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Concrete with Aalborg Portland cement and fly ash

COIN Project report 24 - 2010

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FA 3.1 Crack free concrete structures

SP 3.1.1 Early age cracking

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Preface

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

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

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

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

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

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

For more information, see www.coinweb.no

Tor Arne Hammer
Centre Manager

Summary

This report summarizes the results from a series of experiments carried out in 7 new dilations rigs measuring autogenous deformation in concrete. The intention was to find a relation between autogenous deformation and relative humidity in three different mixes with three different binders. Another objective was to compare and verify the measurements of the new test rigs with corresponding samples tested according to SINTEF's standardized shrinkage test method, which is described in KS 14-05-04-117.

Three different mixtures were used; one with Portland cement only (Portland cement, class CEM I 52,5 N), one with the same Portland cement and 5,2 % silica by cement weight and the third with the Portland cement and 50 % fly ash by cement weight. Three specimens (100×100×500 mm) were cast from each mixture; two in the new dilation rigs and one for SINTEF's standard shrinkage test method. In addition, a specimen for measuring relative humidity (% RH) was cast from each mixture. Data from the measurements of deformation and relative humidity were collected in order to map the relation between autogenous deformation and relative humidity at certain concrete ages.

Autogenous deformation was measured with LVDTs (electrical transformers commonly used for measuring linear displacement) in the new Dilation Rigs. To measure relative humidity, a VAISALA Concrete Humidity Measurement System was used. All tests were performed in temperature conditioned environments, and a JULABO FP33 was used to regulate the temperature development in the concrete. Deformation of the reference specimens, were measured by the SINTEF standard shrinkage test method.

Some expected results of the concrete were confirmed during the experiments. Fly ash retards the heat development in the concrete, and further the hardening process. The self-desiccation of the concrete slows down, and seems to result in a higher relative humidity for a longer period.

Considering the results from the new rigs towards the SINTEF standard method, the agreement is very good. However, the new shrinkage test method is still under development, for instance the specific time from which strains should be considered has to be decided. This starting time for zero strain will vary, depending on the rate of the specific concrete mixtures' hardening process. The topic is discussed in the report.

When it comes to the relative humidity measurements, these tests must be regarded as a pilot study where the main goal was to develop the test method and investigate the accuracy of the equipment.

Further experiments, reproducibility test and evaluation must be performed before the methods can be considered as reliable test methods. The project group within COIN will continue the work with other mixtures, and try to improve the test procedure if appropriate.

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1 Introduction

1.1 Background, [1]

Volume changes in concrete take place during the hardening process through internal factors and through self-desiccation (i.e.exchange of moisture with the surroundings, external factors). This often takes place under some form of restraint, which creates tensile stresses and possible cracking. The consequences may be substantial costs for repairs. The visual impression of the structure may also be challenged, and cracks can compromise the durability of the structure.

Volume changes and cracking tendency may be strongly influenced by the concrete constituents and their volume proportions. The curing conditions are also very important. Many laboratory experiments and experience from real structures have shown that a high curing temperature increases the risk of cracking due to external restraint. Because of this, focus has been directed towards finding new mix proportions and development of new cement types witch induce lower heat generation in the hardening process.

New types of cement and addition of other binder materials require new knowledge of their properties in concrete, with regard to autogenous deformation, thermal properties and mechanical properties. The experiments described in this report are part of a larger project within COIN where the intention is to gather more information about new materials and mix proportion.

1.2 Principal objectives and scope

The objective of the tests described in this report was to investigate the volume changes produced by the concrete itself (autogenous deformation) in concretes made with Portland cement, CEM I 52,5 N (MS/LA/ ≤ 2) without and with pozzolanic additions of silica fume or fly ash. The objective was to develop a method for relative humidity (% RH) measurements, in order to correlate RH and deformation.

If a relation between autogenous deformation and relative humidity can be determined, it might be possible to predict the remaining shrinkage in a structure by measuring the relative humidity. This can be especially feasible for concrete slabs.

