NTNU – Trondheim
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Fibre-reinforced Self-compacting Concrete

Prediction of Rheological Properties

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Title: **Fibre-reinforced Self-compacting Concrete**
- Prediction of Rheological Properties

Fiberarmert selvkomprimerende betong
- Mulighet for å forutsi reologiske egenskaper

Written by: Ellen Øfsdahl

Summary:

The purpose of this thesis is to investigate the relationship between measured rheology and proportioning properties with particular attention to maximum packing fraction, thickness of fiber lubricating matrix and fiber rotational overlap.

This is done by conducting experiments on fresh concrete where the amount of matrix and fibres are varied, and comparing the rheological results with the proportioning parameters.

The importance of an accurate grading curve is also evaluated.

The hypothesis is that it is possible to find a correlation between calculated proportioning parameters and resulting rheology that will enable prediction of rheological properties.

The results show that the variation in grading curve for the same aggregate is not very relevant to the proportioning parameters.

The air content is shown to be of great importance regarding the correlation between matrix volume and packing fraction. Also it is found that it can be possible to predict the air volume based on matrix volume and fiber content.

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Master Thesis 2012

For

Ellen Øfsdahl

Fibre-reinforced Self-compacting Concrete
- Prediction of Rheological Properties

Oppgavetekst:

Fiber blir et viktig alternativ/supplement til stangarmering i fremtidens betong. I bærende konstruksjoner kreves det relativt store mengder fiber og god fordeling av denne for å oppnå tilstrekkelig bæreevne og sikkerhet. Store fibermengder bidrar imidlertid til vesentlig redusert støpelighet (redusert flyteevne), hvilket er spesielt uheldig med tanke på ønsket om å utvikle selvkomprimerende betong (SKB) som den fremtidige standardbetongen. Oppgaven går ut på å undersøke hvordan fiber påvirker tilslagspartiklenes pakning og behovet for pasta og matriks og de tilhørende reologiske egenskaper.

Supervisors: Stefan Jacobsen and Mette Geiker
The report shall be submitted to the Department of Structural Engineering by 11 June 2012.

NTNU, January 21st 2012

Stefan Jacobsen
Supervisor

Preface

This document is written for the course TKT4925 Concrete technology, master thesis at the Norwegian University of Science and Technology (NTNU), Faculty of Engineering Science and Technology (IVT), Department of Structural engineering. The master thesis is a continuation of Stein Are Berg's master thesis and Oliver Berget Skjølsvik's 9th semester project.

I would like to thank my supervisors Stefan Jacobsen and Mette Rica Geiker for guidance and help during the whole project.

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Sammendrag

Bruken av selvkomprimerende betong eliminerer behovet for å tilføre energi ved vibrering eller lignende. Dette gjøres for å kvitte seg med luftporer slik at betongen komprimeres. Fiber i betong kan brukes i tillegg til, eller istedenfor, vanlig stangarmering for å øke strekkfastheten til betongen.

Hensikten med denne masteroppgaven er å undersøke forholdet mellom målte reologiske egenskaper (slump-flow, τ, μ) og proporsjoneringsparametere, særlig maksimal pakningsfraksjon (Φ/Φ_m), matrikstykkelse rundt fibrene (t_c) og overlapptall for fibrene (N_{cs}).

Det gjøres eksperimenter med fersk betong hvor mengden matriks og fiber varieres. De reologiske resultatene sammenlignes med proporsjoneringsparametere for tilsvarende betongblandinger. Compressible Packing Model og partikkel-matriksmodellen er brukt for beregningene, mens 4C-rheometer og LCPC-boks er utstyret som brukes til de reologiske målingene.

Betydningen av en nøyaktig siktekurve er også undersøkt.

Hypotesen er at man ved hjelp av forsøk og beregninger kan finne en sammenheng mellom parametere og målt reologi som gjør det mulig å forutsi flytegenskapene til fersk betong.

Resultatene fra denne avhandlingen er ikke pålitelige nok til å kunne konkludere med en konkret sammenheng, men metodene kan være nyttig for videre forsøk med tilsvarende hensikt. I tillegg kan resultatene brukes som en indikasjon på hvilke mengder av matriks og fiber man kan bruke ved videre forsøk.

Det er kommet fram til at variasjonen i siktekurver for forskjellige prøver av samme tilslag er av liten eller ingen betydning for proporsjoneringsparameterne; En representativ siktekurve er nøyaktig nok for beregninger.

Innholdet av luft i betongen viser seg å være av stor betydning for sammenhengen mellom matriksvolum i betongen og pakningsfraksjonen i partikkelfasen. I tillegg synes det sannsynlig å kunne finne en metode for å forutsi luftinnholdet i betong ved hjelp av matriksvolum og fiberinnhold.

Ettersom denne avhandlingen ikke gir noen nøyaktige resultater anbefales det å forske videre på området for å finne en klarere sammenheng for å forutsi egenskapene til fersk betong.

Summary

The use of self-compacting concrete eliminates the process of adding energy, by vibrating the concrete etcetera, to let off encapsulated air pockets to compact the concrete when casting. Fibre-reinforcing in concrete can be used in addition to, or as a substitute for, rebar to increase the tensile strength of the concrete.

The purpose of this thesis is to investigate the relationship between measured rheology (slump-flow, τ, μ) and proportioning properties with particular attention to maximum packing fraction or normalized packing fraction (Φ/Φ_m), thickness of fiber lubricating matrix (t_c) and fiber rotational overlap (N_{cs}). This is done by conducting experiments on fresh concrete where the amount of matrix and fibres are varied, and comparing the rheological results with the calculated proportioning parameters. The compressible packing model and the particle-matrix model are used for the calculations, while the 4C-Rheometer and LCPC-box are the equipment for the rheology measurements.

The importance of accurate grading curve is also evaluated.

The hypothesis is that these experiments and calculations will result in finding a correlation between calculated proportioning parameters and resulting rheology that will make it possible to predict the rheology of fresh concrete.

The results are too unreliable to draw a finite conclusion with regards to correlation. However, the methods can be useful for further experiments with the same purpose, as well as the results are an indication for what amounts of matrix and fibre that can be applicable for tests.

The results show that the variation in grading curve between different samples from the same aggregate for concrete mixing is of small or no relevance to the proportioning parameters.

The air content is shown to be of great importance regarding the correlation between matrix volume and packing fraction. Also it is found that it can be possible to predict the air volume based on matrix volume and fiber content.

Seeing that this thesis does not give precise results, further work on the field is recommended to find an unambiguous correlation for use regarding rheology and air content.

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List of Symbols and Abbreviations

V_m - Matrix volume

V_f - Amount of fibre

Φ - Particle volume

Φ_m - Maximum packing

t_c - Thickness of fibre lubricating matrix

N_{cs} - Rotational overlap number

τ - Yield stress

μ - Plastic viscosity

FRSCC - Fibre-Reinforced Self-Compacting Concrete

SCC - Self-compacting concrete

PMM - Particle-Matrix Model

SP - Super plasticizing (water reducing) admixture

CPM - Compressible Packing Model

SF - Slump-flow

1 Introduction

In the beginning of this thesis you will find a brief description of the basic theory for proportioning of concrete. This includes the theoretical models for analysis used in this thesis followed by the basics of the materials used in concrete. Further on is the basis for the experiments, description of the experiments that are carried out and explanation of the compressible packing model which forms the basis for the calculations. Last the results from the experiments and the calculations are assembled and put up against each other and discussed. A brief conclusion summarizes the results that are found in this thesis.

1.1 Background

The definition of self-compacting concrete as described by the European Concrete Platform is expressed as follows:

"Self-compacting concrete (SCC) is an innovative concrete that does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement." [European Concrete Platform, 2012]

Knowing this, it is implied that the industry can save many working hours by reducing the need for people vibrating the fresh concrete to compact it. When there is no need for compacting, the quality assurance of the vibrating as an uncertain factor, regarding the final result of the concrete, is ruled out.

The most used argument for not using SCC is that it is more expensive than regular vibrated concrete. Despite the high expenses of SCC compared to regular concrete, it is probably more profitable in use by reducing the expenses of vibrating, and by quicker casting. In addition there are several other benefits with using SCC; With no need for vibrating, the working environment is better, the surfaces are improved, there is less need for rework, the execution is more rational, and we get more homogeneous concrete which gives better durability. The downside with SCC is that because of the rheology, the formwork needs to be tighter for the concrete not to flow out. [Kvisvik, 2007]

Another way to save working hours is by adding fibres as a substitute to rebar. By mixing fibres in the fresh concrete increased tensile strength in the hardened concrete can be achieved without need for iron fixers prior to casting.

Fibres in regular vibrated concrete is more uncertain, due to that when vibrating, the fibres will form a cylinder around the vibrator and may not be dispersed as required.

A disadvantage by use of fibres is that the amount that can be used is very limited. The reason is that when using a large amount of fibres the flow properties of the concrete are reduced and in the worst case, fibre balling occurs, thus the fibres are not properly dispersed, resulting in irregular and unreliable concrete. Different manufacturers recommend different amounts of fibre. The recommended maximum amount varies from 1.3 vol-% to 3 vol-% of concrete. [Fibercon, 2012] [Ochi, Okubo and Fukui, 2007]

1.2 Motivation

Currently, there is no reliable way to predict the rheology of fiber-reinforced self-compacting concrete (FRSCC), thus the making of new recipes is done mainly by trial and error. This thesis will hopefully contribute to some extent to enable prediction of rheology of FRSCC.

The interest for this subject is a conception that there is a simpler and more effective way for casting concrete than by extensive use of iron fixers and vibration. More knowledge about FRSCC is probably the best way to help the industry towards an increased use of what is presumably a much more effective and profitable casting process.

1.3 Hypothesis

The rheology of concrete depends on the matrix, both composition and amount. When fibres are introduced in concrete it is presumed that an increase of the matrix surplus evenly distributed by the surface area of the fibres increases the flow ability. It has been found that an increase of the calculated parameter t_c gives a reduction of the measured value for yield stress [Bui, Geiker & Shah, 2003]. In general it is assumed to be possible to find a correlation between the calculated parameters t_c, N_{cs} and Φ/Φ_m, and the measured properties μ and τ.

The expectations for the correlations are shown in Table 1.1. When the maximum packing is increased the void volume is smaller and the matrix will to a greater extent smear the particles and separate the fibres, thus increase t_c and decrease N_{cs}. This results in increased flow ability, which implies the increases and decreases shown by arrows in Table 1.1.

Table 1.1 *Expectations for rheological results when the proportioning parameters are increased*

		T_{500}	μ_{pl}	τ	SF
Φ_m	↑	↓	↓	↓	↑
t_c	↑	↓	↓	↓	↑
$N_{cs,overlap}$	↓	↓	↓	↓	↑

The main assumption is that the matrix phase includes all particles smaller than 0.125 mm, including from the aggregate. This part of the sand is referred to as fines. In addition, calculations are done where the limit is varied by considering particles smaller than 1.0 mm as the matrix.

2 Review, Methods and Models

There are several ways to consider concrete regarding composition and rheology. The theory of the models considered for this thesis is elaborated in the following.

2.1 The Particle-matrix Model

By regarding the properties of the constituents and the interaction between them it is to some extent possible to predict the workability of the fresh concrete. The particle-matrix model (PMM) is an attempt to describe the properties of the concrete by defining concrete as a mix of two phases: the matrix phase and the particle phase. An illustration of this is shown in Figure 2.1. The matrix phase is defined by The Norwegian Concrete Association as all particles smaller than 0.125 mm, which includes water, cement, fines and additives. The particle phase consists of all particles larger than 0.125 mm. These phases are respectively a fluid material and a friction material. Although the matrix phase includes solid particles, they are small enough to fill the voids and smear the larger particles, and can therefore be defined as part of the fluid. For comparison, 1.0 mm will also be considered as a possible limit particle-matrix phase, although this is not traditionally used.

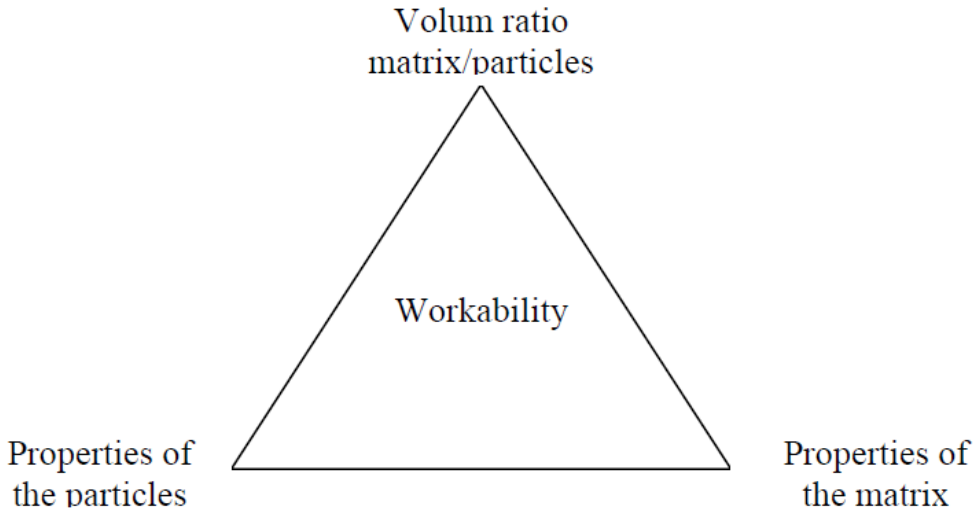


Figure 2.1 *The particle-matrix model [Jacobsen et.al., 2012]*

By using different definitions for the classification of the phases the result of the packing of particles will be completely different. When larger particles are considered part of the matrix phase, the particle phase decrease consequently, see Figure 2.2.

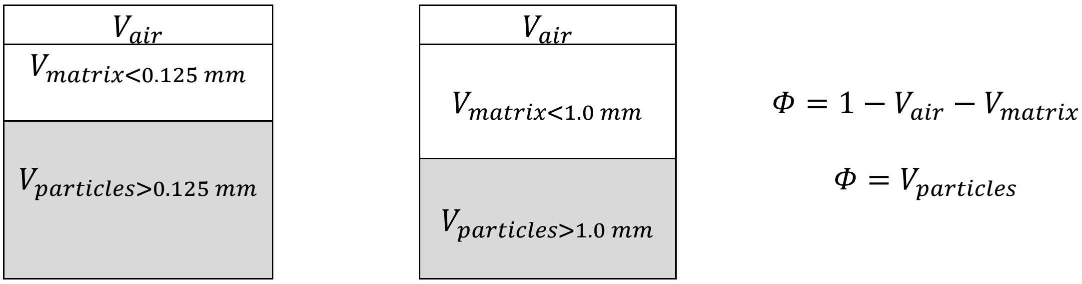


***Figure 2.2** Example of variance in phase volumes because of differing limit for particle-matrix phase for the same composition of concrete*

The phase that affects the concrete the most is referred to as the dominant phase. SCC is always matrix dominated. This implies that the concrete has a large and viscous matrix phase, which is necessary in order to get the flow ability needed for SCC. A disadvantage with the PMM is that it does not help to predict the stability of the concrete. [Norsk Betongforening, 2007]

The main purpose of the matrix is to fill the void in the particle phase. The matrix surplus works as a lubricant that surrounds the particles to give the concrete flow able properties. By calculating the void volume in the particle phase, and the surface area of the particles, one can find the theoretical thickness, t_c, of the matrix around each particle, as shown in Figure 2.3. This calculated parameter affects the flow ability of the concrete.

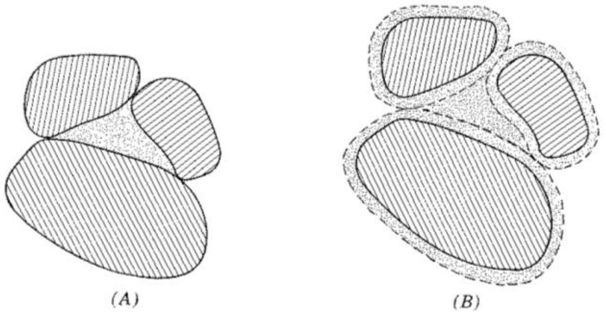


***Figure 2.3** Matrix filling voids between particles (A) with matrix surplus (B) [Jacobsen et.al., 2012]*

The proportioning procedure of the PMM in brief consists of determining strength and durability requirements of the actual concrete. This gives required water/binder-ratio (see Table 3.1 and Table 3.2), binder composition and minimum amount of binder. Then the main steps of the proportioning are:

- Find and evaluate data for constituents: aggregate, cement and admixtures. The relevant data is grading of particle size, density, void volume, water absorption, water/solid content for admixtures and strength characteristics for cement/binder.
- The composition of aggregates regarding minimizing of void volume.
- Decide the composition of the paste and matrix from the requirements for strength and durability, and necessary composition and volume of the matrix for the desired consistency.
- Calculation of the theoretical recipe based on volume and mass.
- Trial mixture and correction.

If the aggregate packing is known the procedure described under Section 4.3 can be used for proportioning with a stepwise procedure minimizing the cement content while obtaining optimum concrete properties. Note that if matrix is used instead of cement paste then the simple expression has to be adjusted, and packing of only the particle phase should be used while applying the matrix phase as lubricating phase instead of cement.

2.2 Bingham's Model

A good way to describe the rheological properties of fresh concrete is to regard it as a Bingham fluid. Bingham's model describes a fluid that needs a certain force applied to start flowing (τ_0) and has an approximately linear relation between continuing force and flow ability, see Figure 2.4.

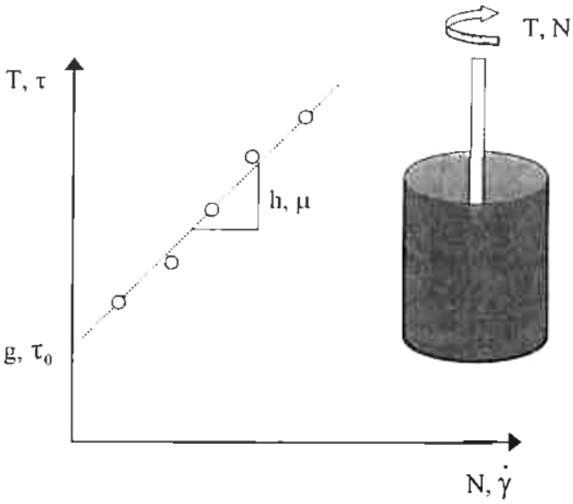


Figure 2.4 *Bingham's model [Norsk Betongforening, 2007]*

The yield stress is expressed by the formula

$$\tau = \tau_0 + \mu * \dot{\gamma}$$

Where: τ is the yield stress, value in Pa
τ_0 is the yield value, value in Pa
μ is the plastic viscosity, value in Pa*s
$\dot{\gamma}$ is the rate of shear, value in 1/s

2.3 Compressible Packing Model

The worksheet 'CPM-regneark' (Appendix E), developed by Stein Are Berg [Berg, 2008], is used to calculate properties for the mortars. It is based on the compressible packing model described in de Larrard, 1999. The theory of the worksheet is explained by Berg (2008) and extended by Skjølsvik (2010). The worksheet calculates several parameters. The ones used in this thesis is t_c, N_{cs} and Φ_m, where t_c is the thickness of the lubricating matrix around each fibre (see Section 2.1, Figure 2.3 and Figure 2.5).

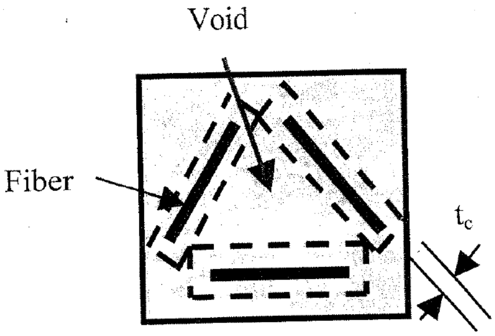


Figure 2.5 *Average thickness of matrix enveloping around fibre [Bui, Geiker and Shah, 2003]*

$N_{cs,overlap} = 1 - (1/_{N_{cs}})$ is the rotational overlap number referring to the distance between the centers of the fibres when distributed in a cubical arrangement. $N_{cs} = 0.966 * (V_{fb}(L/_D)^2)^{1/3}$ where $V_{fb} = c_v =$ vol-% of fibre in the concrete, L is the length of the fibres and D is the diameter of the fibres. The degree of overlap varies between 0 and 1; Overlap smaller than 0 means that the fibres are not overlapping at all $(N_{cs} < 1)$ and overlap that converges towards 1 means full overlap (large N_{cs}), see Figure 2.6.

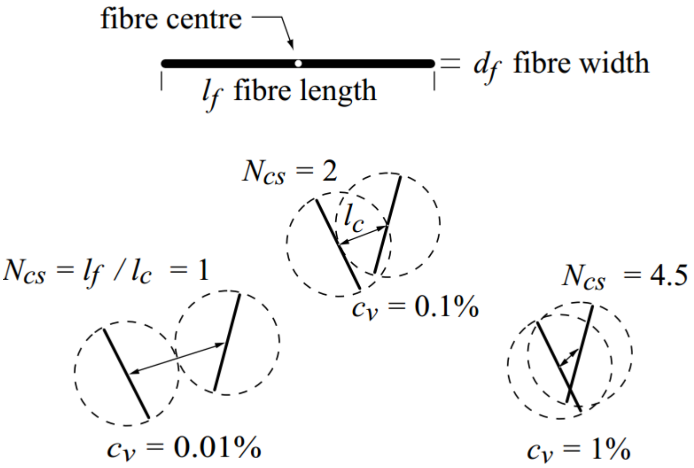


Figure 2.6 *Rotational overlap number [Ulf Björkman, 2007]*

While Φ can be calculated from the corrected values of the constituents in concrete, Φ_m is only a theoretical value. The value for Φ found from the CPM-worksheet is the theoretical volume fraction of the particles in the concrete mix, but the value for Φ used in this thesis is as explained in Section 2.1. Φ_m is the virtual maximum packing of the particles that is theoretically possible to achieve. It calculates how the particles of different size interact with each other and affects the packing of the particle phase. In [De Larrard, 1999] these interactions are explained as a loosening effect from small particles and a wall effect from large particles, both related to a dominant particle size. By finding the maximum packing of the particles, the void volume is known and thus the needed matrix volume to fill the voids is known. The matrix surplus after filling the voids is divided by the total surface area of the fibres to find t_c.

The maximum packing fraction is noted Φ/Φ_m and is a basic parameter for the rheology of suspensions. For a given lubricating or dispersive phase and type of particle both yield stress and plastic viscosity relate to this.

3 Materials in Concrete

To mix concrete there are several materials that needs to be regarded. The types of materials as well as the amount and interactions between them affect the concrete properties, and thereby quality. Concrete is a composite made primarily from cement, water, aggregates and admixtures. The choices regarding materials are accounted for in the following.

3.1 Cement

Cement is the main constituent in concrete, the part that keeps it all together. When mixed with water cement forms a paste that hardens after some time.

