., Concrete workability and fibre content - State of the art, (2007), Report number SBF BK A07029, ISBN 978-82-536-0994-2

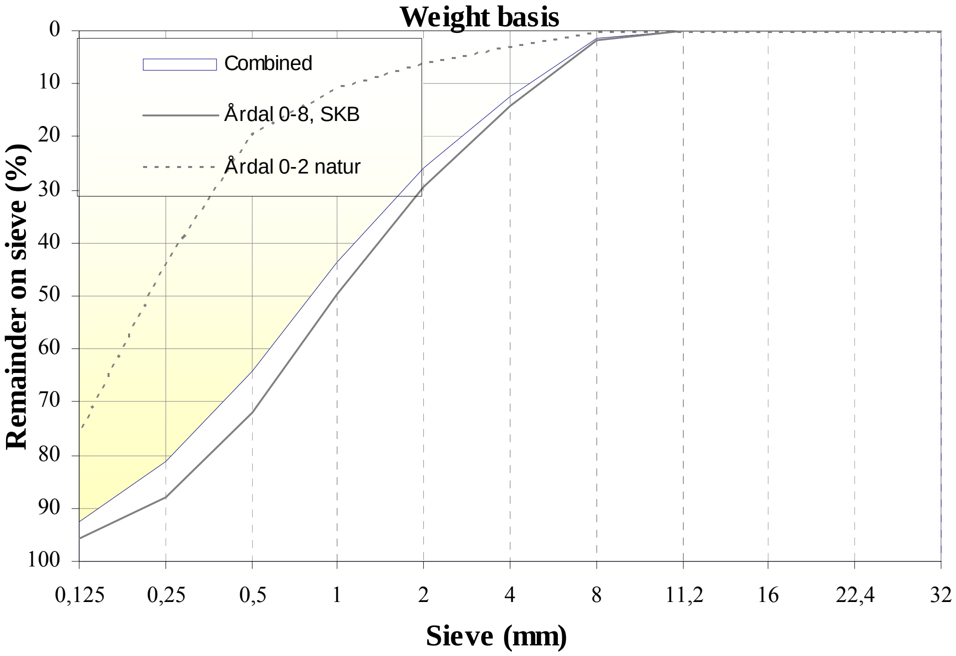
Vikan, H., Justnes, H., Rheology of cementitious paste with silica fume or limestone, *Cement and Concrete Research,* **Vol 37 (11)** (2007) pp. 1512-1517

Vikan H., Kjellsen K.O., ”Influence of Cement Composition on Concrete Rheology”, SCC2008: Challenges and barriers to Application. The Third North American Conference on the Design and Use of Self-Consolidating Concrete, November 10-12 2008 Chicago, Proceedings Volume 2, pp. 584-589, The Center for Asdvanced Cement-Based Materials

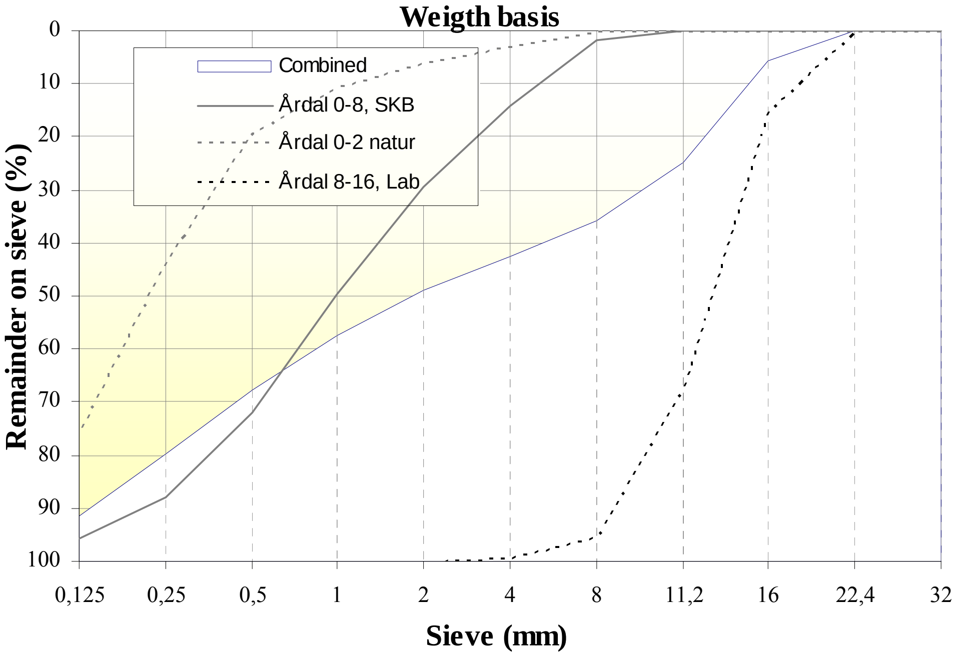
Wallevik, J.E., Rheology of Particle Suspensions. Fresh Concrete, Mortar and Cement paste with Various Types of Lignosulfonates, PhD Thesis 2003:18, NTNU, ISBN 82-471-5566-4

APPENDIX

A1: Sieve curve mixture 11



A2: Sieve curve mixture 12-17



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

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

Technology for a better society

www.sintef.no