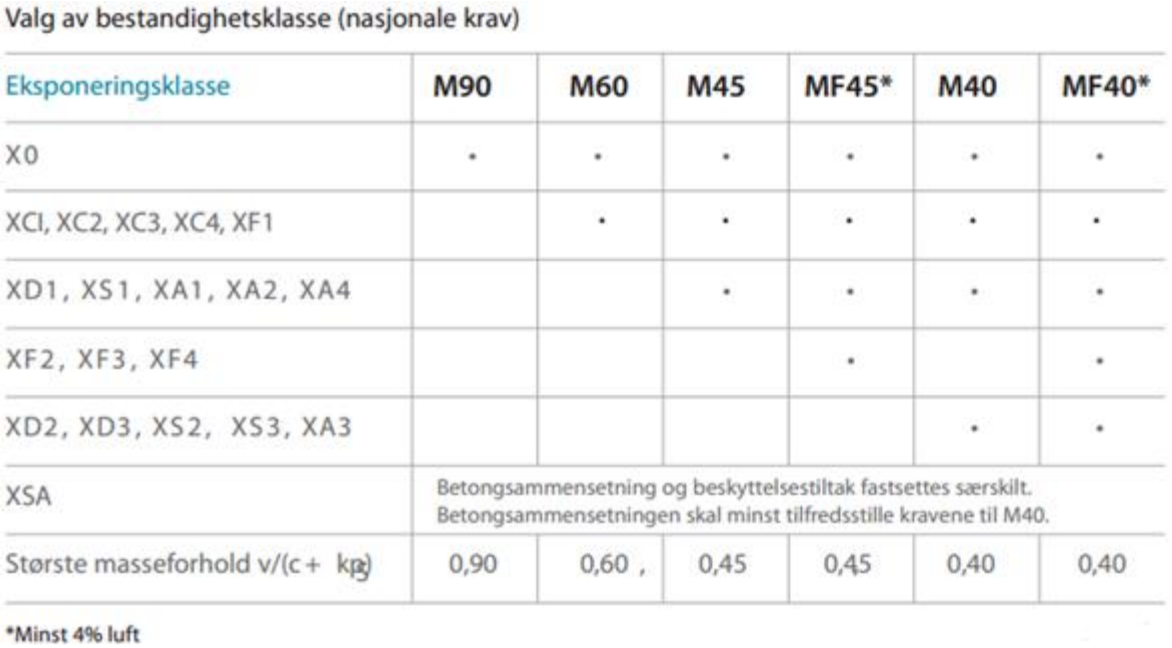
Norcem Standard FA is a type of cement commonly used in Norway. This qualifies as Portland fly ash cement EN 197-1-CEM II/A-V, where 20 % of fly ash is added. The cement is approved to be used for concrete in all durability classes, exposure classes and strength classes, according to Heidelberg cement [HeidelbergCement, 2012]. The same source tells us that when using this type of cement, the relationship between strength class and water/binder-ratio (mass ratio, m) is as shown in Table 3.1. This applies for concrete without air entraining admixtures.

Table 3.1 *Relationship between strength class and mass ratio [HeidelbergCement, 2012]*

Strength class	*B20*	*B25*	*B30*	*B35*	*B45*
Mass ratio	*0.72-0.65*	*0.65-0.57*	*0.57-0.51*	*0.51-0.44*	*0.44-0.35*

NS-EN 206-1 (2007) requires $\mathrm{m} = \frac{\mathrm{V_{eff}}}{\mathrm{c+k*s}} \leq 0.6$ for SCC. Knowing this Table 3.1 shows that SCC has to be of strength class B30 or higher. For the same reason we also know from looking at Table 3.2 that SCC has to be of durability class M60 or lower. For the mass ratio formula c is the content of cement (measured in kg), s is the content of silica, k is the efficiency of silica, and V_{eff} is the effective water content in the concrete. V_{eff} is the total water content minus the absorbed water in the aggregate.

Table 3.2 *Durability class [Heidelbergcement, 2012]*



Valg av bestandighetsklasse (nasjonale krav)

Eksponeringsklasse	M90	M60	M45	MF45*	M40	MF40*
X0	•	•	•	•	•	•
XCl, XC2, XC3, XC4, XF1		•	•	•	•	•
XD1, XS1, XA1, XA2, XA4			•	•	•	•
XF2, XF3, XF4				•		•
XD2, XD3, XS2, XS3, XA3					•	•
XSA	Betongsammensetning og beskyttelsestiltak fastsettes særskilt. Betongsammensetningen skal minst tilfredsstille kravene til M40.					
Største masseforhold v/(c + kp)	0,90	0,60	0,45	0,45	0,40	0,40

*Minst 4% luft

3.2 Water

The requirements for water used when mixing concrete is specified in [NS-EN 1008:2002, 2004]. The requirements cover mainly chemical conditions such as pH-value, alkalis, chlorides and sulfates. It also provides guidelines in terms of color and odor. The standards regarding potable water are more stringent than that of mixing water for concrete, thus potable water is approved for concrete without further testing.

The water used in the tests is deionized tap water. The amount is adjusted for the matrix volume in each mix and the determined $\frac{w}{c+\sum kp} - ratio = 0.49$.

3.3 Admixtures

Admixtures are defined as materials that are added to the concrete during the mixing process to modify the properties of the concrete, both in fresh and hardened state. The quantity of admixtures in concrete should not exceed 5 % by mass of cement. [NS-EN 934-2, 2009]

In self-compacting concrete it is customary to use viscosity modifying agents, such as water reducing/super plasticizing admixtures (SP). These have the ability to reduce the water demand and/or increase the flow of the fresh concrete. The requirement of SCC being slump-flow of 650 mm, use of super plasticizers allows production of SCC without excessive use of expensive cement.

The most commonly used super plasticizer in Norway recently is polycarboxylate, also referred to as co-polymers. Normal dosage is in the range 1-7 kg/m^3. [Jacobsen et. al., 2012]

For these experiments the SP used is Sika ViscoCrete RMC-420. Recommended normal dosage for this co-polymer is 0.2-2.0 % of cement weight. Density is 1.04 ± 0.02 kg/l and total dry matter content of 18 % ± 1 %. From trials for these experiments 0.4 % of cement weight is used in the mortar and 0.8 % in the concrete.

3.4 Fibres

Experience and experiments shows that a large amount of fibre is not beneficial, especially with longer fibres, regarding stability and homogeneity. Too much fibre leads to fibre balling, meaning the fibre gets hooked to each other causing poor dispersion. Both steel and polypropylene are normal materials in fibres for concrete. Steel fibre of type Dramix 65/60 is used for these experiments. Three different amounts of fibre is used; 0, 1 and 2 vol-% of the mortar. After adding the coarse aggregate the percentage volume is reduced as the amount remains the same.

3.5 Aggregates

The quality of the aggregates is of big importance in combination with cement. The water demand of the aggregate influences the need of cement. When using aggregate with low water demand, the amount of cement can be reduced without affecting the strength class or mass ratio. This means it can be economically profitable to invest in quality aggregates to save expenses on cement. [Jacobsen et.al., 2012]

It is of big importance that the grain size distribution is as consistent as possible in all test batches to ensure comparable results. To make a grading curve for all aggregates used is not realistic for use in the industry, or for research purposes. A representative sample of each aggregate is taken to make a grading curve to be used in computations. The most decisive factor regarding the aggregate is the content of fines. Since the coarse aggregate is washed, the content of fines in these is negligible. However, the content of fines in the aggregate 0-8 mm is essential when it comes to the composition of the matrix. The elaboration of the grading curves including fines in aggregate is explained in 0.

The choices regarding composition of the aggregates in these tests are based on results of packing density simulations done by Skjølsvik in his project [Skjølsvik, 2010]. His work explores the composition of Årdal aggregates in the ranges 0-8, 8-11 and 11-16 mm and which combination gives the best packing. The best packing is achieved with a large content of fine aggregate (0-8 mm) in combination with a good dispersion of grain sizes. In these tests the mix of aggregates will be kept constant as we vary the amount of matrix and fibre. The best combination of aggregate in terms of packing varies with different amount of fibre, so this cannot be optimized for all concrete mixes. The combination of amounts is chosen to be as shown in Table 3.3.

Table 3.3 *Composition of aggregates*

Årdal 0.125-8 mm	Årdal 8-11 mm	Årdal 11-16 mm
60 %	16 %	24 %

Note that the 60 % of the particles consisting of 0-8 mm does not include fines, thus it reads 0.125-8 mm.

The grading curves used for the proportioning and calculations for this thesis is shown in Figure 3.1, Figure 3.2 and Figure 3.3.

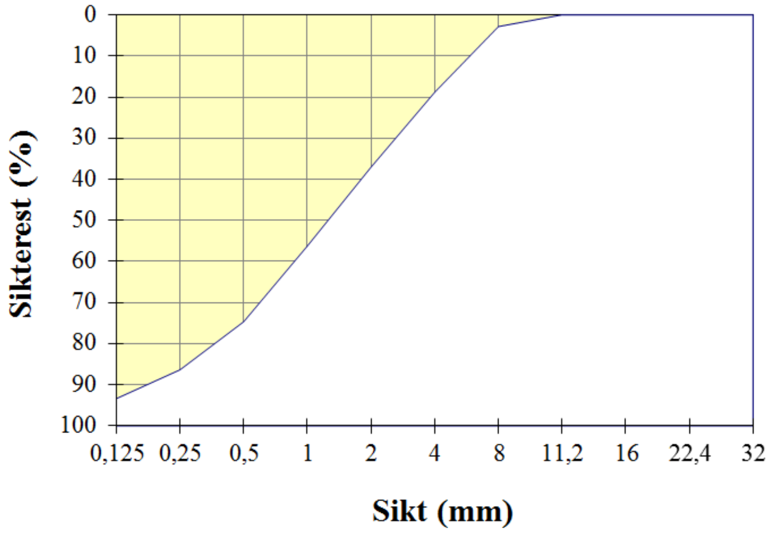


Figure 3.1 *Grading curve for 0-8 mm aggregate*

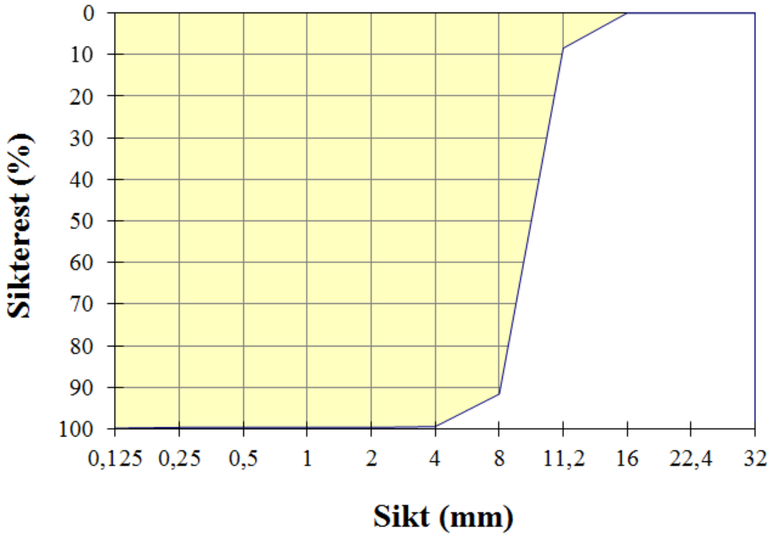


Figure 3.2 *Grading curve for 8-11 mm aggregate*

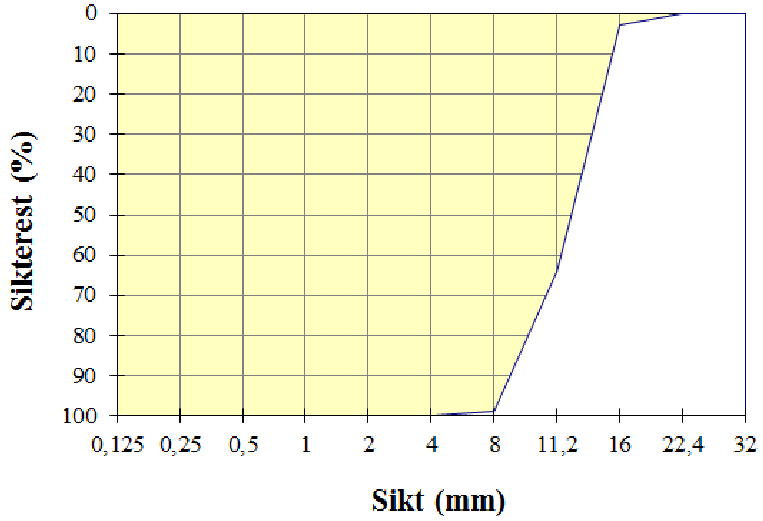


Figure 3.3 *Grading curve for 11-16 mm aggregate*

3.5.1 Fines in Aggregate

In order to get good results regarding the variation of few variables in the experiments, the other parameters need to be as constant as possible.

The variable that is hardest to keep constant, relative to its importance, is the grading of the fine aggregate. This concerns sand with a size range of 0-8 mm.

This thesis aims, among other things, to find how the amount of matrix affects the rheology of fresh concrete. In order to do that, it is important to be able to control the amount of matrix. The main assumption is that the matrix phase includes all particles smaller than 0.125 mm, including from the aggregate. This part of the sand is referred to as fines. To be able to control the matrix volume, the amount of fines in the aggregate should be known.

However, controlling every bit of aggregate would not be beneficial for the industry, nor for research purposes, because it is a time consuming activity. A fair alternative is to take samples of the sand finding a representative value of fines to be used when planning the experiments, and also in the computations. To find a representative grading curve, four samples of the sand is tested. Three are taken from different corners of the batch, while the fourth (Sample 1) is mixed homogenized (spun around in a barrel for about 5 minutes for the different grain sizes to be equally dispersed) sand from the same batch. By comparing these results, it is possible to see how the difference in grading of sand may affect the matrix volume, and get a clue on whether homogenizing of aggregate is critical when making a grading curve.

3.5.2 Importance of the Grading Curve

The grading curve of aggregate shows the distribution of the grain size in the aggregate. It is known that the variation of distribution affects the packing of the aggregate and thereby the concrete, but not to which extent. It is not possible to make a complete overview of the aggregate, so we depend on a representative grading curve to get good results. To quantify how big influence it has that the aggregate can differ from the grading curve to be used, four different grading curves are made for comparison. The samples are taken from different places in the batch of 0-8 mm aggregate. The grading curves from the samples are applied to the worksheet 'CPM-regneark' (Appendix E) one by one. All other variables are kept constant while the grading curve is varied.

The reference mortar and concrete is used as an example to analyze the affect from differing aggregate. Since the CPM-worksheet does not take into account the air in the concrete, the air is assumed to be part of the matrix. The reference mortar contains 500 l matrix and 1 vol-% fibre. Assumed air content for this mortar is 4.5 %, i.e. the matrix volume is 545 l/m^3. To get the right combination of matrix volume and fibre $k = \frac{1-\varphi}{1-\varphi_m} = 2.163$ is found to give the planned composition of the mortar. The high k-value is caused by the high matrix volume in the mortar and the assumption that the air volume is part of the matrix. For the corresponding concrete k=1,810 gives the right value of 0.77 % of fiber and 420 liters of matrix (Values from Table 4.3).

3.6 Air

The volume of air in the concrete is important for the rheology of the fresh concrete and for the strength of the hardened concrete. If the air content increases from 2-5 vol-% (30 l/m^3), it can affect the workability the same way increasing the matrix volume with 15 l/m^3 would have done [Norsk Betongforening, 2007]. But the amount and the effect of different amount of air in concrete is hard to predict.

NS-EN 206-1 (2007) provides guidelines for the accepted air content in concrete in Norway, saying the air content should be within 4-8 vol-%.

For calculations based on the particle-matrix model it is important to decide how to relate to the air. It can be considered as particles or part of the matrix phase. Planning of casting with a particular amount of matrix, as in this thesis, is difficult if considering air as part of the matrix, because the air content cannot be predicted. However, the air pores will fill the void in the particle phase just like matrix does.

3.7 Matrix Composition

The basis of matrix chosen for experiments:

- Requirement from NS-EN 206-1 (2007) for SCC for water/binder-ratio:

  $$\frac{w}{b} = \frac{w}{c + \sum kp} \leq 0.6$$

  With a low water/binder-ratio we need a larger matrix volume. Also, reduced w/b-ratio contributes to increased stability.
- Jacobsen et.al. recommends:

  $$\frac{water}{powder} - ratio = [0.30 - 0.45]$$
- Matrix volume is usually in the range 330-360 l/m^3 depending on the void volume in the particle phase [Jacobsen et.al., 2012]
- Air void content should not exceed 5 %, and is usually 2-3 % in concrete and higher in fibre-reinforced concrete. [Jacobsen et.al., 2012]

4 Experimental

In this chapter you will find a description of the experiments and calculations that are carried out with fresh concrete. The tests include use of 4C-rheometer and LCPC-box. In addition to the physical tests several calculations are carried out with the worksheet 'CPM-regneark' (Appendix E) [Berg, 2007/2008] corresponding to the mixes from the tests. The basis for the mixes is a mortar containing 450-550 l/m^3 of matrix and 0-2 vol-% of fibres. The same mortars are used for concrete by adding coarse aggregate. The numbering of the mortar is shown in Table 4.1.

Table 4.1 *Numbering of mortar*

fibre Matrix l/m^3	0 %	1 %	2 %	
450	1	2	3	
500	4	5	6	
550	7	8	9	
Air content	3 %	4.5 %	6 %	Assumed values

4.1 Basics for the Experiments

To get workable results from the experiments we need a basic recipe for concrete, with only matrix and fibres as variables. By keeping it basic and only vary one parameter at a time, the tests will hopefully give clear results showing how this parameter affects the properties of the fresh concrete.

The composition of the matrix is kept constant; meaning the relationship between fines, paste and cement is kept constant, (see Section 3.7). The composition of the aggregate is also kept constant, (see Section 3.5). The experiments are run first for a mix of mortar containing matrix, 0-8 mm aggregates, fibre and a small amount of co-polymers. Then the tests are run again after adding coarse aggregate with grains larger than 8 mm and some additional co-polymers.

The specific mixture of each batch of concrete is found by use of the worksheet 'Proporsjonering' (Appendix C) [Smeplass, 2004]. The wanted content of matrix and fibre, as well as assumed air volume is entered, along with values for density, damp and water absorption for the aggregates. The $\frac{w}{c+\sum kp}$-ratio is chosen to be 0.49, which for the chosen mixes gives a $\frac{water}{powder}$-ratio of 0.41. The amount of matrix in the mortar varies from 450–550 l/m^3, and for the concrete between 334-441 l/m^3.

4.1.1 Composition of Concrete

When executing the experiments, the tests are done twice for every variable, before and after adding coarse aggregates. The mixture containing only matrix, fibre and 0-8 mm aggregates is referred to as mortar. After adding aggregates larger than 8 mm the mix is defined as concrete. The experiments are carried out by first making a basic mixture of mortar and concrete, and then vary the amount of matrix and fibre.

For the reference mortar the amount of matrix (excluding air voids) is chosen to be 500 l/m^3, the amount of fibre is chosen to be 1 vol-% (10 l/m^3) and the content of air is assumed to be 4.5 vol-% (45 l/m^3). With these chosen values the amount of fine aggregate (particles in the size range 0.125 – 8 mm) in the mortar is 1000-500-10-45=445 l/m^3. Note that the fines (described in Section 0) in the 0-8 mm aggregate are considered as part of the matrix. The relationship between fine and coarse aggregate is 60/40; After completing tests with the mortar 297 l aggregate is added by 119 l 8-11 mm and 178 l 11-16 mm. After adding the coarse aggregates the matrix-, fibre- and air content is changed. The new values are listed in Table 4.3. They are found by the following approach:

Matrix in concrete: $$V_{m,concrete} = \left(\frac{V_{m,mortar}}{V_m+V_f+V_{air}+V_{0-8}+V_{8-11}+V_{11-16}}\right) * 1000$$

Fibre in concrete: $$V_{f,concrete} = \left(\frac{V_{f,mortar}}{V_m+V_f+V_{air}+V_{0-8}+V_{8-11}+V_{11-16}}\right) * 1000$$

Air in concrete: $$V_{air,concrete} = \left(\frac{V_{air,mortar}}{V_m+V_f+V_{air}+V_{0-8}+V_{8-11}+V_{11-16}}\right) * 1000$$

Mark that these formulas do not take SP into account, hence they are not accurate, and are not the ones being used for planning the experiments. They are shown to demonstrate the principle for finding the new amount of constituents in the concrete. The correct values are found by use of the worksheet 'Amount constituents' (Appendix D).

***Table 4.2** Theoretical composition of mortar*

No.	Matrix l/m^3	fibre		Air		0.125-8 mm
		Vol-%	l	Vol-%	l	l
1	450	0	0	3	30	520
2	450	1	10	4.5	45	495
3	450	2	20	6	60	470
4	500	0	0	3	30	470
5	500	1	10	4.5	45	445
6	500	2	20	6	60	420
7	550	0	0	3	30	420
8	550	1	10	4.5	45	395
9	550	2	20	6	60	370

After doing tests on the rheology of the mortar, coarse aggregate is added to the mixtures so the relationship between fine and coarse aggregate is 60/40, coarse aggregate implies 8-11 and 11-16 mm. This gives a new total amount of the mix and thus a new percentage of the components of the concrete. The concrete compositions are shown in Table 4.3.

***Table 4.3** Theoretical composition of concrete*

No	Matrix	Fibre		Air		0.125-8 mm	8-11 mm	11-16 mm
	l/m^3	Vol-%	l/m^3	Vol-%	l/m^3	l/m^3	l/m^3	l/m^3
1	334.2	0	0	2.228	22.28	386	103	155
2	338.3	0.752	7.52	3.383	33.83	272	99	149
3	342.6	1.523	15.23	4.569	44.69	358	95	143
4	380.7	0	0	2.284	22.84	358	95	143
5	386.1	0.771	7.71	3.470	34.70	343	92	137
6	390.6	1.563	15.63	4.688	46.88	328	88	131
7	429.7	0	0	2.344	23.44	328	88	131
8	435.4	0.792	7.92	3.562	35.62	313	83	125
9	441.2	1.604	16.04	4.813	48.13	297	79	119

4.1.2 Applicable Tests

The Eurocode [NS-EN 12350, 2009/2010] gives plenty of tests that are suitable to get relevant information about self-compacting concrete, see Table 4.4.

The purpose of this thesis is to compare certain parameters to rheology, so the adequate tests are the ones that give viscosity (η) and yield stress (τ). In addition slump-flow is measured to determine to what extent the concrete is in fact self-compacting, and for visual evaluation.

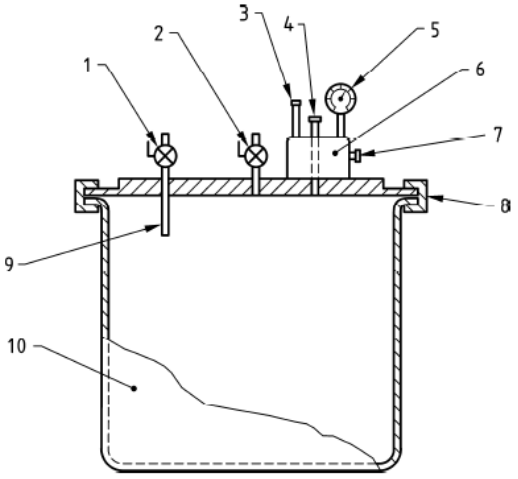
Table 4.4 *Applicable tests for SCC [NS-EN 12350, 2009/2010] and [Roussel, 2007]*

Properties	Method	Procedure
Air content	Pressure methods	NS-EN 12350-7
Flow ability	Slump-flow test	NS-EN 12350-8
Viscosity	T_{500}, slump-flow time	NS-EN 12350-8
Viscosity	V-funnel	NS-EN 12350-9
Passing ability	L-box	NS-EN 12350-10
Segregation	Sieve (Segregation resistance)	NS-EN 12350-11
Passing ability	J-ring test	NS-EN 12350-12
Yield stress	LCPC-box	Nicolas Roussel
Stability/Homogeinity	Visual evaluation	See Section 5

Air Content

The air content is measured by using the pressure gauge method as described in NS-EN 12350-7 (2009). However it is important to know the air content when transferring the measured results to the worksheet CPM-worksheet because the air is assumed a part of the matrix. The equipment for measuring the air is shown in Figure 4.1.

Before starting, calibration of the apparatus has to be done. Regarding SCC the container is to be filled in one operation, and no mechanical compaction is added. The pressure gauge gives a value for apparent air content.



1 Valve A
2 Valve B
3 Pump
4 Main air valve
5 Pressure gauge
6 Air chamber
7 Air bleeder valve
8 Clamping device
9 Extension tubing for calibration checks
10 Container

Figure 4.1 *Pressure gauge method apparatus [NS-EN 12350-7, 2009]*

Slump-flow Test

The flow ability is of big importance. We need to know that the slump-flow measures at least 650 mm to make sure the concrete is in fact self-compacting. This test is done using the 4C-rheometer. This equipment also tells us the flow rate by measuring the time the concrete uses to reach flow of 500 mm, which is the T_{500}. The test is executed in accordance with NS-EN 12350-8 (2010).

LCPC-box

The LCPC-box is, next to 4C-rheometer, a way to find the yield stress. The usual way to find yield stress is from the slump-flow, but when dealing with SCC this has been shown to give rather imprecise values. By using the LCPC-box the concrete is channelized instead of flowing in all directions. This gives more precise values. The geometry of the LCPC-box is shown in Figure 4.2.

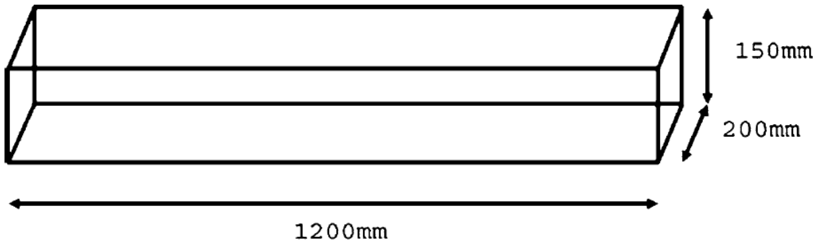


Figure 4.2 *Geometry of the LCPC-box [Roussel, 2007]*

6 liter concrete is poured in one end of the box in a given speed so that it takes about 30 seconds to pour all the concrete in the box. By measuring the spread length the concrete reaches in the box, the graph in Figure 4.3 is used to find the SCC’s yield stress. When the concrete in the LCPC-

box gives a flow length of 480 mm or less, this method does not give a value for the yield stress, as shown on the graph. Also, a yield stress higher than 60 Pa does not correspond to self-compacting concrete.

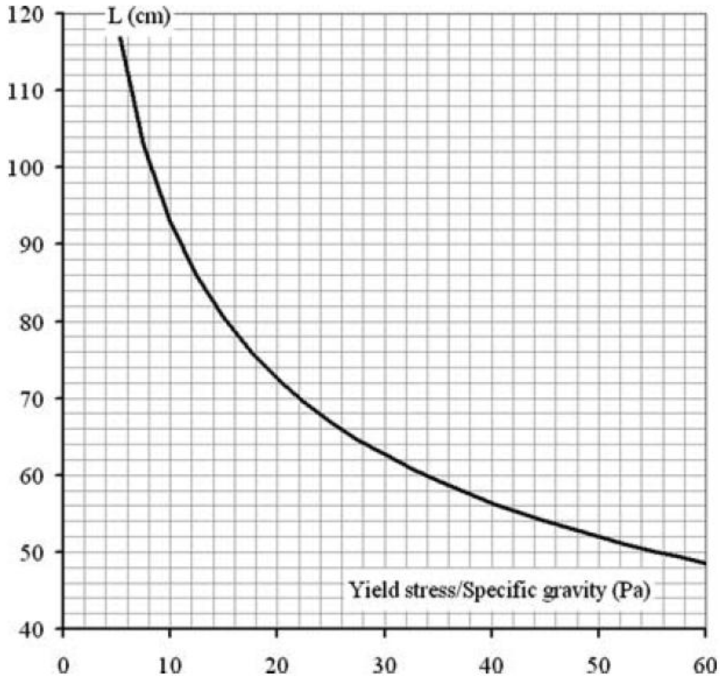


Figure 4.3 *Correlation between spread length L and yield stress for SCC in LCPC-box [Roussel, 2007]*

Visual registration

It is a requirement that the mortar and concrete does not separate. Separation includes bleeding (separation of water), paste separation, segregation (mortar- or coarse aggregate separation) and fibre balling. The mixture has to be homogeneous in order to be satisfactory for usage, i.e. all the constituents has to be evenly dispersed. These requirements are verified by visual registration when testing the slump-flow (SF), by evaluating the occurrence of fibre balling and matrix separation.

4.2 Execution of Tests

The procedure for the tests is the following: First the mortar is mixed; Dry matter is mixed together, that is, aggregate 0-8 mm, fines and cement. Water is poured in steadily and then 0.4 % of cement weight super plasticizer is added. In the mixes where fibre is added these comes last in the mix of the mortar. After waiting for two minutes for the SP to take effect the tests are carried out.

First the density is measured by weighing one liter of mortar. Then a six liter bucket is filled with mortar to be poured in the cone in the 4C-rheometer. At the same time the bucket for measuring the air content is filled up. The measuring of air happens simultaneously as the tests with 4C-rheometer and the LCPC-box. After running the 4C-rheometer, manual measurements of slump-flow are noted. The mortar from the 4C-rheometer is gathered back in the six liter bucket and reused for the LCPC-box. After measuring the flow in the box all the mortar is poured back into the mixer as thoroughly as possible. At this point the coarse aggregate is added including additional 0.4 % of cement weight SP, so that the concrete contains a total of 0.8 % of cement weight SP. After leaving the mix for two more minutes while cleaning the equipment for testing, all the same test are run for the concrete in the same way and same order of events as for the mortar. In Figure 4.4 you can see an example of how the results from the 4C-rheometer are shown.

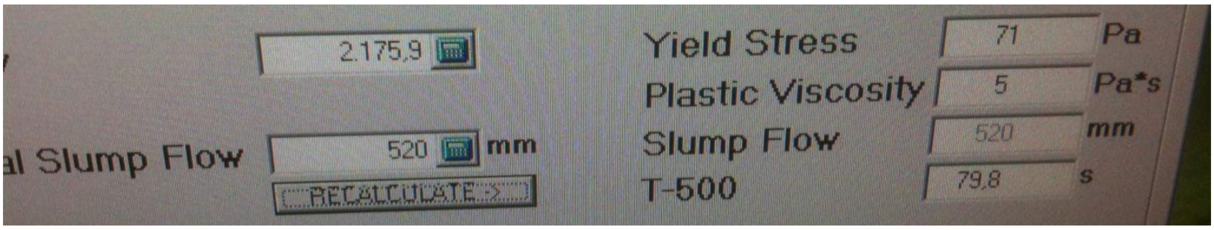

2.175,9
al Slump Flow 520 mm
Yield Stress 71 Pa
Plastic Viscosity 5 Pa*s
Slump Flow 520 mm
T-500 79,8 s

Figure 4.4 *Example for results from 4C-rheometer*

4.3 Computations

The parameters thickness of fibre lubricating matrix around fibres (t_c), fibre rotational overlap (N_{cs}) and maximum packing density (Φ_m) is computed using the program 'CPM-regneark' (Appendix E)[Berg, 2008]. There are several parameters that need to be considered using this program.

- Compacting factor, K
- Factor for increase of the matrix volume, $k = \frac{1-\varphi}{1-\varphi_m}$
- Limit matrix-particle phase
- Value of X in $\frac{d_p}{X}$, limit for particle size

Berg 2008 has done experiments and calculations to find the best approximation to the value of the compacting factor K, when using the CPM-worksheet. Bergs thesis concludes that for comparison of mixtures with and without fibre, 4.75 is the best value for K, thus this thesis will use $K = 4.75$ in all computations.

The factor for increase of matrix volume k, is the ratio between matrix volume fraction and particle void space at maximum packing. This parameter relates to the maximum packing fraction (Φ/Φ_m) and is useful for proportioning since the cement content (m_c) can be calculated based on w/c-ratio from it:

$$m_c = \frac{(k(1-\Phi_m)V_{tot} - V_{air})}{(\frac{1}{\rho_c} + \frac{1}{w/c})}$$

By measuring or calculating Φ_m, assuming air void content, knowing the cement density and selecting w/c-ratio from design criteria for strength and durability, k can be found from experience and trial mixing based on constant consistency, constant admixture dosage or some other suitable experimental proportioning procedure.

In this thesis the k-factor is used to manipulate the wanted matrix volume to match the amounts of components found in the worksheet 'Amount constituents', (Appendix D) which is used to plan the amount of coarse aggregate to be added to the mortar.

The limit value for which particles are part of the lubricating mass around the fibres is denoted $\frac{d_p}{X}$. If replacing one fibre with a spherical particle, d_p is the diameter the sphere would have to affect the packing density equally as the fibre. The lubricating mass in this thesis is mainly calculated and assumed to be the matrix, i.e. $\frac{d_p}{X} = 0.125$ is the same value as the limit for matrix-particle phase. For comparison, calculations of matrix volume and t_c are also done where the lubricating mass consists of particles up to the same size as the diameter of the fibers, i.e. 1.0 mm. To do this in the CPM-worksheet, the limit particle-matrix phase and $\frac{d_p}{X}$ is set for 1.0 mm. d_p for the fibres is 26.113, thus X is set for 209 for $\frac{d_p}{X} = 0.125$ and 26.1 for $\frac{d_p}{X} = 1.0$.

The CPM-worksheet does not take into account the air volume in the mixtures, thus the calculations are not realistic. Nevertheless the air volume has to be considered, as its assumed value constitutes up to 6 % of the volume of the mortar, and the measured values might be even higher. Since the experiments in this thesis is based on chosen values for matrix volume, fibre volume and air volume in mortar, a separate worksheet, ‘Amounts constituents’, is produced to calculate the amounts of the components taking into account an assumed amount of air. When using the CPM-worksheet it is assumed that the air volume is a part of the matrix. In practice this means that if in the worksheet ‘Proporsjonering’, the matrix volume is 380 l/m^3 and the air volume is assumed to be 3 vol-% (30 l/m^3), in the CPM-worksheet the value for matrix volume for the same mixture will be 410 l/m^3.

For the calculations, values for matrix volume from the tests are used as a basis. These values are calculated with ‘Amounts constituents’ based on corrected values from ‘Proporsjonering’ after entering the measured air content and density.

When running the calculations in the CPM-worksheet, the value for k is adjusted to match the matrix volume and amount of fibre from the tests.

4.4 Sources of Error

Experiments like the ones executed for this thesis can never be completely reliable. One must always assume that human error may occur regarding the handling of materials and equipment. Also the equipment itself may not be calibrated. All experiments are based on worksheets. For this to be reliable it is required that the presumptions that form the basis for the programming are correct and that the worksheets are handled correct. None of these can be guaranteed for.

An addition of possible sources of error for the experiments in specific are listed last in Appendix B.

5 Results

For a mortar or concrete to be accountable it has to be homogeneous. The homogeneity is evaluated based on fiber balling and matrix separation. In the tables this is expressed by Visually Homogeneous (VH) or Visually Inhomogeneous (VI). Table 5.1 and Table 5.2 show the results from the experiments.

***Table 5.1** Results for experiments with mortar*

Matrix l/m^3 (excl. air)	fibre	0 %	1 %	2 %
450	Homogeneity	VH	VI	VH
	Slump-flow	(low)	420 mm	330 mm
	T_{500}	-	-	-
	Air content	4.2 %	7.5 %	10 %
	Pl. viscosity (μ)	-	25	0
	Yield stress (τ) (LCPC/4C)	-	-/193	-/502
500	Homogeneity	VH	VH	VI
	Slump-flow	565 mm	443 mm	350 mm
	T_{500}	-	-	-
	Air content	1.5 %	3.4 %	8.0 %
	Pl. viscosity (μ)	24	28	0
	Yield stress (τ) (LCPC/4C)	-/50	-/159	-/438
550	Homogeneity	VH	VI	-
	Slump-flow	518 mm	495 mm	
	T_{500}	4.1	(2.9)	
	Air content	1.2 %	2.2 %	
	Pl. viscosity (μ)	19	21	
	Yield stress (τ) (LCPC/4C)	49/74	60/94	
	Assumed air content	3 %	4.5 %	6 %

The mortar and concrete number 1, 4, 5 and 7, and to some extent 2, are satisfactory, thus these are the ones being considered for further investigation. Results and calculations for the non-accepted mixes are also shown for comparison, but in a greyscale. Due to the bad results regarding stability for the mixes 6 and 8, a decision was made not to go through with mix number 9. It was expected to be subject for serious separation and fiber balling, and would not have given useful results.

***Table 5.2** Results for experiments with concrete*

Matrix l/m^3 (excl. air)	Fibre	0 %	0.75-0.79 %	1.52-1.60 %
334 - 343	Homogeneity	VH	VI	VI
	Slump-flow	590 mm	600 mm	520 mm
	T_{500}	5.8 s	3.2 s	-
	Air content	1.3 %	5.2 %	11 %
	Pl. viscosity (μ)	141	89	5
	Yield stress (τ) (LCPC/4C)	49/43	54/37	-/71
381 - 391	Homogeneity	VH	VH	VI
	Slump-flow	720 mm	650 mm	530 mm
	T_{500}	1.5 s	2.8 s	5.5 s
	Air content	0.6 %	4.4 %	7.5 %
	Pl. viscosity (μ)	22	62	161
	Yield stress (τ) (LCPC/4C)	22/14	47-60/26	-/66
430 - 441	Homogeneity	VH	VI	-
	Slump-flow	705 mm	700±50 mm	
	T_{500}	3.2 s	2.7 s	
	Air content	0.8 %	1.8 %	
	Pl. viscosity (μ)	59	49	
	Yield stress (τ) (LCPC/4C)	12-22/17	15-38/18	

The worksheet 'Proporsjonering' (Appendix C) [Smeplass, 2004] gives corrections for the amounts of constituents after measuring the achieved air content and density. These corrections give different matrix volumes than what is planned for. The values and correlations discussed in this thesis are based on this method for correcting the values in the mixes. The procedure for the corrections is as follows, where ε_{air} is air volume and ρ is density:

- Volume corrected for air content is found:

$$V_{concrete} = (1 - \varepsilon_{air,theor} + \varepsilon_{air,measured})$$

- Mass of each constituent in 1 m^3 concrete is corrected for measured air content

$$m' = m * \frac{1}{(1 - \varepsilon_{air,theor} + \varepsilon_{air,measured})}$$

- Corrected mass for all constituents are added together to find the density corrected for the measured air content

$$\sum m' = \rho'_{concrete}$$

- Mass of each constituent in 1m^3 concrete is corrected for measured density

$$m'' = m' * \frac{\rho_{concrete,measured}}{\rho'_{concrete}}$$

- Corrected mass for all constituents are added together to find the final density corrected for the measured density

$$\sum m'' = \rho''_{concrete}$$

The new values for matrix volume are shown in Table 5.3, with and without air as part of the matrix. To make the connection clearer, the air volume is listed as well.

Table 5.3 *Matrix volume in mortar and concrete corrected for measured air content and density. All values in liter.*

	$V_{air,}$ mortar	$V_{m,\ mortar}$ incl. air	$V_{m,\ mortar}$ excl. air	$V_{air,}$ concrete	$V_{m,\ concrete}$ incl. air	$V_{m,}$ concrete excl. air
1	**42**	**498**	**456**	**13**	**348**	**338**
2	**75**	**504**	**429**	**52**	**362**	**323**
3	100	517	417	110	401	318
4	**15**	**531**	**516**	**6**	**397**	**393**
5	**34**	**547**	**513**	**75**	**454**	**396**
6	80	566	486	75	439	380
7	**12**	**582**	**570**	**8**	**452**	**445**
8	22	607	585	18	477	463

The variation in the amount of the components has occurred mainly as a result of varying amount of air compared to assumed value.

In Table 5.4 and Table 5.5 all relevant parameters for all mixes are shown, both measured in fresh concrete and calculated with the 'CPM-regneark' (Appendix E). The results are separated into mortar and concrete. To show which results are the most relevant, the quality of the mixes are expressed by occurrence of separation and fiber balling. They are both explained by following remarks: no mark: homogeneous, some=less homogeneous, yes=inhomogeneous.

The tables are divided into three sections. The first section shows the results from the experiments, including homogeneity, the amount of fiber and air, the rheological parameters and the corrected volume fraction of particles. The two last sections both show the matrix volume without and with air included in the matrix, calculated parameters from the CPM-worksheet and the resulting packing fraction. The difference between these two sections is the size which defines the limit particle-matrix phase. In the second section the matrix is defined according to the traditional particle-matrix model, i.e. with lubricating mass consisting of all particles smaller than 0.125 mm. The last section considers all particles smaller than 1.0 mm as part of the matrix phase. 1.0 mm is chosen because it is the size of sieve when grading the aggregate closest to the diameter of the fibers, which is 0.9 mm.

Table 5.4 Proportioning parameters and rheological properties for mortar

	1	2	3	4	5	6	7	8
Separation								yes
Fib.balling			some			some		yes
V_f [%]	0	0.95	1.86	0	1.03	1.95	0	1.06
$V_{air,assumed}$ [%]	3	4.5	6	3	4.5	6	3	4.5
$V_{air,measured}$ [%]	4.2	7.5	10	1.5	3.4	8	1.2	2.2
SF [mm]	Small	420	330	565	443	530	518	495
μ [*Pas*]	-	25	0	24	28	161	19	21
τ [pa]	-	193	502	50	159	66	74	94
$\Phi_{d<0.125mm}$	0.51	0.49	0.47	0.48	0.46	0.43	0.43	0.42
$\Phi_{d<1.0mm}$	0.31	0.30	0.29	0.29	0.28	0.27	0.26	0.25
d_p<0.125 mm								
$V_{m,excl.air}$	456	429	417	516	513	486	570	585
$V_{m,incl.air}$	498	504	517	531	547	566	582	607
$t_{c,f}$ [mm]		0.44	0.13		0.44	0.15		0.49
$N_{cs,ov,con}$		0.71	0.77		0.72	0.77		0.72
Φ_m	0.79	0.78	0.78	0.79	0.78	0.78	0.79	0.78
Φ/Φ_m	0.65	0.63	0.60	0.61	0.59	0.55	0.54	0.54
d_p<1.0 mm								
$V_{m,excl.air}$	665	617	591	709	695	649	743	752
$V_{m,incl.air}$	707	692	691	724	729	729	755	774
$t_{c,f}$ [mm]		0.68	0.25		0.66	0.25		0.68
$N_{cs,ov,con}$		0.71	0.77		0.72	0.77		0.72
Φ_m	0.79	0.79	0.78	0.78	0.78	0.78	0.79	0.78
Φ/Φ_m	0.39	0.38	0.37	0.37	0.36	0.35	0.33	0.32

Table 5.5 *Proportioning parameters and rheological properties for concrete*

	1	2	3	4	5	6	7	8
Separation	some	some	yes	some	some	yes	yes	yes
Fib.balling		some	yes		some	Yes		yes
V_f [%]	0	0.72	1.41	0	0.79	1.52	0	0.84
$V_{air,assumed}$ [%]	2.2	3.4	4.5	2.3	3.5	4.7	2.3	3.6
$V_{air,measured}$ [%]	1.3	5.2	11	0.6	7.5	7.5	0.8	1.8
SF [mm]	590	600	520	720	650	530	705	64-74
μ [Pas]	141	89	5	22	62	161	59	49
τ [pa]	43	37	71	14	26	66	17	18
$\Phi_{d<0.125mm}$	0.64	0.62	0.60	0.60	0.58	0.56	0.55	0.53
$\Phi_{d<1.0mm}$	0.48	0.47	0.46	0.46	0.44	0.43	0.42	0.41
$d_p<0.125$ mm								
$V_{m,excl.air}$	456	429	417	516	513	486	570	585
$V_{m,incl.air}$	348	362	401	397	454	439	452	477
$t_{c,f}$ [mm]		0.42	0.14		0.51	0.15		0.50
$N_{cs,ov,con}$		0.68	0.75		0.69	0.75		0.70
Φ_m	0.80	0.80	0.79	0.80	0.80	0.79	0.80	0.79
Φ/Φ_m	0.80	0.78	0.76	0.75	0.73	0.71	0.69	0.67
$d_p<1.0$ mm								
$V_{m,excl.air}$	494	464	450	540	536	507	581	595
$V_{m,incl.air}$	525	520	526	551	561	570	590	612
$t_{c,f}$ [mm]		0.70	0.25		0.67	0.25		0.70
$N_{cs,ov,con}$		0.68	0.75		0.69	0.75		0.70
Φ_m	0.80	0.80	0.79	0.80	0.80	0.79	0.80	0.80
Φ/Φ_m	0.60	0.59	0.58	0.58	0.55	0.54	0.53	0.51

Table 5.4 and Table 5.5 show that the maximum packing Φ_m is almost the same for all mixes, with a small decrease for the highest amount of fibers. The volume fraction of particles decreases as the matrix volume and amount of fibre increases, which is natural when other constituents forms a larger part of the concrete. This results in decreasing values for the maximum packing fraction. The correlation between the maximum packing fraction and the matrix volume is shown in Figure 5.1 to Figure 5.4. The graphs show that there is an almost linear relation between the maximum packing fraction and the matrix volume when considering the air volume as part of the matrix, while for the matrix that does not include air, the correlation don’t seem reliable. These results are valid for both cases, i.e. for standard particle-matrix model with limit 0.125 mm and when regarding the matrix phase as all particles smaller than 1.0 mm.

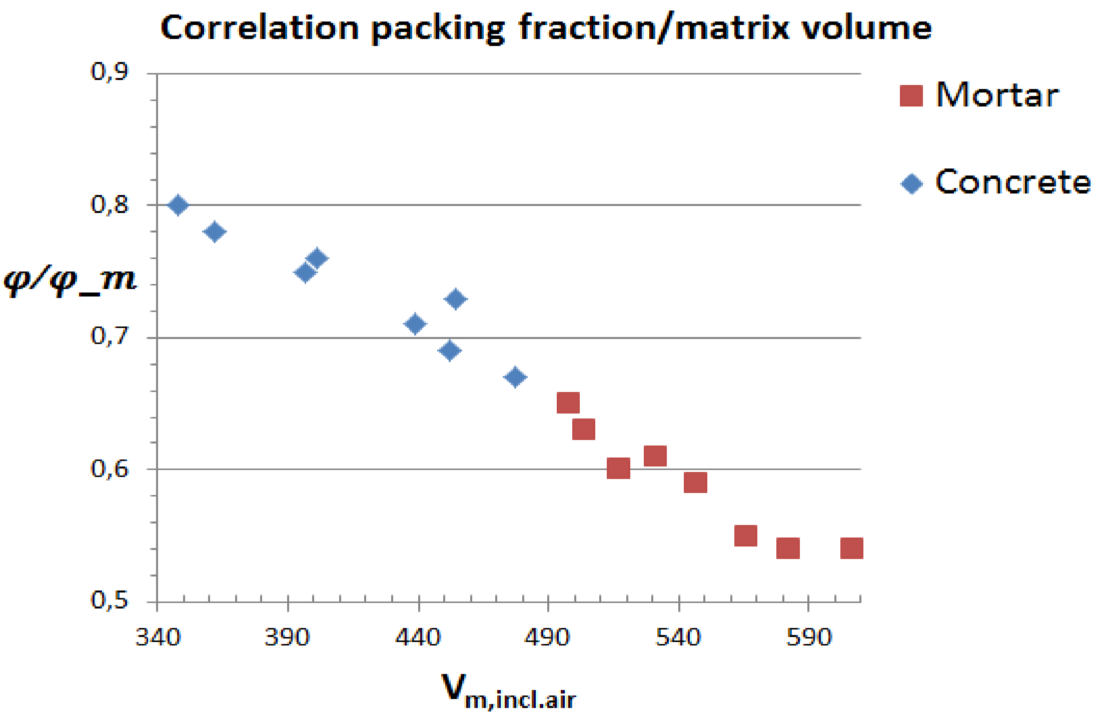


Figure 5.1 *Correlation between matrix volume and packing fraction. Particle phase includes all particles larger than 0.125 mm.*
Air volume is included in matrix volume.

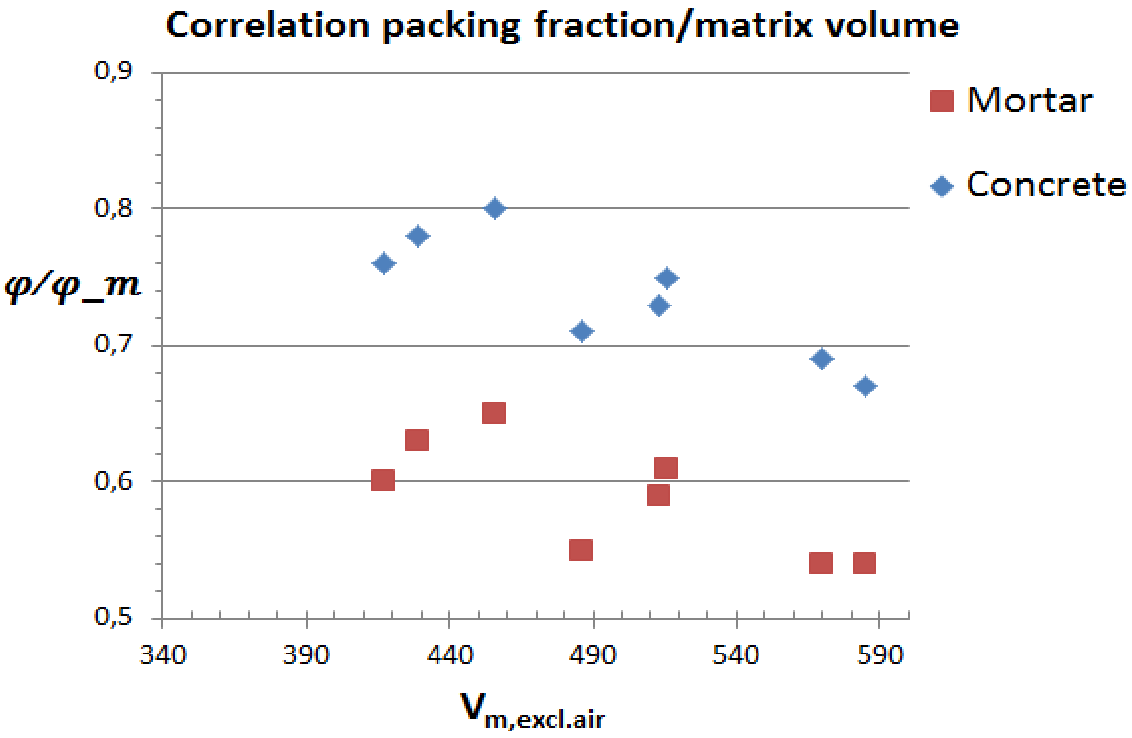


Figure 5.2 *Correlation between matrix volume and packing fraction. Particle phase includes all particles larger than 0.125 m.*
Air volume is not included in the matrix volume.

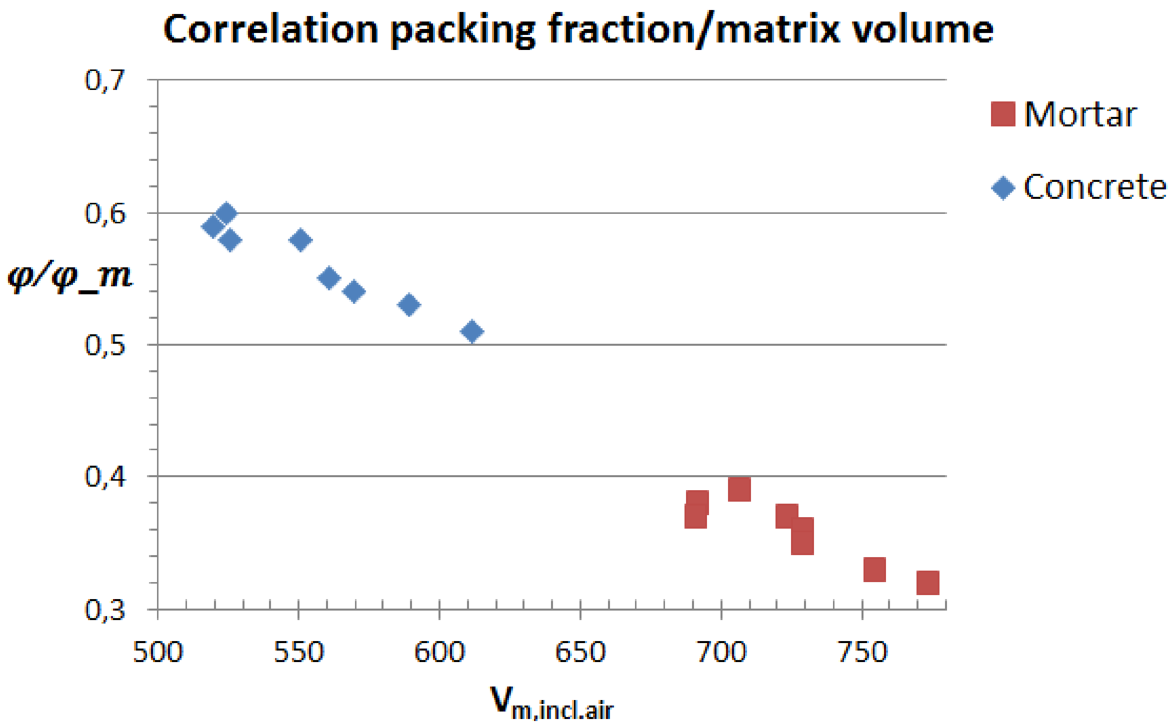


Figure 5.3 *Correlation between matrix volume and packing fraction. Particle phase includes all particles larger than 1.0 mm.*
Air volume is included in the matrix volume.

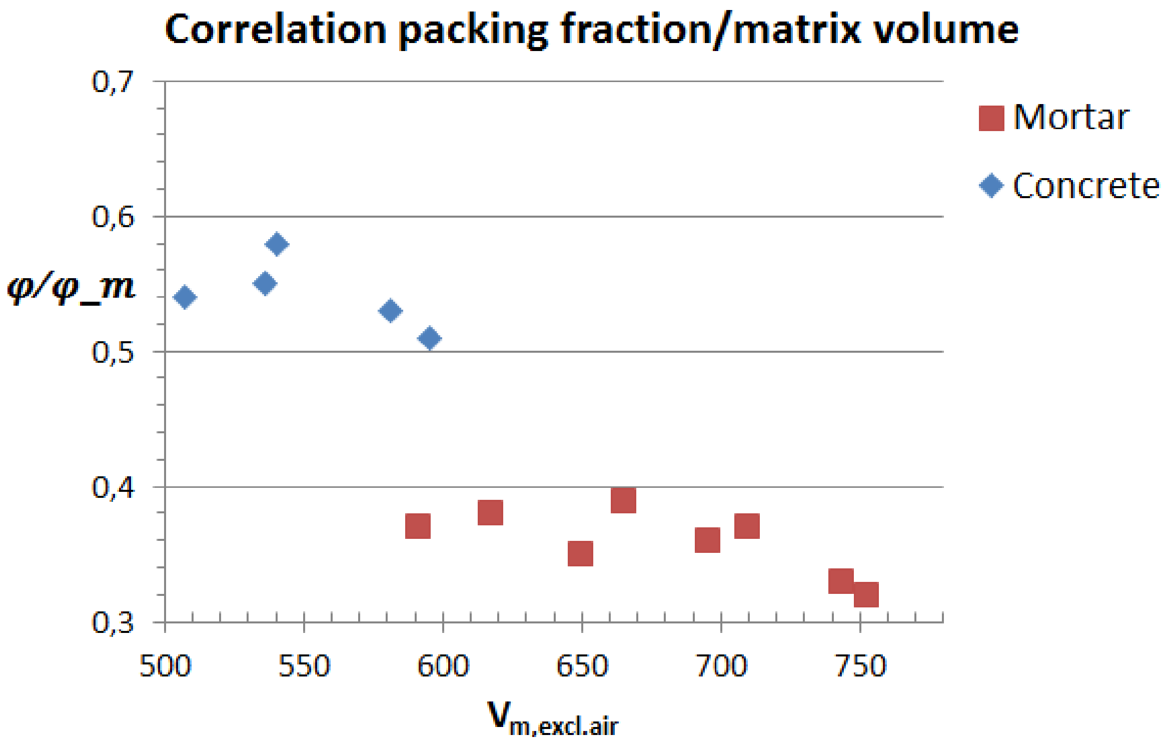


Figure 5.4 *Correlation between matrix volume and packing fraction. Particle phase includes all particles larger than 1.0 mm.*
Air volume is <u>not</u> included in the matrix volume

In general, there are some unexpected results regarding the air content in both mortar and concrete. The values vary over a broad span, and seem to be associated with the amount of fibre. For both mortar and concrete the air content increases with more fibre and mostly decreases with a larger matrix volume. The experiments make it seem legit that there is a correlation between these amounts of constituents. The possible correlation factor that is tried out here is ${V_m}^{0,7} + (55 * V_f)$. The result of this assumed correlation is shown in Figure 5.5.

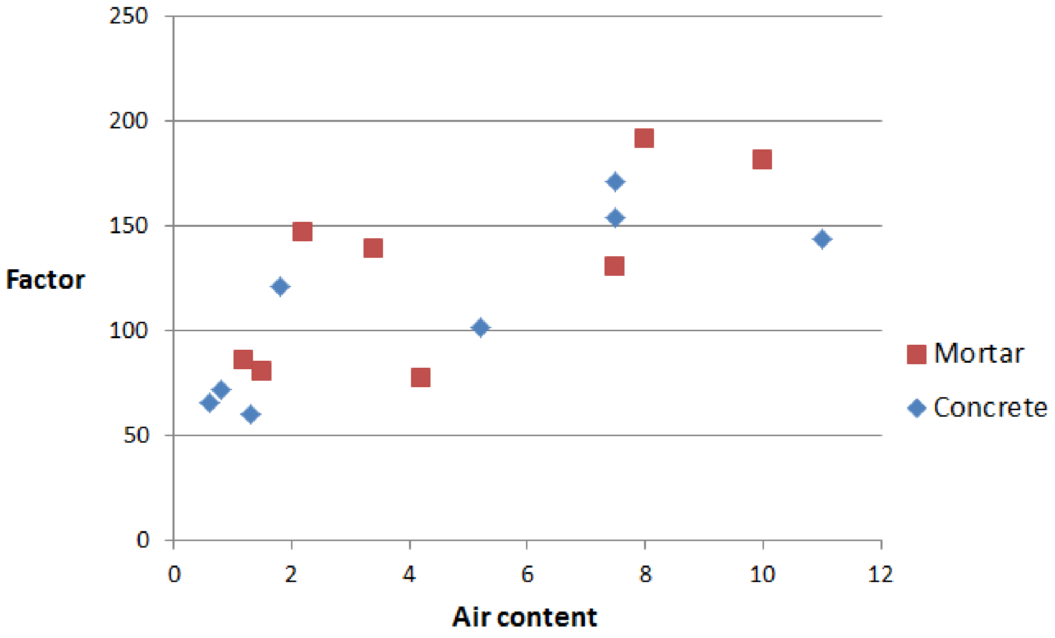


Figure 5.5 *Possible correlation between the amounts of matrix, fiber and air in concrete*

5.1 Comparison with Earlier Experiments

It would be advantageous to know whether these experiments correspond with earlier experiments about the same subject. The results executed for this thesis are to be compared with results from [Bui et.al., 2003], and are expected to be more or less corresponding. Bui et.al uses relative yield stress and relative plastic viscosity as a correlation factor. Relative here implies the relationship between measured values for concrete and mortar. The parameters are denoted differently in different places, so for clarification, the parameters are explained in Table 5.6. The mortar Bui et.al has used is of particles up to 4 mm, while the mortar in this thesis includes particles up to 8 mm. This means that the results are not completely comparable, but can still be used as an indication for the correlation. Bui et.al uses four different types of fibres of which none are the same as for the experiments in this thesis. They also use four different matrix compositions.

Table 5.6 Symbols as used by Bui et.al and in this thesis

	Bui et.al	Here
Yield stress concrete	σ_B	τ_c
Yield stress mortar	σ_{B^0}	τ_m
Relative yield stress	${\sigma_B}/{\sigma_{B^0}}$	${\tau_c}/{\tau_m}$
Pl. viscosity concrete	η_{pl}	μ_c
Pl. viscosity mortar	η_{pl^0}	μ_m
Relative plastic viscosity	${\eta_{pl}}/{\eta_{pl^0}}$	${\mu_c}/{\mu_m}$

Figure 5.6 and Figure 5.8 are examples of the correlations found by Bui et.al. (2003). All results show the same tendency, displayed with a consinous line. The graphs made by Bui et.al shows that the matrix thickness increases both for decreasing relative yield stress and for decreasing relative plastic viscosity. Figure 5.7 shows that the relative yield stress and matrix thickness follows the same tendencies in this thesis as for Bui et.al. (2003). However, Figure 5.9 does not show any clear tendendy at all. It lacks of resemplance with Figure 5.8, thus the results are not reliable. The following figures show that the resemblance might not be as expected.

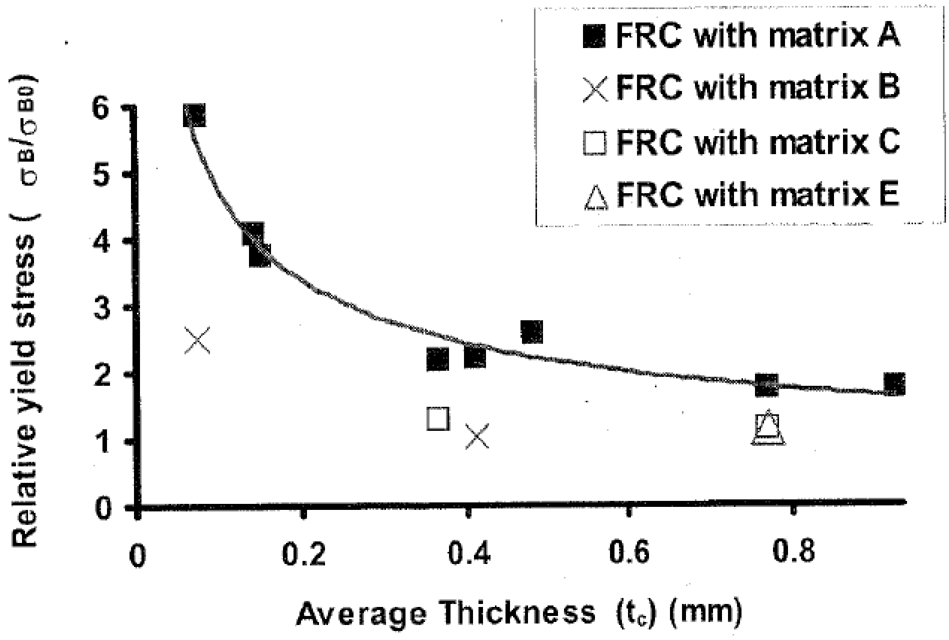


Figure 5.6 *Relative yield stress versus average of matrix thickness [Bui et.al, 2003]*

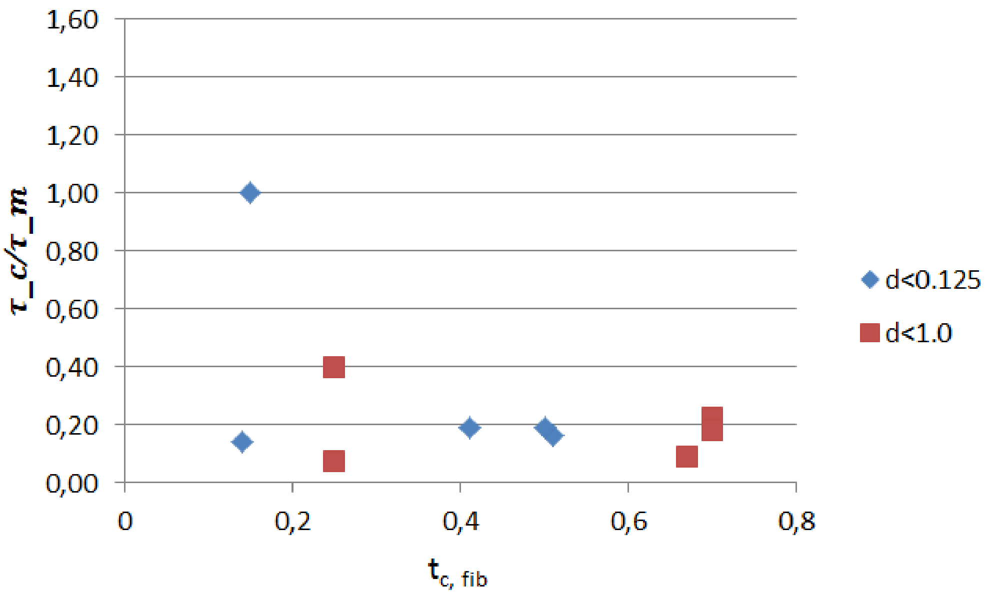


Figure 5.7 *Relative yield stress versus average of matrix thickness. Good resemblance with the results in Figure 5.6*

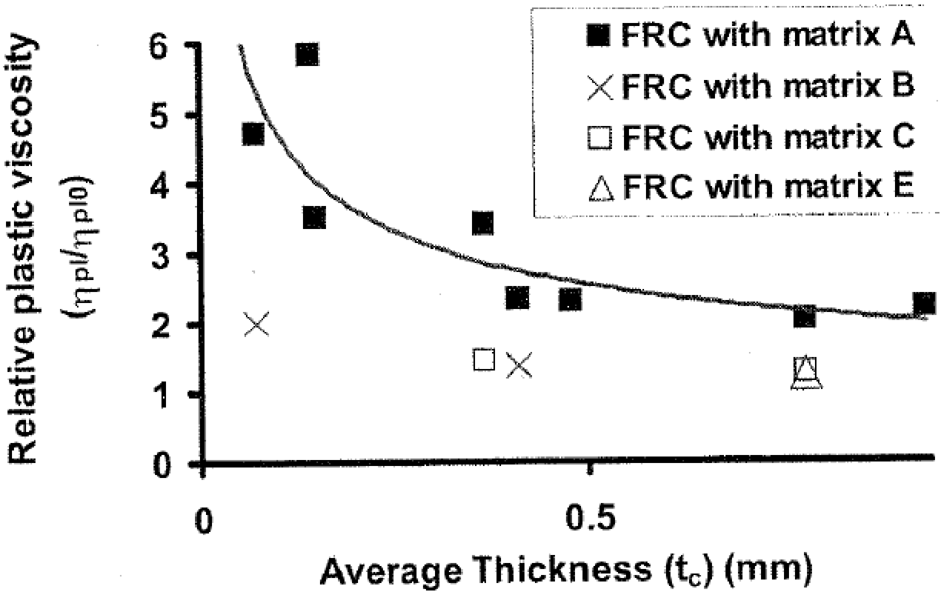


Figure 5.8 *Relative plastic viscosity versus average of matrix thickness [Bui et.al, 2003]*

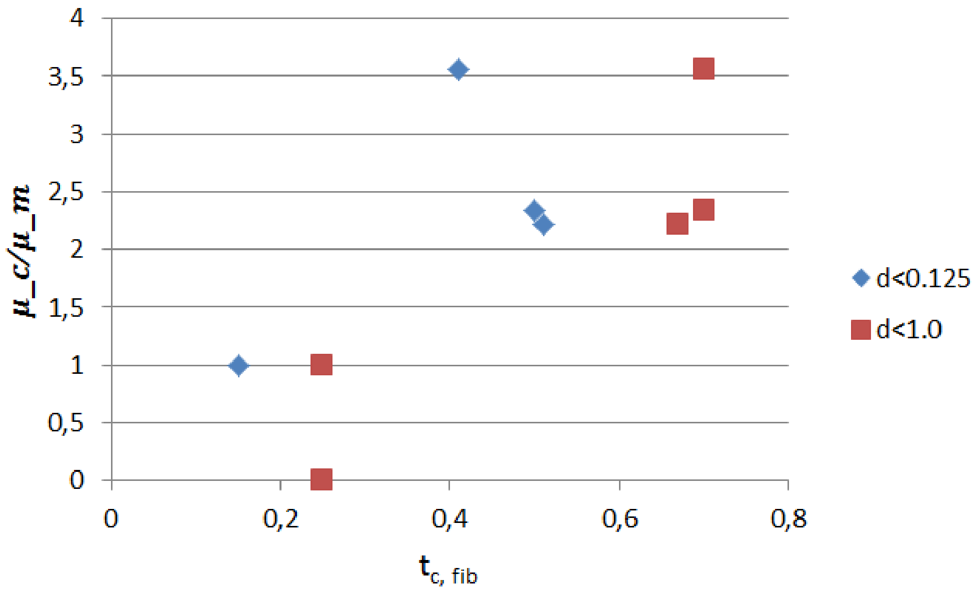


Figure 5.9 *Relative plastic viscosity versus average matrix thickness. No Resemblance with the results in Figure 5.8*

The lack of similarity regarding plastic viscosity might be caused by the lack of flow ability that several of the concrete mixes showed in the experiments. The used values for yield stress and plastic viscosity are from the 4C-rheometer, which is intended for homogeneous self-compacting concrete. Several of the mixes had too low measurements for slump-flow to qualify as self-compacting, or were subject for fiber balling and/or matrix separation. This might lead to unreliable values from the 4C-rheometer.

5.2 Exploration of Grading Curves

To know the importance of an accurate grading curve, tests are run with several different grading curves. The basis for, and execution of, the tests is explained in 3.5.

5.2.1 Fines in Aggregate

The different tests of fine aggregate gave very similar grading curves, thus the variation is small and has little effect on the matrix. The amount of fines varies from 6.6 % to 6.9 %. For 1 m^3 of fresh concrete with 450 l of matrix and 520 l of aggregate 0-8 mm, this difference (0.3 %) will be 1.56 l, i.e. 0.156 % of the concrete volume. When increasing the matrix volume, the amount of aggregate is consequently reduced and we need to add additional fines to keep control of the matrix volume and composition. If we begin with a concrete with 450 l of matrix and then increase the matrix volume to 500 l, we can see how the difference in amount of fines in the aggregate affects the need for additional fines:

With a 6.6 % amount of fines, 50 l increase of matrix volume results in the need for 7.62 l of additional fines. For comparison, when the amount of fines is 6.9 %, the need for additional fines is 7.99 l. Thus the amount of supplementary filler needed when increasing the matrix volume with 50 l increases with less than 5 % when the fines are increased from 6.6 to 6.9 % of the aggregate. These results are based on the demand for a constant relationship between fines (both part of sand and added) and paste in the matrix.

5.2.2 Importance of the Grading Curve

The procedure and basis for these tests are explained in 3.5.2. The results are shown in Table 5.7 and Table 5.8.

Table 5.7 *Parameters from mortar with different grading curves from CPM-worksheet*

Grading curve	φ/φ_m	$t_{c,\ fib}$	N_{cs} matrix overlap	N_{cs} concrete overlap
1	0.67	0.46	0.79	0.72
2	0.67	0.46	0.79	0.72
3	0.67	0.46	0.79	0.72
4	0.67	0.46	0.79	0.72

Table 5.8 *Parameters from concrete with different grading curves from CPM-worksheet*

Grading curve	φ/φ_m	$t_{c,\ fib}$	N_{cs} matrix overlap	N_{cs} concrete overlap
1	0.79	0.47	0.79	0.69
2	0.79	0.47	0.79	0.69
3	0.79	0.47	0.79	0.69
4	0.79	0.47	0.79	0.69

These results show that the difference between the grading curves representing sand from different places in the batch does not affect the important calculated parameters at all.

6 Discussion

It is attempted to try and find the extent to which the observed results can be used to predict the rheological properties of fresh fibre-reinforced self-compacting concrete.

The tests with fresh concrete executed for this thesis shows that it is difficult to find a correlation between some parameters because of the unpredictable nature of concrete. A theorist will assume it is possible to find a correlation, but is also aware that to do so require experiments where most parameters are kept constant. A practitioner will claim that when you plan to make a good self-compacting concrete you cannot plan the amount of super-plasticizer exactly, at least not with such a big difference in the matrix volume used for these experiments. The tests for this thesis proves the assumption that increasing the matrix volume, and reducing the maximum packing fraction, makes a concrete more flow able, but it is not precise enough to show a correlation that is descriptive enough for use to plan the flow ability of fresh concrete.

The experiments show that with such large fibres both 2 % of mortar and 1.5 % of concrete, fibre balling occurs. When the experiments are so few with each amount of fibre, the processing of the results requires that the results from the tests are accurate. When one out of three tests with 1 % of fibre is not satisfactory (two out of six mixes with fibre gives accepted results), it is difficult to make a firm assumption for the correlations. Any result based on so few experiments would not be reliable, but can work as a basis for further investigation. It would probably have given better results with 0.5, 1 and 1.5 % instead of 0, 1 and 2 %, seeing that all mixes with 2 % did not give any reliable measurements worth working with, and knowing that a mix without fibres does not give any results for t_c or N_{cs}.

Because of the uncertainties of the measurements it is not wise to put too much into the values, but rather look at the trends for how the variables affect each other. With this way of analyzing the results, it is not relevant which method of measuring plastic viscosity is regarded, which is an advantage when the values are so divergent. When looking at the problem this way, the results found in Table 5.1 and Table 5.2 indicate that a decrease in plastic viscosity and yield stress give an increase in t_c and N_{cs}. This means that, as assumed, a larger matrix volume gives a thicker layer of matrix surplus around each fibre. Also a larger amount of fibre gives a larger rotational overlap number for the fibres. In practice the result is that larger t_c gives a concrete with better flow ability because of the reduced friction between the particles.

A problem that occurred for all concretes was matrix separation. This may have been caused by too much water in the mix combined with super plasticizer. With a smaller value for $\frac{w}{c+\sum kp}$-ratio bleeding might have been less of a problem.

Presumably the most valuable results from this thesis are the ones regarding air content. A suggestion for correlation between matrix volume, fiber volume and resulting air content is presented. This can, to some extent, make it possible to predict the air content of concrete. Also it is found that the correlation between matrix volume and maximum packing fraction is most applicable when regarding the air volume as part of the matrix. However, to reach these results, the calculations are done including the measured air content. To make these correlations useful, it is still necessary to assume an initial value for air volume. If further investigation develops a reliable correlation that can find the air volume from the matrix and fiber volume, presumably iteration from assumed initial air content will converge towards the resulting participated air volume. For this assumption to be valid, the results found in this thesis require that the air volume is considered a part of the matrix volume.

7 Compilation

7.1 Improvements

It would have been preferred to run several tests on the exact same recipe to determine the deviation that can be expected. This would for example result in conducting the same procedure as explained in Section 4, but with more than one tests for each mix, and with different concretes that are more similar to each other. A matrix volume of 460, 480 and 500 l/m^3 in mortar would probably give better and more comparable results than 450, 500 and 550 l/m^3 did. The same goes for the amount of fibres; it would probably have given better results with 0.5, 1 and 1.5 % instead of 0, 1 and 2 %, seeing that all mixes with 2 % did not give any measurements worth working with, and knowing that a mix without fibres does not give any results for t_c or N_{cs}. It is also necessary to see if the correlations are applicable for several types of fibre, or if different correlations can be found.

Use of a lower water/binder-ratio would probably make matrix separation less of a problem. This is recommended to be considered for further experiments to get more homogeneous mixes resulting in more reliable results.

7.2 Conclusion

The results found indicate that an increase in t_c and N_{cs} gives a decrease in plastic viscosity and yield stress. This means that, as assumed, a larger matrix volume gives a thicker layer of matrix surplus around each fibre. Also a larger amount of fibre gives a larger rotational overlap number for the fibres. In practice the result is that larger t_c gives a concrete with better flow ability because of the reduced friction between the particles

An interesting result was the varying amount of air in the mixes. An attempt has been done to find a correlation between the matrix volume, fiber volume and measured air content. Trials with formulas using the measurements from the experiments makes it seem possible to find a way to predict the amount of air. Regardless of this, it is found that the correlation between matrix volume and maximum packing fraction is most applicable when regarding the air volume as part of the matrix.

The grading curve is not a critical value. A representative grading curve from the manufacturer is accurate enough for calculation of proportioning parameters.

7.3 Further Work

For further investigation it might be profitable to contact several concrete manufacturers to consider the recipes most used in the industry to use as a basis. This might ensure sufficient slump-flow without separation, because the recipe would be proven to be satisfactory for use.

The methods and correlations investigated in this thesis presuppose that the air volume is part of the matrix. For these results to be beneficial it is necessary to be able to predict the air content more precise than what is currently usual. Therefor further investigation concerning measurement of air content could prove beneficial for further improvements with respect to predicting the rheology of FRSCC.

It might be easier to find a correlation if using shorter types of fibre which are as prone to fibre balling. It would in general be of interest to find a correlation regardless of the main recipe for concrete. To do so requires investigation concerning the affect from different types of fibres, cement and admixtures, and different composition of aggregates.

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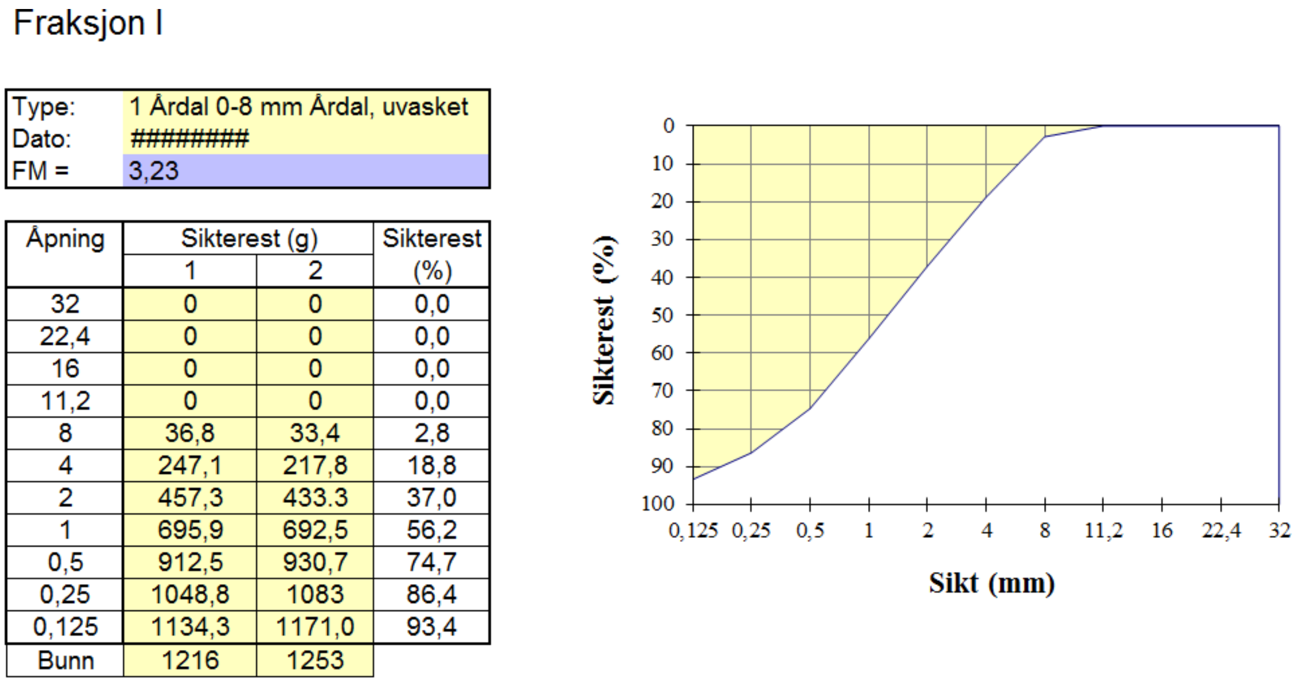
Appendix

A. Grading curves

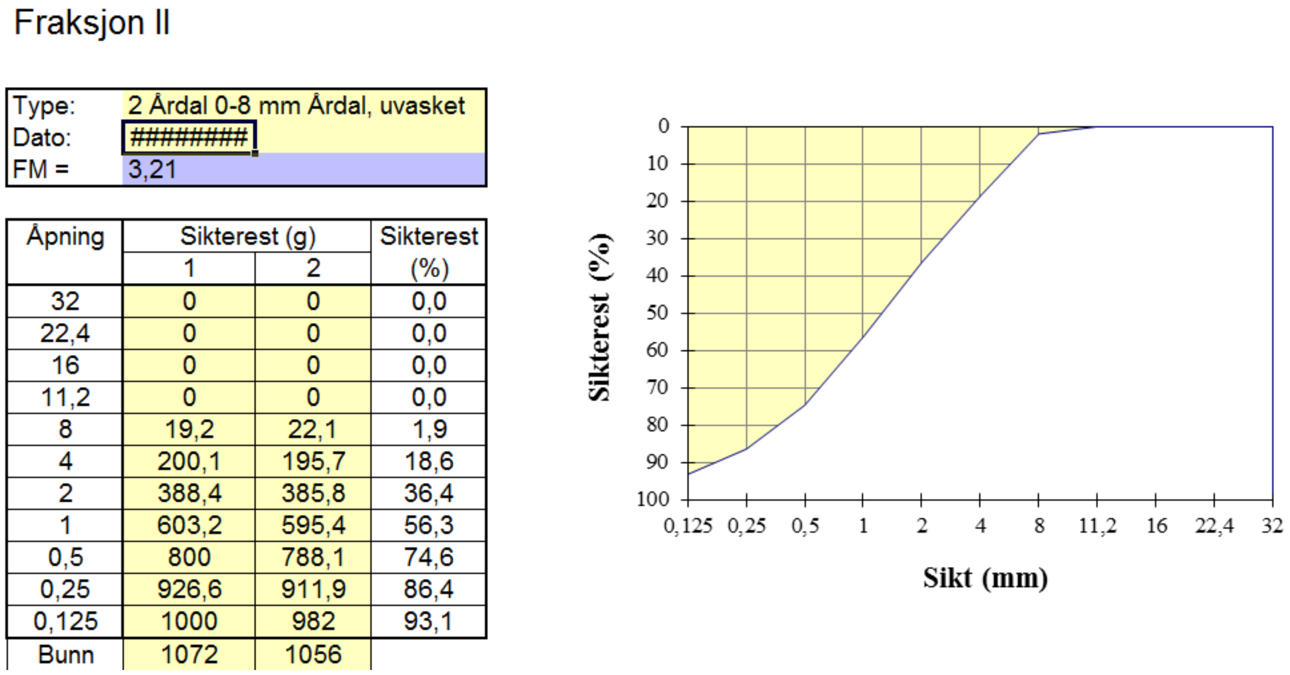


Fraksjon I

Type:	1 Årdal 0-8 mm Årdal, uvasket
Dato:	#########
FM =	3,23

Åpning	Sikterest (g)		Sikterest
	1	2	(%)
32	0	0	0,0
22,4	0	0	0,0
16	0	0	0,0
11,2	0	0	0,0
8	36,8	33,4	2,8
4	247,1	217,8	18,8
2	457,3	433.3	37,0
1	695,9	692,5	56,2
0,5	912,5	930,7	74,7
0,25	1048,8	1083	86,4
0,125	1134,3	1171,0	93,4
Bunn	1216	1253	

Figure A.1 Sample 1, 0-8 mm



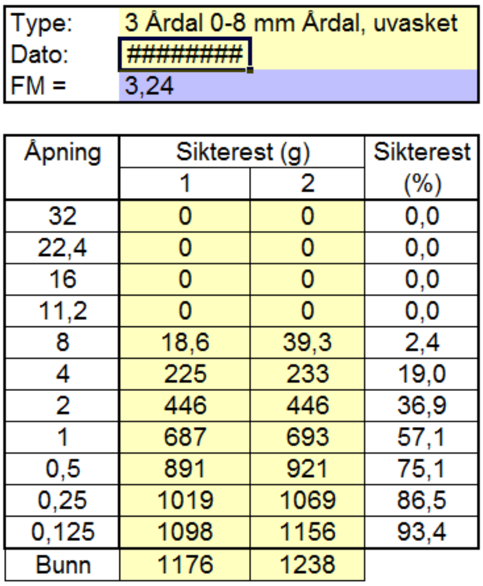
Fraksjon II

Type:	2 Årdal 0-8 mm Årdal, uvasket
Dato:	#########
FM =	3,21

Åpning	Sikterest (g)		Sikterest
	1	2	(%)
32	0	0	0,0
22,4	0	0	0,0
16	0	0	0,0
11,2	0	0	0,0
8	19,2	22,1	1,9
4	200,1	195,7	18,6
2	388,4	385,8	36,4
1	603,2	595,4	56,3
0,5	800	788,1	74,6
0,25	926,6	911,9	86,4
0,125	1000	982	93,1
Bunn	1072	1056	

Figure A.2 Sample 2, 0-8 mm

Fraksjon III



Type:	3 Årdal 0-8 mm Årdal, uvasket
Dato:	#########
FM =	3,24

Åpning	Sikterest (g)		Sikterest
	1	2	(%)
32	0	0	0,0
22,4	0	0	0,0
16	0	0	0,0
11,2	0	0	0,0
8	18,6	39,3	2,4
4	225	233	19,0
2	446	446	36,9
1	687	693	57,1
0,5	891	921	75,1
0,25	1019	1069	86,5
0,125	1098	1156	93,4
Bunn	1176	1238	

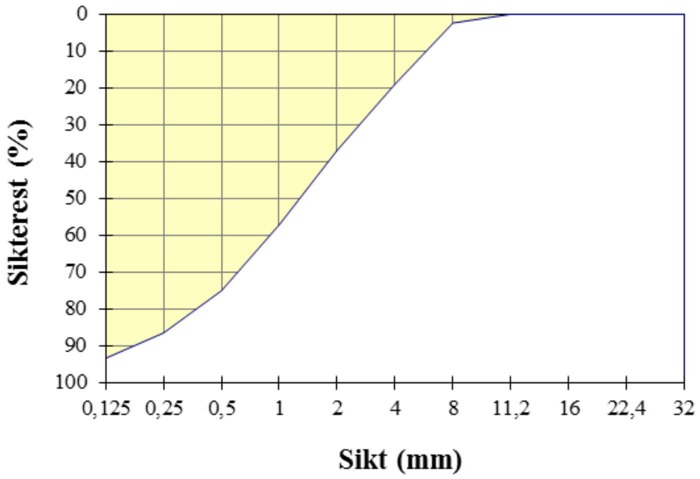
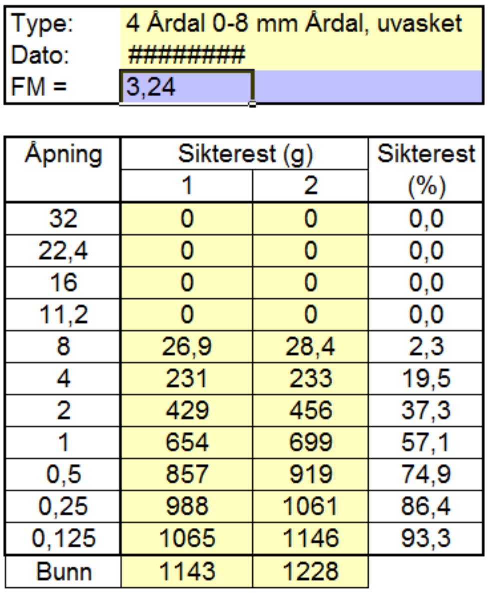


Figure A.3 Sample 3, 0-8 mm

Fraksjon IV



Type:	4 Årdal 0-8 mm Årdal, uvasket
Dato:	#########
FM =	3,24

Åpning	Sikterest (g)		Sikterest
	1	2	(%)
32	0	0	0,0
22,4	0	0	0,0
16	0	0	0,0
11,2	0	0	0,0
8	26,9	28,4	2,3
4	231	233	19,5
2	429	456	37,3
1	654	699	57,1
0,5	857	919	74,9
0,25	988	1061	86,4
0,125	1065	1146	93,3
Bunn	1143	1228	

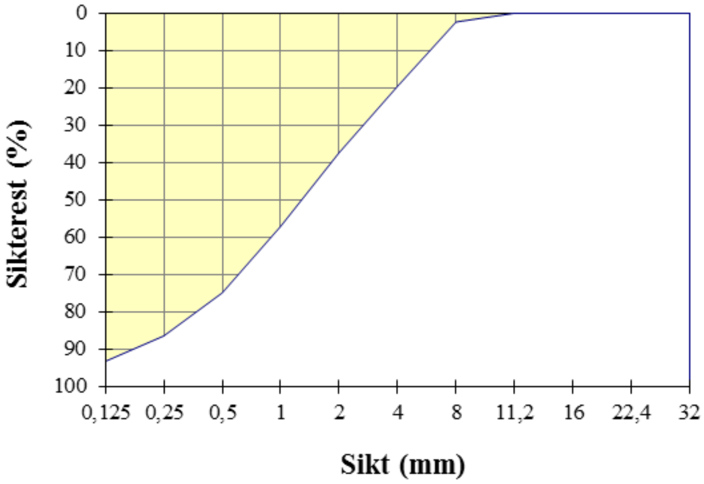


Figure A.4 Sample 4, 0-8 mm

Fraksjon V

Type:	Årdal 8-11mm, vasket
Dato:	########
FM =	6,39

Åpning	Sikterest (g)		Sikterest
	1	2	(%)
32	0	0	0,0
22,4	0	0	0,0
16	0	0	0,0
11,2	405	442,8	8,5
8	4594,4	4593,3	91,6
4	4986,5	4984	99,4
2	4996,2	4995,7	99,6
1	4996,2	4995,7	99,6
0,5	4996,2	4995,7	99,6
0,25	4996,2	4995,7	99,6
0,125	5002	5007	99,8
Bunn	5011	5017	

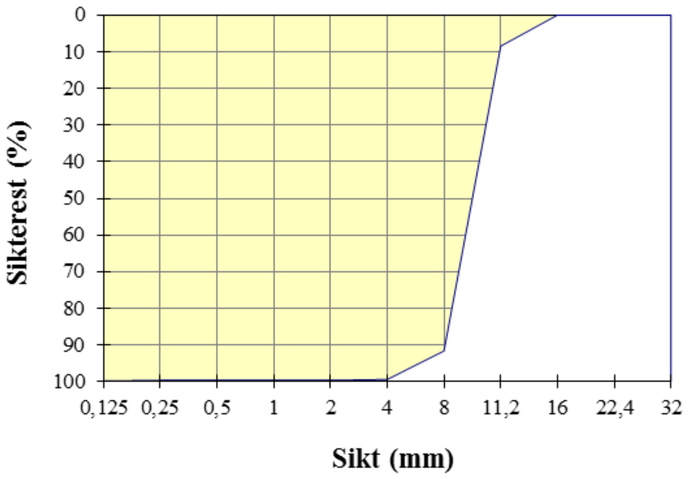


Figure A.5 Sample 5, 8-11 mm

Fraksjon VI

Type:	Årdal 11-16mm, vasket
Dato:	########
FM =	6,92

Åpning	Sikterest (g)		Sikterest
	1	2	(%)
32	0	0	0,0
22,4	0	0	0,0
16	199,3	88,8	2,9
11,2	3189,4	3229,6	64,1
8	4954,9	4945,4	98,8
4	5010,9	4998,6	99,9
2	5912,1	4999	108,9
1	5912,1	4999	108,9
0,5	5912,1	4999	108,9
0,25	5912,1	4999	108,9
0,125	5912,1	4999	108,9
Bunn	5016	5003	

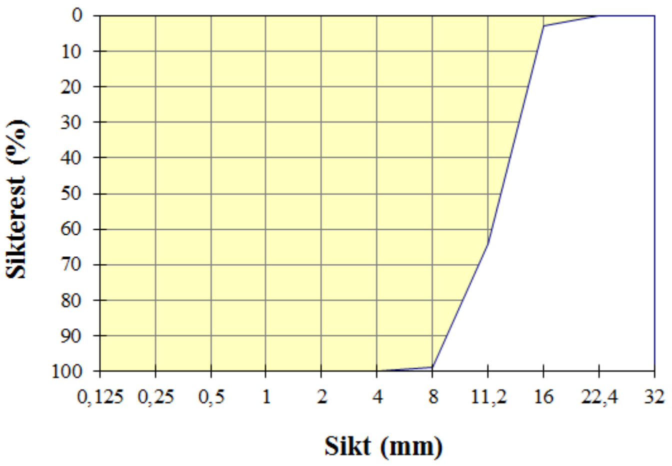
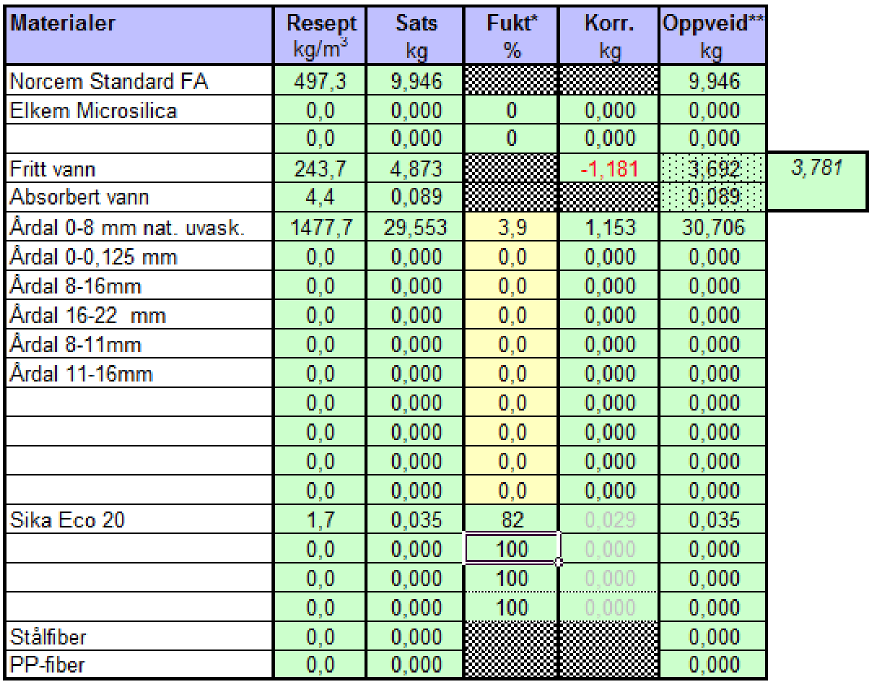


Figure A.6 Sample 6, 11-16 mm

Appendix A

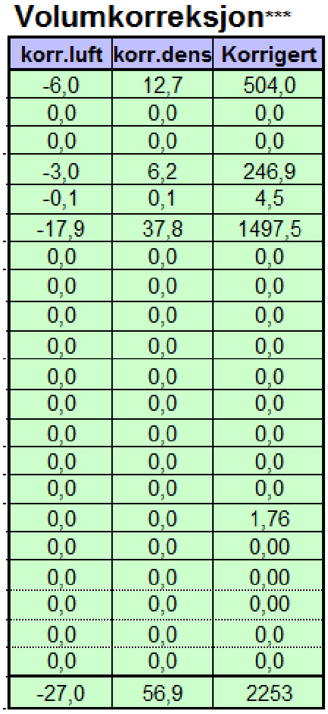
B. Results from laboratory experiments

Results mix 1, 02.05.12



Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	497,3	9,946			9,946	
Elkem Microsilica	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
Fritt vann	243,7	4,873		-1,181	3,692	3,781
Absorbert vann	4,4	0,089			0,089	
Årdal 0-8 mm nat. uvask.	1477,7	29,553	3,9	1,153	30,706	
Årdal 0-0,125 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000	
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000	
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika Eco 20	1,7	0,035	82	0,029	0,035	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
Stålfiber	0,0	0,000			0,000	
PP-fiber	0,0	0,000			0,000	

Figure B.1 Proportioning mortar 1



Volumkorreksjon***

korr.luft	korr.dens	Korrigert
-6,0	12,7	504,0
0,0	0,0	0,0
0,0	0,0	0,0
-3,0	6,2	246,9
-0,1	0,1	4,5
-17,9	37,8	1497,5
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	1,76
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,0
0,0	0,0	0,0
-27,0	56,9	2253

Figure B.2 Volume correction mortar 1

Table B.1 Results from tests with mortar and concrete 1

Measured values	Mortar	Concrete
Yield stress (Pa)		43
Plastic viscosity (Pas)		141
T_{500} (s)		5.8
Flow (mm)		590
Air content (%)	4,2	1,3
Density (kg/l)	2252	2377.0
LCPC-box, L (cm)	28	52
LCPC-box, yield stress	-	49

From 4C-rheometer

This mortar cannot in fact be called self-compacting considering the bad flow-ability. The slump-flow was not possible to measure properly, and the 4C-rheometer could not give any values. The length of the flow in the LCPC-box was outside of range for the graph to give a value. The mortar might have been better behaving with the use of more super plasticizer. This solution, however, is regarded irrelevant considering the tests are based on constant values of everything but matrix volume and amount of fiber. And it is assumed that a larger amount of super plasticizer would lead to segregation for the mixes with a larger matrix volume. However, considering this mix does not even have any fiber, it was considered wise to increase the amount of SP somewhat. In this mortar 0.35 % of cement weight is used. For the remaining mortars, 0.4 % of cement weight is used.

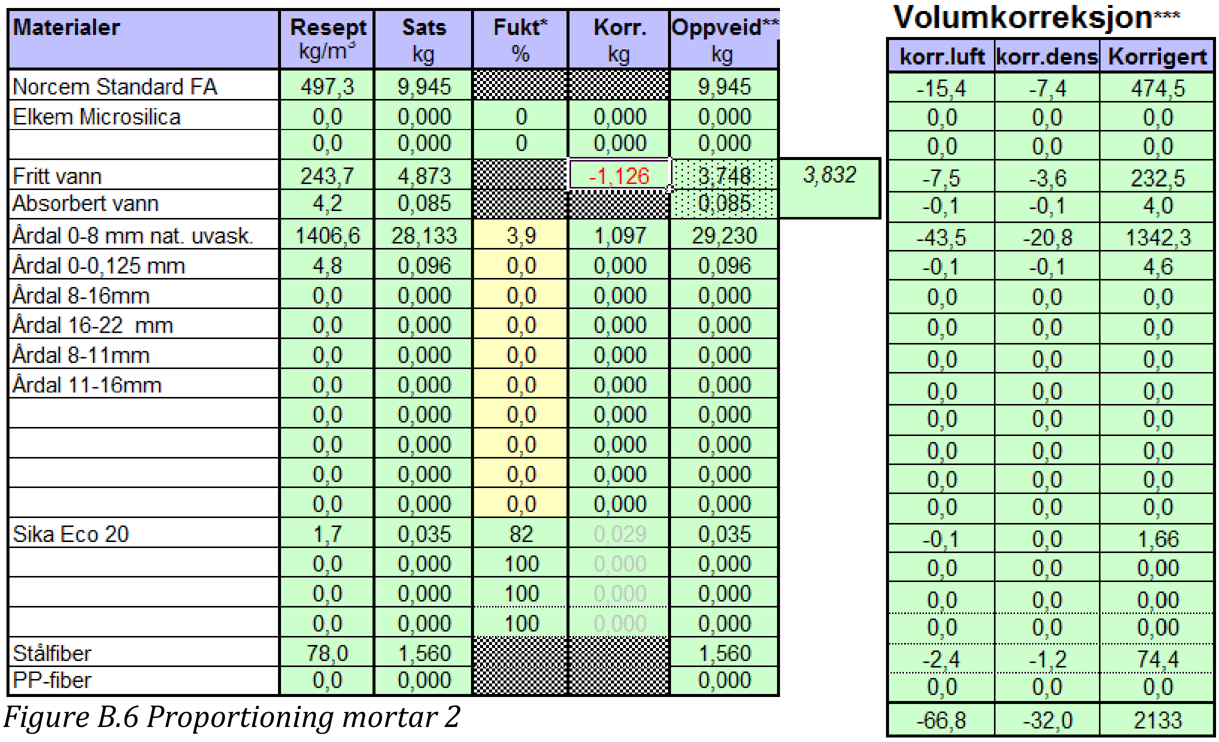
Further, after adding coarse aggregate and more SP, the concrete was a lot better than the correlating mortar. It behaved like a self-compacting concrete, and carried the coarse aggregate all the way. However the concrete suffered somewhat from matrix separation, see Figure B.5.

Figure B.3 Mortar 1

Figure B.4 Concrete 1

Figure B.5 Concrete 1

Results mix 2, 02.05.12



Volumkorreksjon***

Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg		korr.luft	korr.dens	Korrigert
Norcem Standard FA	497,3	9,945			9,945		-15,4	-7,4	474,5
Elkem Microsilica	0,0	0,000	0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0	0,000	0,000		0,0	0,0	0,0
Fritt vann	243,7	4,873		-1,126	3,748	3,832	-7,5	-3,6	232,5
Absorbert vann	4,2	0,085			0,085		-0,1	-0,1	4,0
Årdal 0-8 mm nat. uvask.	1406,6	28,133	3,9	1,097	29,230		-43,5	-20,8	1342,3
Årdal 0-0,125 mm	4,8	0,096	0,0	0,000	0,096		-0,1	-0,1	4,6
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Sika Eco 20	1,7	0,035	82	0,029	0,035		-0,1	0,0	1,66
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
Stålfiber	78,0	1,560			1,560		-2,4	-1,2	74,4
PP-fiber	0,0	0,000			0,000		0,0	0,0	0,0
							-66,8	-32,0	2133

Figure B.6 Proportioning mortar 2

Measured values	Mortar	Concrete
Yield stress (Pa)	193	37
Plastic viscosity (Pas)	25	89
T_{500} (s)	-	3,2
Flow (mm)	420	600
Air content (%)	7,5	5,2
Density (kg/l)	2135	2200
LCPC-box, L (cm)	37	50
LCPC-box, yield stress	-	54

From 4C-rheometer

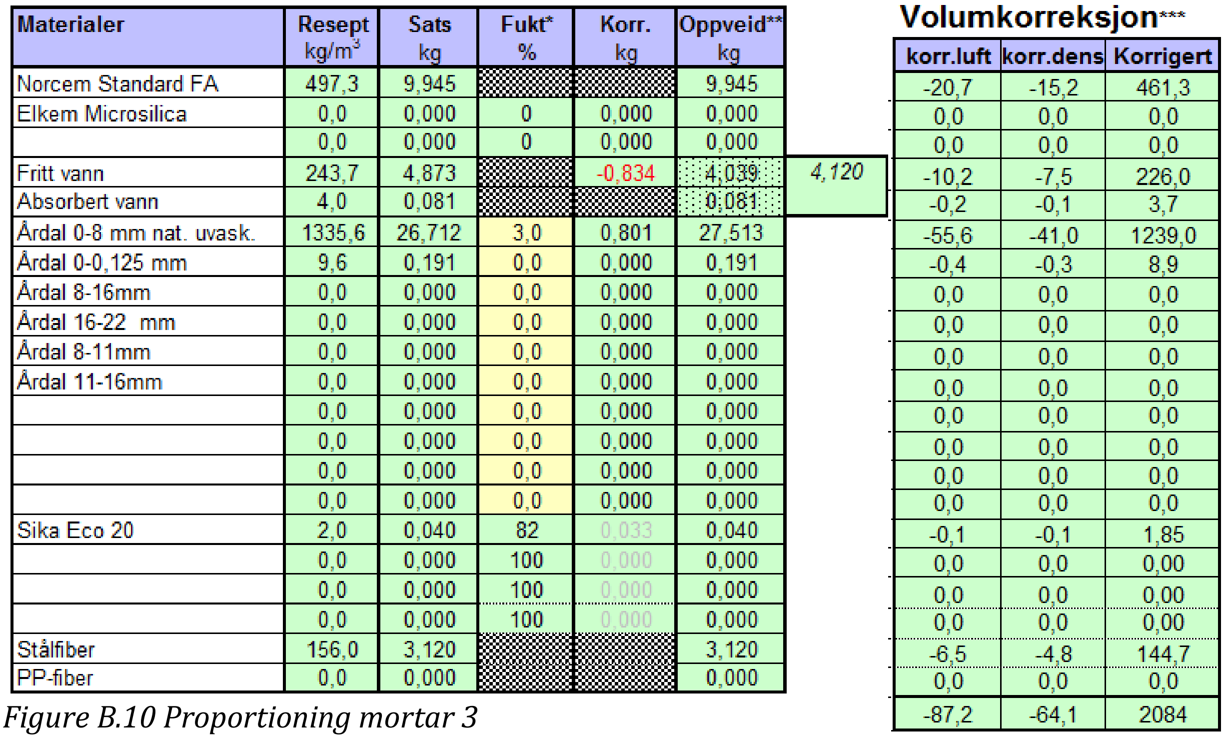
This mortar has low slump-flow. The concrete suffers slightly from both fiber balling and matrix separation. However, it is homogeneous enough to give useable values for calculation.

Figure B.7 Mortar 2

Figure B.8 Concrete 2

Figure B.9 Concrete 2

Results mix 3, 03.05.12



Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	497,3	9,945	▨	▨	9,945	
Elkem Microsilica	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
Fritt vann	243,7	4,873	▨	-0,834	4,039	4,120
Absorbert vann	4,0	0,081	▨	▨	0,081	
Årdal 0-8 mm nat. uvask.	1335,6	26,712	3,0	0,801	27,513	
Årdal 0-0,125 mm	9,6	0,191	0,0	0,000	0,191	
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000	
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000	
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika Eco 20	2,0	0,040	82	0,033	0,040	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
Stålfiber	156,0	3,120	▨	▨	3,120	
PP-fiber	0,0	0,000	▨	▨	0,000	

Volumkorreksjon***

korr.luft	korr.dens	Korrigert
-20,7	-15,2	461,3
0,0	0,0	0,0
0,0	0,0	0,0
-10,2	-7,5	226,0
-0,2	-0,1	3,7
-55,6	-41,0	1239,0
-0,4	-0,3	8,9
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
-0,1	-0,1	1,85
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,00
-6,5	-4,8	144,7
0,0	0,0	0,0
-87,2	-64,1	2084

Figure B.10 Proportioning mortar 3

Measured values	Mortar	Concrete
Yield stress (Pa)	502	71
Plastic viscosity (Pas)	0	5
T_{500} (s)	-	-
Flow (mm)	330	520
Air content (%)	10	11
Density (kg/l)	2090	2175.9
LCPC-box, L (cm)	29	31
LCPC-box, yield stress	-	-

From 4C-rheometer

The mortar is not at all flow able as self-compacting concrete should be.

There was serious fiber balling in the concrete, as well as tendancy to bleeding. This concrete is not at all satisfactory.

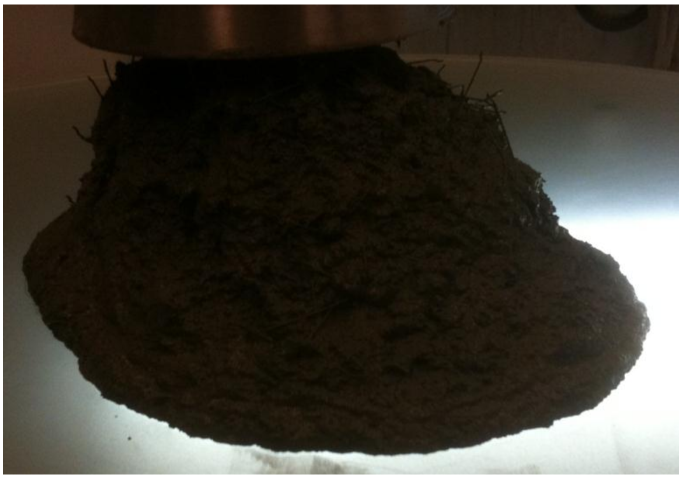
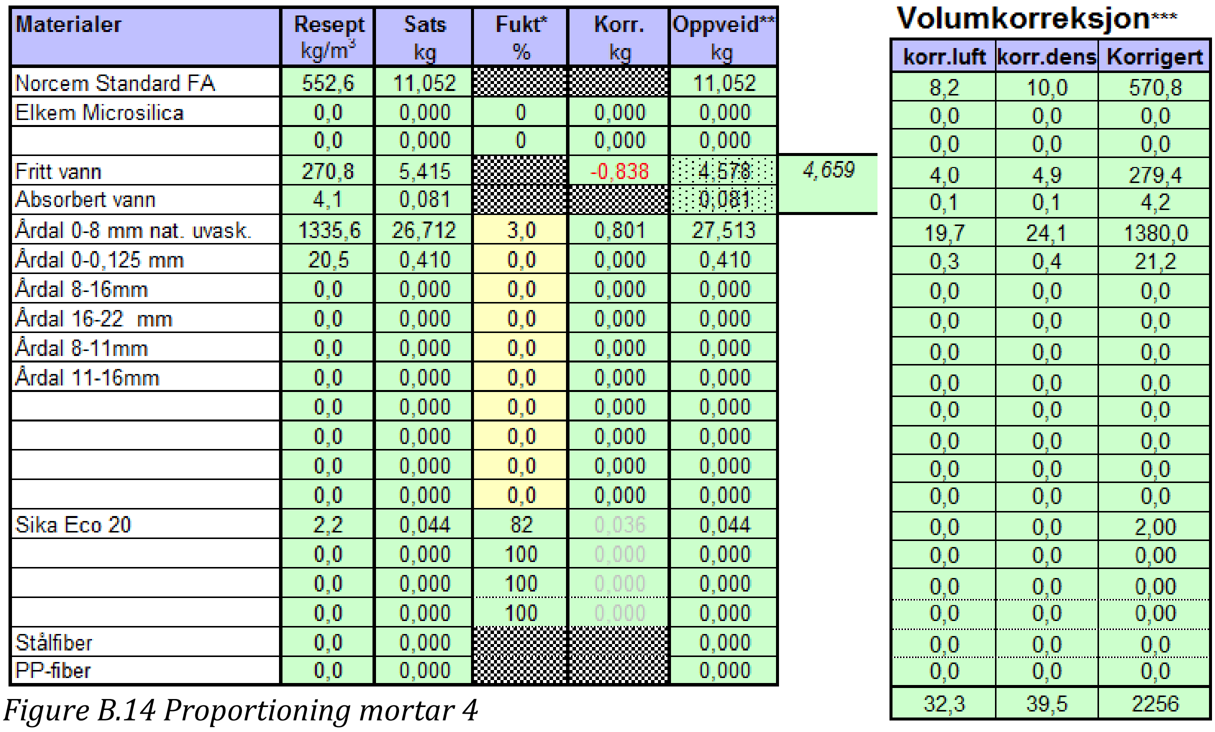


Figure B.11 Mortar 3

Figure B.12 Concrete 3

Figure B.13 Concrete 3

Results mix 4, 03.05.12



Materialer	Resept kg/m^3	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	552,6	11,052	▨	▨	11,052	
Elkem Microsilica	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
Fritt vann	270,8	5,415	▨	-0,838	4,578	4,659
Absorbert vann	4,1	0,081	▨	▨	0,081	
Årdal 0-8 mm nat. uvask.	1335,6	26,712	3,0	0,801	27,513	
Årdal 0-0,125 mm	20,5	0,410	0,0	0,000	0,410	
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000	
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000	
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika Eco 20	2,2	0,044	82	0,036	0,044	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
Stålfiber	0,0	0,000	▨	▨	0,000	
PP-fiber	0,0	0,000	▨	▨	0,000	

Volumkorreksjon***

korr.luft	korr.dens	Korrigert
8,2	10,0	570,8
0,0	0,0	0,0
0,0	0,0	0,0
4,0	4,9	279,4
0,1	0,1	4,2
19,7	24,1	1380,0
0,3	0,4	21,2
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	2,00
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,0
0,0	0,0	0,0
32,3	39,5	2256

Figure B.14 Proportioning mortar 4

Measured values	Mortar	Concrete	
Yield stress (Pa)	50	14	From 4C-rheometer
Plastic viscosity (Pas)	24	22	
T_{500} (s)	-	1.5	
Flow (mm)	565	720	
Air content (%)	1.5	0.6	
Density (kg/l)	2255.6	2358.5	
LCPC-box, L (cm)	42	70	
LCPC-box, yield stress (Pa)	-	22	

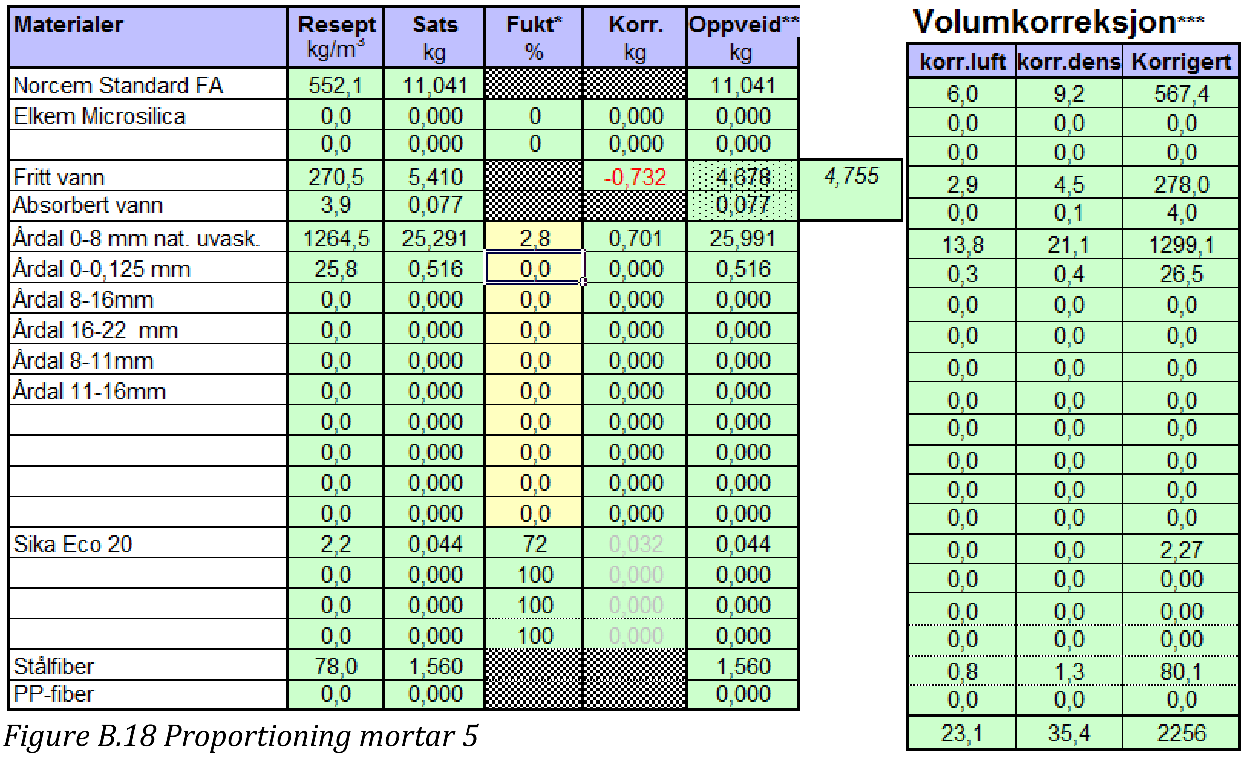
This mortar is visually homogeneous, but the slump-flow is not completely satisfactory for a self-compacting concrete, and the 4C-rheometer could not give a value for T_{500}. The mortar suffers from bleeding, but is otherwise satisfactory.

Figure B.15 Mortar 4

Figure B.16 Mortar 4

Figure B.17 Concrete 4

Results mix 5, 30.04.2012



Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	552,1	11,041	▨	▨	11,041	
Elkem Microsilica	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
Fritt vann	270,5	5,410	▨	-0,732	4,678	4,755
Absorbert vann	3,9	0,077	▨	▨	0,077	
Årdal 0-8 mm nat. uvask.	1264,5	25,291	2,8	0,701	25,991	
Årdal 0-0,125 mm	25,8	0,516	0,0	0,000	0,516	
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000	
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000	
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika Eco 20	2,2	0,044	72	0,032	0,044	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
Stålfiber	78,0	1,560	▨	▨	1,560	
PP-fiber	0,0	0,000	▨	▨	0,000	

Volumkorreksjon***

korr.luft	korr.dens	Korrigert
6,0	9,2	567,4
0,0	0,0	0,0
0,0	0,0	0,0
2,9	4,5	278,0
0,0	0,1	4,0
13,8	21,1	1299,1
0,3	0,4	26,5
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	2,27
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,00
0,8	1,3	80,1
0,0	0,0	0,0
23,1	35,4	2256

Figure B.18 Proportioning mortar 5

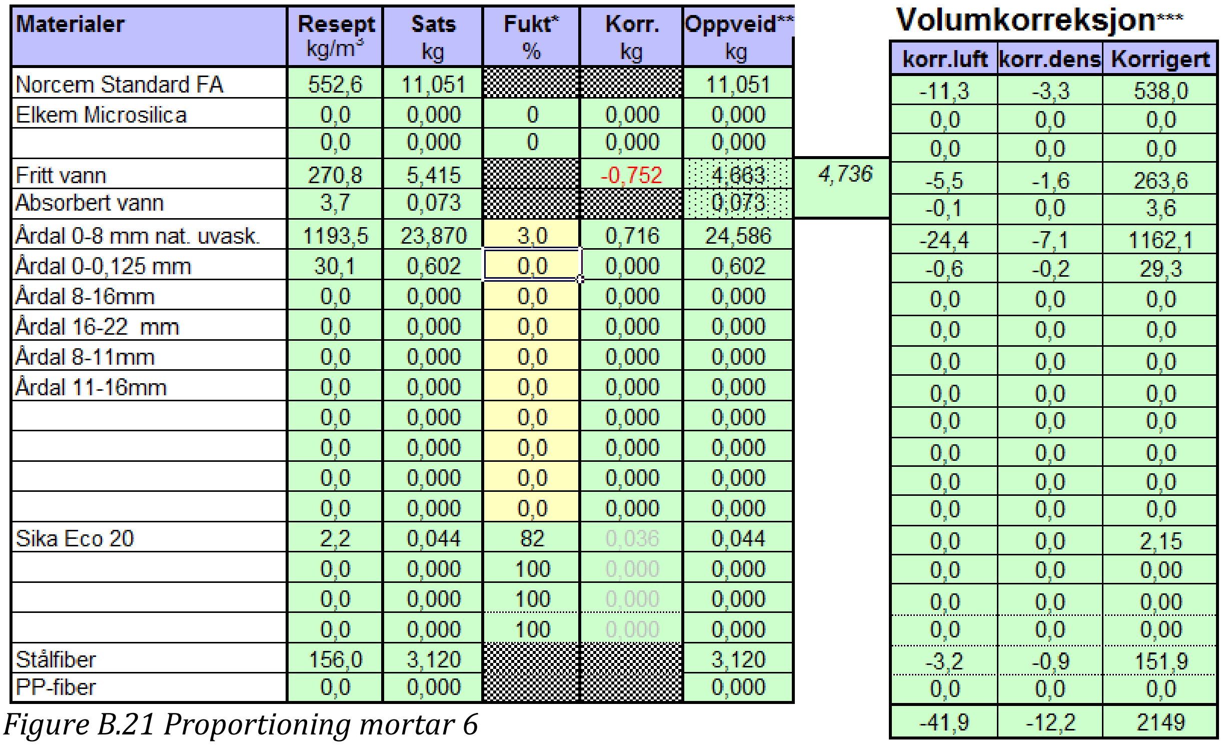
Measured values	Mortar	Concrete	
Yield stress (Pa)	159	26	From 4C-rheometer
Plastic viscosity (Pas)	28	62	
T_{500} (s)	-	2,8	
Flow (mm)	443	648	
Air content (%)	3,4	4,4	
Density (kg/l)	2255	2265	
LCPC-box, L (cm)	40,5	47-60	
LCPC-box, yield stress	-	>34	

The mortar has a slump-flow of under 500 mm and has thus not a value for T_{500}. The value for yield stress is very high. The concrete suffers from separation and fibre balling; hence the values are not completely reliable.

Figure B.19 Mortar 5

Figure B.20 Concrete 5

Results mix 6, 04.05.12



Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg		Volumkorreksjon***		
							korr.luft	korr.dens	Korrigert
Norcem Standard FA	552,6	11,051			11,051		-11,3	-3,3	538,0
Elkem Microsilica	0,0	0,000	0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0	0,000	0,000		0,0	0,0	0,0
Fritt vann	270,8	5,415		-0,752	4,663	4,736	-5,5	-1,6	263,6
Absorbert vann	3,7	0,073			0,073		-0,1	0,0	3,6
Årdal 0-8 mm nat. uvask.	1193,5	23,870	3,0	0,716	24,586		-24,4	-7,1	1162,1
Årdal 0-0,125 mm	30,1	0,602	0,0	0,000	0,602		-0,6	-0,2	29,3
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Sika Eco 20	2,2	0,044	82	0,036	0,044		0,0	0,0	2,15
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
Stålfiber	156,0	3,120			3,120		-3,2	-0,9	151,9
PP-fiber	0,0	0,000			0,000		0,0	0,0	0,0
							-41,9	-12,2	2149

Figure B.21 Proportioning mortar 6

Measured values	Mortar	Concrete
Yield stress (Pa)	438	66
Plastic viscosity (Pas)	0	161
T_{500} (s)	-	5,5
Flow (mm)	350	530
Air content (%)	8	7,5
Density (kg/l)	2152	2225
LCPC-box, L (cm)	27	-
LCPC-box, yield stress	-	-

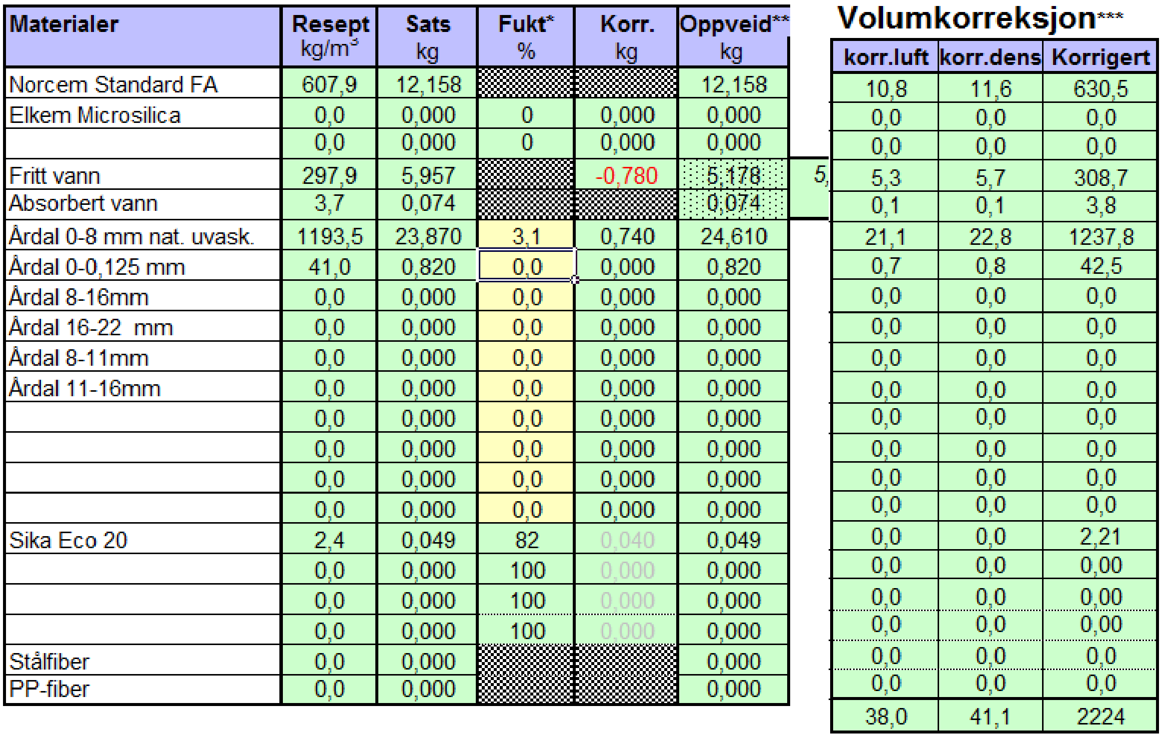
} From 4C-rheometer

Both mortar and concrete suffers from serious fibre balling. In addition, the concrete suffers from matrix separation. The results for these measurements are not reliable.

Figure B.22 Mortar 6

Figure B.23 Concrete 6

Results mix 7, 04.05.12



Volumkorreksjon***

Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg		korr.luft	korr.dens	Korrigert
Norcem Standard FA	607,9	12,158			12,158		10,8	11,6	630,5
Elkem Microsilica	0,0	0,000	0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0	0,000	0,000		0,0	0,0	0,0
Fritt vann	297,9	5,957		-0,780	5,178	5,	5,3	5,7	308,7
Absorbert vann	3,7	0,074			0,074		0,1	0,1	3,8
Årdal 0-8 mm nat. uvask.	1193,5	23,870	3,1	0,740	24,610		21,1	22,8	1237,8
Årdal 0-0,125 mm	41,0	0,820	0,0	0,000	0,820		0,7	0,8	42,5
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
	0,0	0,000	0,0	0,000	0,000		0,0	0,0	0,0
Sika Eco 20	2,4	0,049	82	0,040	0,049		0,0	0,0	2,21
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
	0,0	0,000	100	0,000	0,000		0,0	0,0	0,00
Stålfiber	0,0	0,000			0,000		0,0	0,0	0,0
PP-fiber	0,0	0,000			0,000		0,0	0,0	0,0
							38,0	41,1	2224

Figure B.24 Proportioning mortar 7

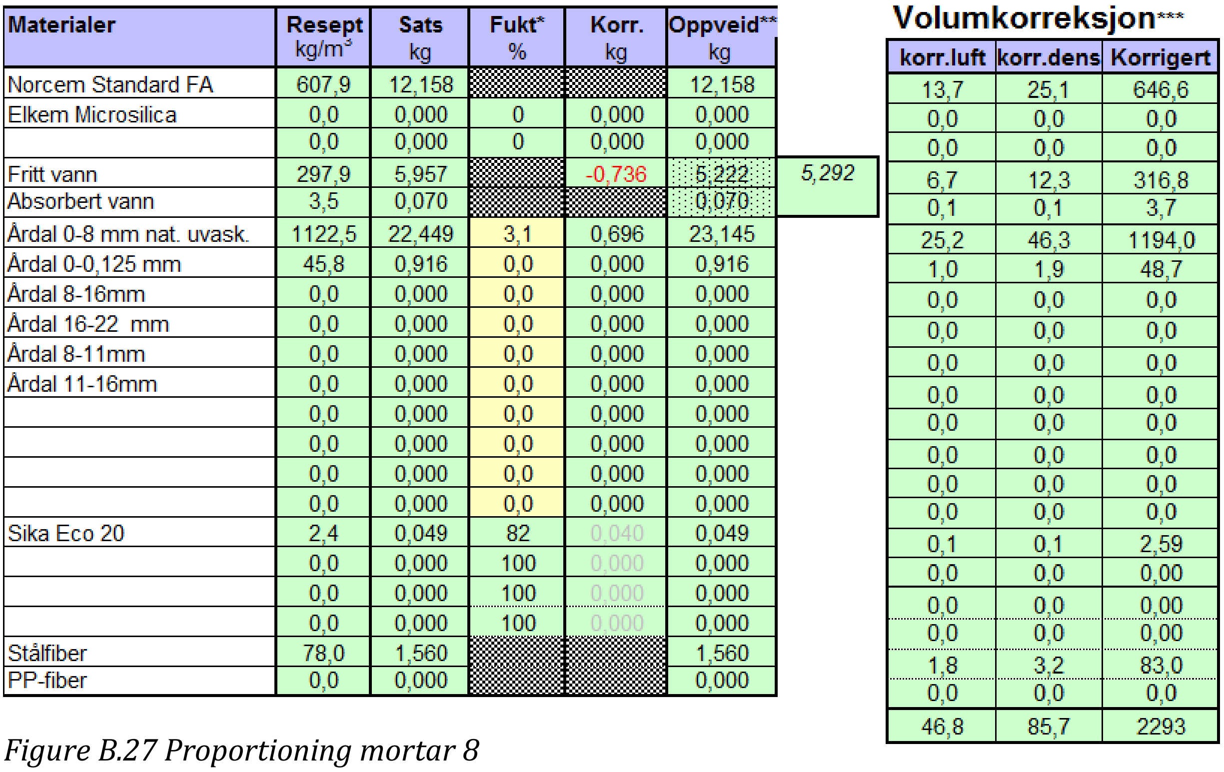
Measured values	Mortar	Concrete	
Yield stress (Pa)	74	17	From 4C-rheometer
Plastic viscosity (Pas)	19	59	
T_{500} (s)	4,1	2,3	
Flow (mm)	518	705	
Air content (%)	1,2	0,8	
Density (kg/l)	2223,7	2347	
LCPC-box, L (cm)	52	70-86	
LCPC-box, yield stress	49	12-22	

The mortar was stable, but not as flowing as expected. The concrete however was the opposite. The slump-flow is satisfactory, but it was separating, as you can see in Figure B.26.

Figure B.25 Mortar 7

Figure B.26 Concrete 7

Results mix 8, 07.05.12



Materialer	Resept kg/m^3	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	607,9	12,158	▨	▨	12,158	
Elkem Microsilica	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
Fritt vann	297,9	5,957	▨	-0,736	5,222	5,292
Absorbert vann	3,5	0,070	▨	▨	0,070	
Årdal 0-8 mm nat. uvask.	1122,5	22,449	3,1	0,696	23,145	
Årdal 0-0,125 mm	45,8	0,916	0,0	0,000	0,916	
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000	
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000	
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika Eco 20	2,4	0,049	82	0,040	0,049	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
Stålfiber	78,0	1,560	▨	▨	1,560	
PP-fiber	0,0	0,000	▨	▨	0,000	

Volumkorreksjon***

korr.luft	korr.dens	Korrigert
13,7	25,1	646,6
0,0	0,0	0,0
0,0	0,0	0,0
6,7	12,3	316,8
0,1	0,1	3,7
25,2	46,3	1194,0
1,0	1,9	48,7
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	0,0
0,1	0,1	2,59
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,00
1,8	3,2	83,0
0,0	0,0	0,0
46,8	85,7	2293

Figure B.27 Proportioning mortar 8

Measured values	Mortar	Concrete	
Yield stress (Pa)	94	18	From 4C-rheometer
Plastic viscosity (Pas)	21	49	
T_{500} (s)	(2,9)	2,7	
Flow (mm)	495	64 - 74	
Air content (%)	2,2	1,8	
Density (kg/l)	2291,5	2374,7	
LCPC-box, L (cm)	48	58 - 80	
LCPC-box, yield stress	60	15 - 38	

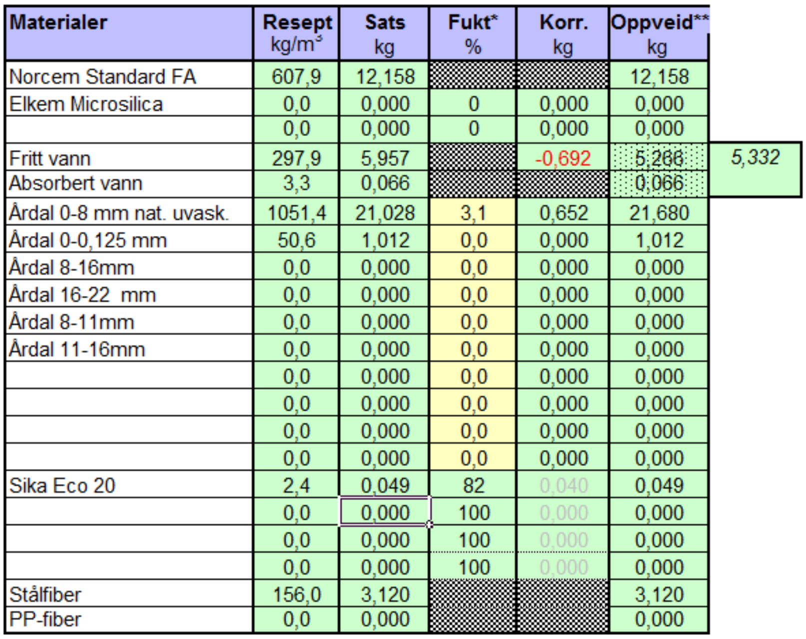
Serious fiber balling and matrix separation occurred in both mortar and concrete. The values are not reliable for calculations.

Figure B.28 Mortar 8

Figure B.29 Concrete 8

Results mix 9, 07.05.12

Seeing that both the mortar and the concrete in mix 8 suffers from fiber balling and has a significant halo, a decision is made not to go through with testing of mix 9 as this one has the same properties other than the amount of fiber. Increasing the amount of fiber from 1 % to 2 % is guaranteed to cause even more serious fiber balling, thus known not to give useful results for the research.



Materialer	**Resept** kg/m³	**Sats** kg	**Fukt*** %	**Korr.** kg	**Oppveid**** kg	
Norcem Standard FA	607,9	12,158	▨	▨	12,158	
Elkem Microsilica	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
Fritt vann	297,9	5,957	▨	-0,692	5,266	5,332
Absorbert vann	3,3	0,066	▨	▨	0,066	
Årdal 0-8 mm nat. uvask.	1051,4	21,028	3,1	0,652	21,680	
Årdal 0-0,125 mm	50,6	1,012	0,0	0,000	1,012	
Årdal 8-16mm	0,0	0,000	0,0	0,000	0,000	
Årdal 16-22 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8-11mm	0,0	0,000	0,0	0,000	0,000	
Årdal 11-16mm	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika Eco 20	2,4	0,049	82	0,040	0,049	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
	0,0	0,000	100	0,000	0,000	
Stålfiber	156,0	3,120	▨	▨	3,120	
PP-fiber	0,0	0,000	▨	▨	0,000	

Figure B.30 Proportioning mortar 9

Sources of error

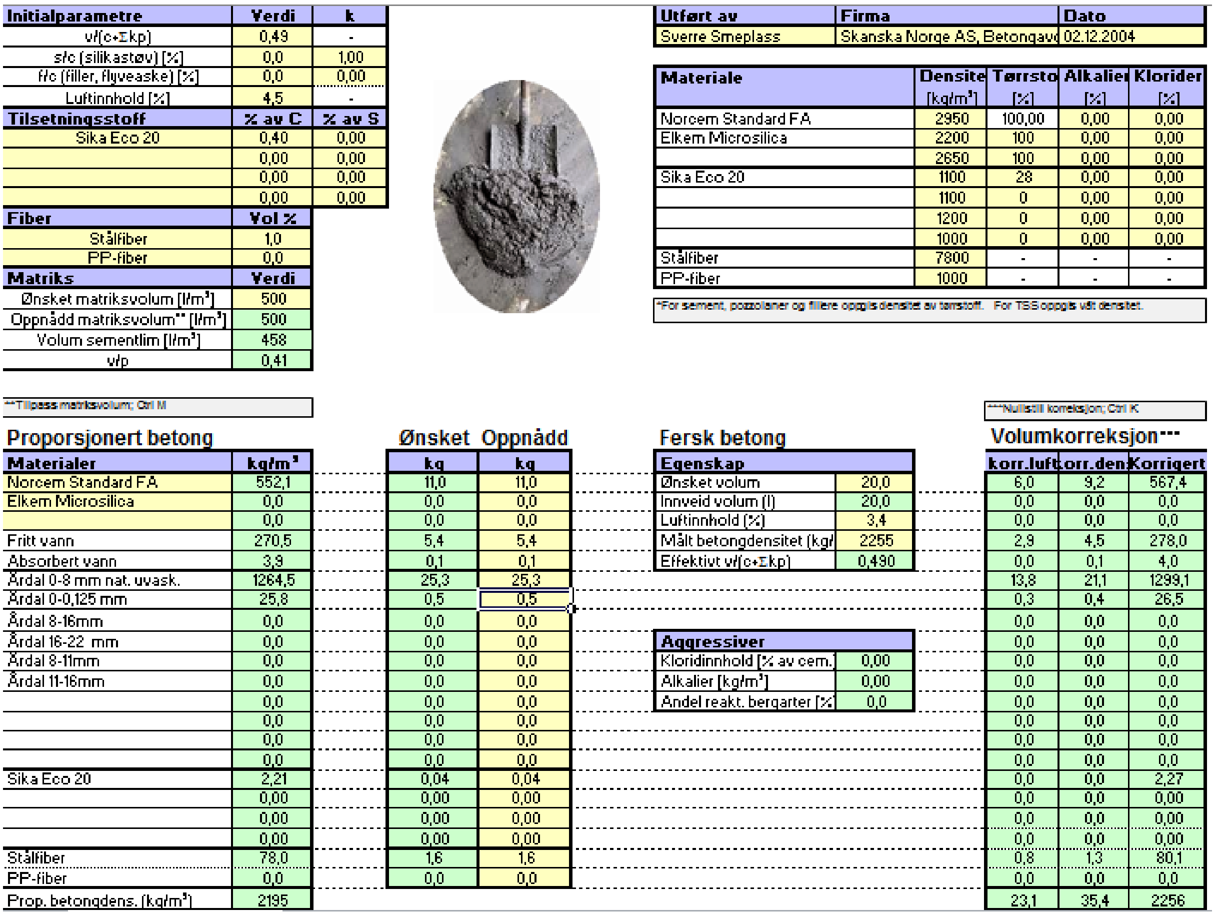
The measurement of the density of the mortar and concrete is not guaranteed to be representative. The fibers are relatively long compared to the size of the shovel used to move the concrete; hence the fibers may be cumbersome to move to get a representative test. The fiber density is much larger than that of the other components in the concrete, thus the variation in amount of fiber gives large effect on the overall density.

After running tests on the mortar it is taken back in the mixer and reused for the concrete. Naturally some of the mortar remains in the test instruments. This causes uncertainties in the relationship between the components in the concrete. However, the tests are carried out in the same way and by the same people for all mixes so it is assumed that it is somewhat the same loss of mortar for all mixes, and the variation will not be critical.

The content of moisture in the aggregate can vary. The moisture has to be calculated for when planning the mix. For these tests a certain amount of aggregate 0-8 mm is put away in a sealed container and measured for moist before using. For the moisture in the aggregate to remain as measured it is provided that the container actually is tight enough to keep the moist from evaporating.

The fines in the aggregate 0-8 mm can vary somewhat and will affect the matrix volume accordingly. This uncertainty is accounted for in the reports chapter 0.

C. Worksheet for proportioning: ‘Proporsjonering’



Initialparametre	Verdi	k
v/(c+Σkp)	0,49	-
s/c (silikastøv) [%]	0,0	1,00
f/c (filler, flyveaske) [%]	0,0	0,00
Luftinnhold [%]	4,5	-
Tilsetningsstoff	**% av C**	**% av S**
Sika Eco 20	0,40	0,00
	0,00	0,00
	0,00	0,00
	0,00	0,00
Fiber	**Vol %**	
Stålfiber	1,0	
PP-fiber	0,0	
Matriks	**Verdi**	
Ønsket matriksvolum [l/m³]	500	
Oppnådd matriksvolum** [l/m³]	500	
Volum sementlim [l/m³]	458	
v/p	0,41	

**Tilpass matriksvolum; Ctrl M

Utført av	Firma	Dato
Sverre Smeplass	Skanska Norge AS, Betongavd	02.12.2004

Materiale	Densitet [kg/m³]	Tørrsto [%]	Alkalier [%]	Klorider [%]
Norcem Standard FA	2950	100,00	0,00	0,00
Elkem Microsilica	2200	100	0,00	0,00
	2650	100	0,00	0,00
Sika Eco 20	1100	28	0,00	0,00
	1100	0	0,00	0,00
	1200	0	0,00	0,00
	1000	0	0,00	0,00
Stålfiber	7800	-	-	-
PP-fiber	1000	-	-	-

*For sement, pozzolaner og fillere oppgis densitet av tørrstoff. For TSS oppgis våt densitet.

***Nullstill korreksjon; Ctrl K

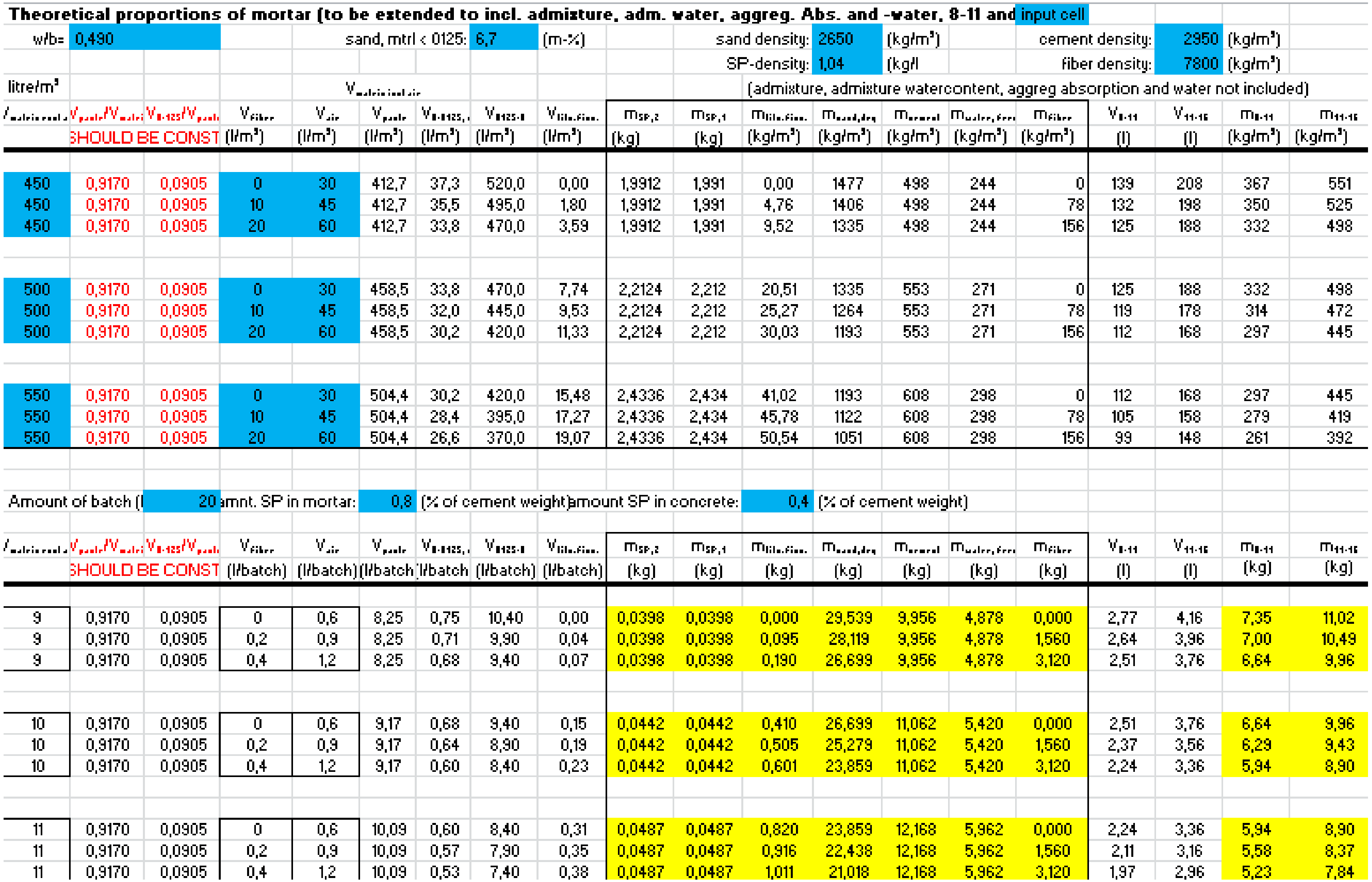
Proporsjonert betong		Ønsket	Oppnådd	Volumkorreksjon***		
Materialer	**kg/m³**	**kg**	**kg**	**korr.luft**	**korr.den**	**Korrigert**
Norcem Standard FA	552,1	11,0	11,0	6,0	9,2	567,4
Elkem Microsilica	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Fritt vann	270,5	5,4	5,4	2,9	4,5	278,0
Absorbert vann	3,9	0,1	0,1	0,0	0,1	4,0
Årdal 0-8 mm nat. uvask.	1264,5	25,3	25,3	13,8	21,1	1299,1
Årdal 0-0,125 mm	25,8	0,5	0,5	0,3	0,4	26,5
Årdal 8-16mm	0,0	0,0	0,0	0,0	0,0	0,0
Årdal 16-22 mm	0,0	0,0	0,0	0,0	0,0	0,0
Årdal 8-11mm	0,0	0,0	0,0	0,0	0,0	0,0
Årdal 11-16mm	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Sika Eco 20	2,21	0,04	0,04	0,0	0,0	2,27
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
Stålfiber	78,0	1,6	1,6	0,8	1,3	80,1
PP-fiber	0,0	0,0	0,0	0,0	0,0	0,0
Prop. betongdens. [kg/m³]	2195			23,1	35,4	2256

Fersk betong

Egenskap	
Ønsket volum	20,0
Innveid volum (l)	20,0
Luftinnhold (%)	3,4
Målt betongdensitet (kg/	2255
Effektivt v/(c+Σkp)	0,490

Aggressiver	
Kloridinnhold [% av cem.]	0,00
Alkalier [kg/m³]	0,00
Andel reakt. bergarter [%]	0,0

D. Worksheet 'Amount constituents'



Theoretical proportions of mortar (to be extended to incl. admixture, adm. water, aggreg. Abs. and -water, 8-11 and input cell

w/b= 0,490 | sand, mtrl < 0125: 6,7 (m-%) | sand density: 2650 (kg/m³) | cement density: 2950 (kg/m³)

SP-density: 1,04 (kg/l | fiber density: 7800 (kg/m³)

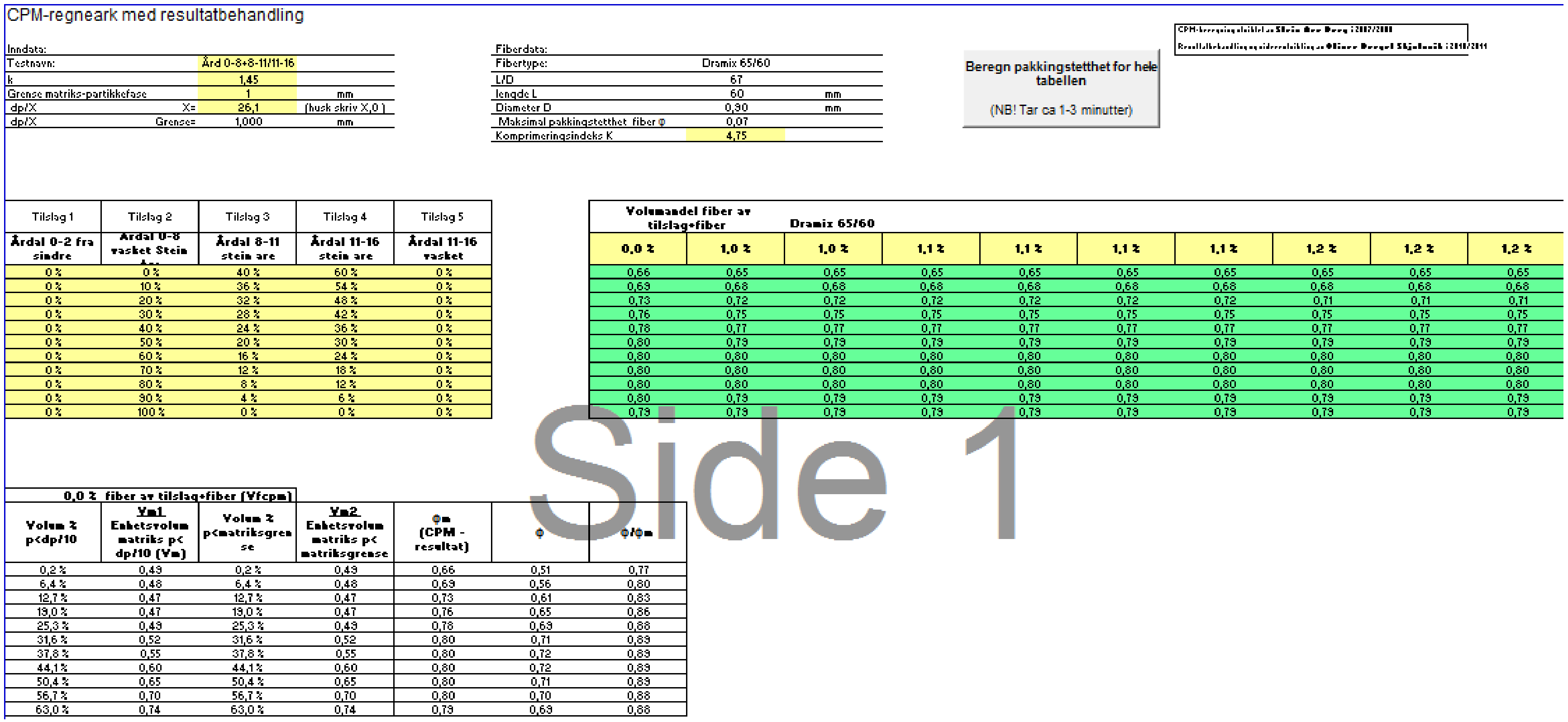
litre/m³ | $V_{matrix\ incl.\ air}$ | (admixture, admixture watercontent, aggreg absorption and water not included)

$V_{matrix\ incl.\ air}$	V_{paste}/V_{matrix}	$V_{0\text{-}125}/V_{paste}$	V_{fiber} (l/m³)	V_{air} (l/m³)	V_{paste} (l/m³)	$V_{0\text{-}0125}$ (l/m³)	$V_{0125\text{-}8}$ (l/m³)	$V_{fille,fines}$ (l/m³)	$m_{SP,2}$ (kg)	$m_{SP,1}$ (kg)	$m_{fille,fines}$ (kg/m³)	$m_{sand,dry}$ (kg/m³)	m_{cement} (kg/m³)	$m_{water,free}$ (kg/m³)	m_{fiber} (kg/m³)	$V_{8\text{-}11}$ (l)	$V_{11\text{-}16}$ (l)	$m_{8\text{-}11}$ (kg/m³)	$m_{11\text{-}16}$ (kg/m³)
	SHOULD BE CONST																		
450	0,9170	0,0905	0	30	412,7	37,3	520,0	0,00	1,9912	1,991	0,00	1477	498	244	0	139	208	367	551
450	0,9170	0,0905	10	45	412,7	35,5	495,0	1,80	1,9912	1,991	4,76	1406	498	244	78	132	198	350	525
450	0,9170	0,0905	20	60	412,7	33,8	470,0	3,59	1,9912	1,991	9,52	1335	498	244	156	125	188	332	498
500	0,9170	0,0905	0	30	458,5	33,8	470,0	7,74	2,2124	2,212	20,51	1335	553	271	0	125	188	332	498
500	0,9170	0,0905	10	45	458,5	32,0	445,0	9,53	2,2124	2,212	25,27	1264	553	271	78	119	178	314	472
500	0,9170	0,0905	20	60	458,5	30,2	420,0	11,33	2,2124	2,212	30,03	1193	553	271	156	112	168	297	445
550	0,9170	0,0905	0	30	504,4	30,2	420,0	15,48	2,4336	2,434	41,02	1193	608	298	0	112	168	297	445
550	0,9170	0,0905	10	45	504,4	28,4	395,0	17,27	2,4336	2,434	45,78	1122	608	298	78	105	158	279	419
550	0,9170	0,0905	20	60	504,4	26,6	370,0	19,07	2,4336	2,434	50,54	1051	608	298	156	99	148	261	392

Amount of batch (l 20 | amnt. SP in mortar: 0,8 (% of cement weight) | amount SP in concrete: 0,4 (% of cement weight)

$V_{matrix\ incl.\ air}$	V_{paste}/V_{matrix}	$V_{0\text{-}125}/V_{paste}$	V_{fiber} (l/batch)	V_{air} (l/batch)	V_{paste} (l/batch	$V_{0\text{-}0125}$ l/batch	$V_{0125\text{-}8}$ (l/batch)	$V_{fille,fines}$ (l/batch)	$m_{SP,2}$ (kg)	$m_{SP,1}$ (kg)	$m_{fille,fines}$ (kg)	$m_{sand,dry}$ (kg)	m_{cement} (kg)	$m_{water,free}$ (kg)	m_{fiber} (kg)	$V_{8\text{-}11}$ (l)	$V_{11\text{-}16}$ (l)	$m_{8\text{-}11}$ (kg)	$m_{11\text{-}16}$ (kg)
	SHOULD BE CONST																		
9	0,9170	0,0905	0	0,6	8,25	0,75	10,40	0,00	0,0398	0,0398	0,000	29,539	9,956	4,878	0,000	2,77	4,16	7,35	11,02
9	0,9170	0,0905	0,2	0,9	8,25	0,71	9,90	0,04	0,0398	0,0398	0,095	28,119	9,956	4,878	1,560	2,64	3,96	7,00	10,49
9	0,9170	0,0905	0,4	1,2	8,25	0,68	9,40	0,07	0,0398	0,0398	0,190	26,699	9,956	4,878	3,120	2,51	3,76	6,64	9,96
10	0,9170	0,0905	0	0,6	9,17	0,68	9,40	0,15	0,0442	0,0442	0,410	26,699	11,062	5,420	0,000	2,51	3,76	6,64	9,96
10	0,9170	0,0905	0,2	0,9	9,17	0,64	8,90	0,19	0,0442	0,0442	0,505	25,279	11,062	5,420	1,560	2,37	3,56	6,29	9,43
10	0,9170	0,0905	0,4	1,2	9,17	0,60	8,40	0,23	0,0442	0,0442	0,601	23,859	11,062	5,420	3,120	2,24	3,36	5,94	8,90
11	0,9170	0,0905	0	0,6	10,09	0,60	8,40	0,31	0,0487	0,0487	0,820	23,859	12,168	5,962	0,000	2,24	3,36	5,94	8,90
11	0,9170	0,0905	0,2	0,9	10,09	0,57	7,90	0,35	0,0487	0,0487	0,916	22,438	12,168	5,962	1,560	2,11	3,16	5,58	8,37
11	0,9170	0,0905	0,4	1,2	10,09	0,53	7,40	0,38	0,0487	0,0487	1,011	21,018	12,168	5,962	3,120	1,97	2,96	5,23	7,84

E. Excerpt from the worksheet ‘CPM-regneark’



CPM-regneark med resultatbehandling

Inndata:			
Testnavn:		Ård 0-8+8-11/11-16	
k		1,45	
Grense matriks-partikkefase		1	mm
dp/X	X=	26,1	(husk skriv X,0)
dp/X	Grense=	1,000	mm

Fiberdata:		
Fibertype:	Dramix 65/60	
L/D	67	
lengde L	60	mm
Diameter D	0,90	mm
Maksimal pakkingstetthet fiber φ	0,07	
Komprimeringsindeks K	4,75	

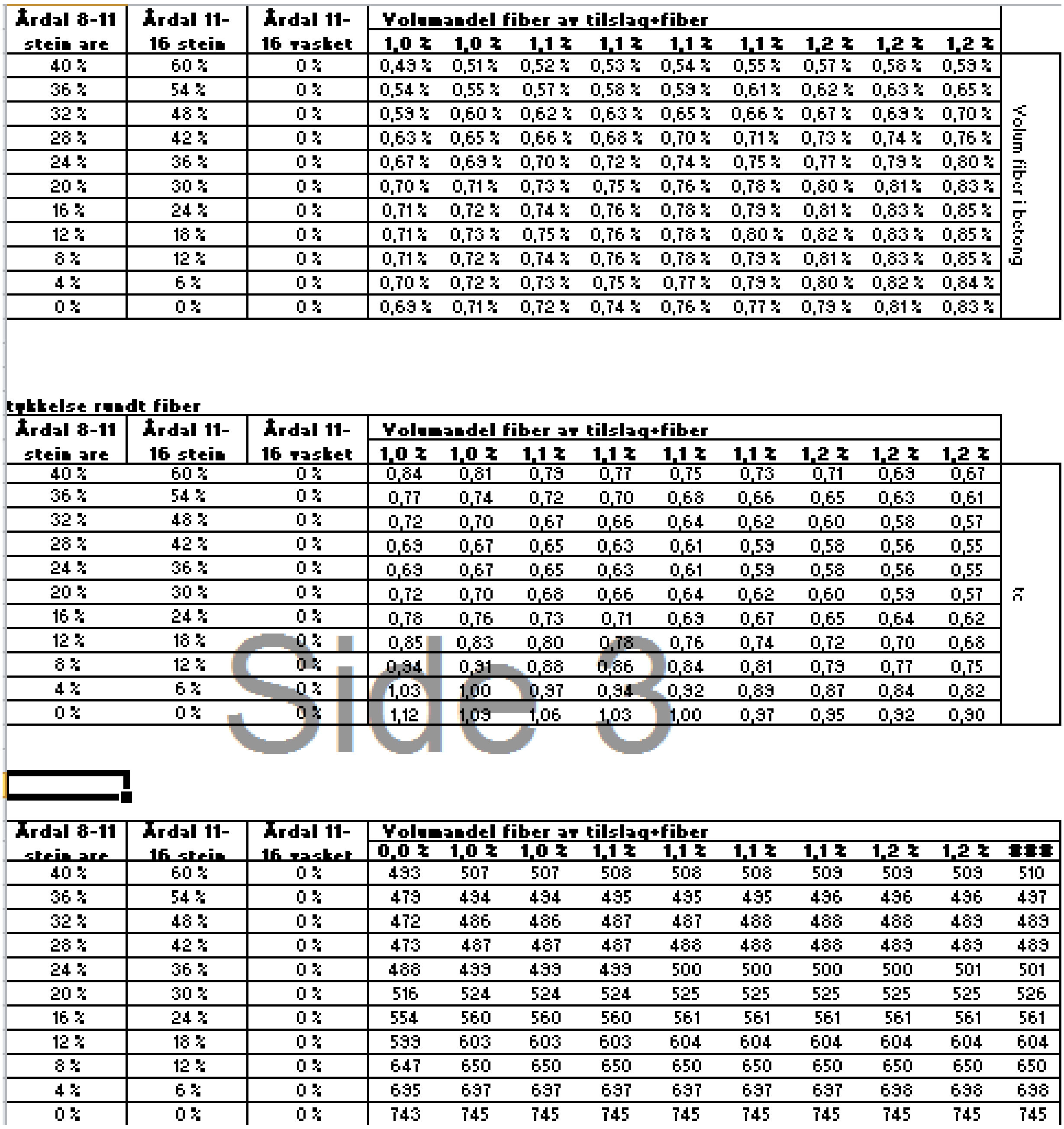
Beregn pakkingstetthet for hele tabellen

(NB! Tar ca 1-3 minutter)

Tilslag 1	Tilslag 2	Tilslag 3	Tilslag 4	Tilslag 5
Årdal 0-2 fra sindre	Årdal 0-8 vasket Stein	Årdal 8-11 stein are	Årdal 11-16 stein are	Årdal 11-16 vasket
0 %	0 %	40 %	60 %	0 %
0 %	10 %	36 %	54 %	0 %
0 %	20 %	32 %	48 %	0 %
0 %	30 %	28 %	42 %	0 %
0 %	40 %	24 %	36 %	0 %
0 %	50 %	20 %	30 %	0 %
0 %	60 %	16 %	24 %	0 %
0 %	70 %	12 %	18 %	0 %
0 %	80 %	8 %	12 %	0 %
0 %	90 %	4 %	6 %	0 %
0 %	100 %	0 %	0 %	0 %

Volumandel fiber av tilslag+fiber	Dramix 65/60								
0,0 %	1,0 %	1,0 %	1,1 %	1,1 %	1,1 %	1,1 %	1,2 %	1,2 %	1,2 %
0,66	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65
0,69	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68
0,73	0,72	0,72	0,72	0,72	0,72	0,72	0,71	0,71	0,71
0,76	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75
0,78	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77
0,80	0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79
0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
0,80	0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79
0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79	0,79

0,0 % fiber av tilslag+fiber (Vfcpm)						
Volum % p<dp/10	Vm1 Enhetsvolum matriks p< dp/10 (Vm)	Volum % p<matriksgrense	Vm2 Enhetsvolum matriks p< matriksgrense	φm (CPM - resultat)	φ	φ/φm
0,2 %	0,49	0,2 %	0,49	0,66	0,51	0,77
6,4 %	0,48	6,4 %	0,48	0,69	0,56	0,80
12,7 %	0,47	12,7 %	0,47	0,73	0,61	0,83
19,0 %	0,47	19,0 %	0,47	0,76	0,65	0,86
25,3 %	0,49	25,3 %	0,49	0,78	0,69	0,88
31,6 %	0,52	31,6 %	0,52	0,80	0,71	0,89
37,8 %	0,55	37,8 %	0,55	0,80	0,72	0,89
44,1 %	0,60	44,1 %	0,60	0,80	0,72	0,89
50,4 %	0,65	50,4 %	0,65	0,80	0,71	0,89
56,7 %	0,70	56,7 %	0,70	0,80	0,70	0,88
63,0 %	0,74	63,0 %	0,74	0,79	0,69	0,88



Årdal 8-11 stein are	Årdal 11-16 stein	Årdal 11-16 vasket	Volumandel fiber av tilslag+fiber									
			1,0 %	1,0 %	1,1 %	1,1 %	1,1 %	1,1 %	1,2 %	1,2 %	1,2 %	
40 %	60 %	0 %	0,49 %	0,51 %	0,52 %	0,53 %	0,54 %	0,55 %	0,57 %	0,58 %	0,59 %	Volum fiber i betong
36 %	54 %	0 %	0,54 %	0,55 %	0,57 %	0,58 %	0,59 %	0,61 %	0,62 %	0,63 %	0,65 %	
32 %	48 %	0 %	0,59 %	0,60 %	0,62 %	0,63 %	0,65 %	0,66 %	0,67 %	0,69 %	0,70 %	
28 %	42 %	0 %	0,63 %	0,65 %	0,66 %	0,68 %	0,70 %	0,71 %	0,73 %	0,74 %	0,76 %	
24 %	36 %	0 %	0,67 %	0,69 %	0,70 %	0,72 %	0,74 %	0,75 %	0,77 %	0,79 %	0,80 %	
20 %	30 %	0 %	0,70 %	0,71 %	0,73 %	0,75 %	0,76 %	0,78 %	0,80 %	0,81 %	0,83 %	
16 %	24 %	0 %	0,71 %	0,72 %	0,74 %	0,76 %	0,78 %	0,79 %	0,81 %	0,83 %	0,85 %	
12 %	18 %	0 %	0,71 %	0,73 %	0,75 %	0,76 %	0,78 %	0,80 %	0,82 %	0,83 %	0,85 %	
8 %	12 %	0 %	0,71 %	0,72 %	0,74 %	0,76 %	0,78 %	0,79 %	0,81 %	0,83 %	0,85 %	
4 %	6 %	0 %	0,70 %	0,72 %	0,73 %	0,75 %	0,77 %	0,79 %	0,80 %	0,82 %	0,84 %	
0 %	0 %	0 %	0,69 %	0,71 %	0,72 %	0,74 %	0,76 %	0,77 %	0,79 %	0,81 %	0,83 %	

tykkelse rundt fiber

Årdal 8-11 stein are	Årdal 11-16 stein	Årdal 11-16 vasket	Volumandel fiber av tilslag+fiber									
			1,0 %	1,0 %	1,1 %	1,1 %	1,1 %	1,1 %	1,2 %	1,2 %	1,2 %	
40 %	60 %	0 %	0,84	0,81	0,79	0,77	0,75	0,73	0,71	0,69	0,67	tc
36 %	54 %	0 %	0,77	0,74	0,72	0,70	0,68	0,66	0,65	0,63	0,61	
32 %	48 %	0 %	0,72	0,70	0,67	0,66	0,64	0,62	0,60	0,58	0,57	
28 %	42 %	0 %	0,69	0,67	0,65	0,63	0,61	0,59	0,58	0,56	0,55	
24 %	36 %	0 %	0,69	0,67	0,65	0,63	0,61	0,59	0,58	0,56	0,55	
20 %	30 %	0 %	0,72	0,70	0,68	0,66	0,64	0,62	0,60	0,59	0,57	
16 %	24 %	0 %	0,78	0,76	0,73	0,71	0,69	0,67	0,65	0,64	0,62	
12 %	18 %	0 %	0,85	0,83	0,80	0,78	0,76	0,74	0,72	0,70	0,68	
8 %	12 %	0 %	0,94	0,91	0,88	0,86	0,84	0,81	0,79	0,77	0,75	
4 %	6 %	0 %	1,03	1,00	0,97	0,94	0,92	0,89	0,87	0,84	0,82	
0 %	0 %	0 %	1,12	1,09	1,06	1,03	1,00	0,97	0,95	0,92	0,90	

Årdal 8-11 stein are	Årdal 11-16 stein	Årdal 11-16 vasket	Volumandel fiber av tilslag+fiber								
			0,0 %	1,0 %	1,0 %	1,1 %	1,1 %	1,1 %	1,1 %	1,2 %	1,2 %	###
40 %	60 %	0 %	493	507	507	508	508	508	509	509	509	510
36 %	54 %	0 %	479	494	494	495	495	495	496	496	496	497
32 %	48 %	0 %	472	486	486	487	487	488	488	488	489	489
28 %	42 %	0 %	473	487	487	487	488	488	488	489	489	489
24 %	36 %	0 %	488	499	499	499	500	500	500	500	501	501
20 %	30 %	0 %	516	524	524	524	525	525	525	525	525	526
16 %	24 %	0 %	554	560	560	560	561	561	561	561	561	561
12 %	18 %	0 %	599	603	603	603	604	604	604	604	604	604
8 %	12 %	0 %	647	650	650	650	650	650	650	650	650	650
4 %	6 %	0 %	695	697	697	697	697	697	697	698	698	698
0 %	0 %	0 %	743	745	745	745	745	745	745	745	745	745