To be able to do all the required measurements, a research group with strong relations to COIN has developed and built a new test-rig for measuring autogenous deformation at isothermal or realistic temperature conditions in concrete. In addition a set-up for measuring relative humidity was used. A pilot project was performed to test and calibrate the rig in May/June 2010. This report describes the first full-scale test-series.

2 Materials

2.1 Cement

In these experiments a Portland cement; CEM I 52.5 N (MS/LA/≤ 2), Aalborg Rapid, was used. The specification as provided by the manufacturer is provided in Table 1.

Physical properties	**Specifications**
1-day strength	23 MPa
2-day strength	35 MPa
7-day strength	53 MPa
28-day strength	66 MPa
Setting time	126 minutes
Fineness	442 m^2/kg
Absolute density	3120 kg/m^3
Heat development	356 kJ/kg
α	1.04
τ	12.0 hours
Bogue composition	
C_3S	62 %
C_2S	13 %
C_3A	8 %
C_4AF	13 %
Secondary components and additives	
SO_3	3.2 %
MgO	0.9 %
Eqv. Na_2O	0.6 %
Cl^-	0.03 %
Loss on ignition (LOI)	2.5 %
Insoluble residue	0.7 %

Table 1: Specifications – Cement [2]

2.2 Pozzolanic additions

Silica fume

Elkem Micro silica Grade 940 Undensified was used in these experiments. Specifications are listed in Table 2.

Chemical and physical requirements	**Specifications**
SiO_2 (%)	> 90
H_2O (moisture content when packed, %)	< 1,0
Loss on ignition (%)	< 3,0
Retained on 45 micron sieve (%)	< 1,5
Bulk density (when packed, kg/m^3)	200 - 350

Table 2: Specifications – Silica fume [3]

Fly ash
The fly ash was supplied by Norcem (LN21-02). The composition and physical properties are listed in Table 3.

Chemical and physical requirements	Specifications
SiO_2	54.40 %
Al_2O_3	22.01 %
Fe_2O_3	5.83 %
CaO	4.80 %
MgO	2.22 %
K_2O	2.21 %
Na_2O	1.15 %
C	3.64 %
Loss on ignition (LOI)	4.08 %
SO_3	0.52 %
Blaine	388 m^2/kg
Specific density	2.20 g/cm^3
Sieve analysis	
90 [μm]	3.8 % Acc.
64 [μm]	11.8 % Acc.
30 [μm]	58.2 % Acc.
24 [μm]	100 % Acc.

Table 3: Composition and physical properties - Fly-ash [4]

2.3 Admixtures

Super plasticizer
A polycarboxylate based super plasticizer, BASF Glenium Sky 552, was used for all mixes. Specifications are listed in Table 4.

Properties	Declares values
Dry substance	(17.5 ± 1.0) %
Density	(1.04 ± 0.02) kg/l
pH-value	6.5 ± 1.5
Equivalent Na2O	< 2.0 %
Chloride content	< 0.01 %

Table 4: Specifications – Super-plasticizer [5]

2.4 Aggregates

Each of the concrete mixes contained three fractions of aggregate; one fraction from Årdal (16-24 mm) and two fractions from Svelvik (0-8 and 8-16 mm).

Årdal aggregate is dominated by granite and gneiss, and has an expected E-modulus of 32 GPa. Svelvik aggregate is dominated by gneiss/granite, feldspatic rocks, dark rocks and sedimentary rocks.

Sieve analysis and humidity tests were performed before mixing, and data are included in the proportioning spreadsheets shown in Appendix A1.

3 Concrete mixing forms

3.1 Mixture 1, 2 and 3

The mixing forms for mixture 1, 2 and 3 are shown in Table 5, while further details are reported in the proportioning spreadsheets which are included in Appendix A2.

Mixture 2 is a reference mix without pozzolanic materials, while Mixture 1 has a silica/cement ratio of 5.2 % by cement weight and Mixture 3 has a fly ash/cement-ratio of 50 % by cement weight. The mix with 50 % fly ash is expected to have a retarded hardening process, and thereby a lower heat development which might lead to reduced autogenous deformation in the concrete.

Materials	**Mixture 1**	**Mixture 2**	**Mixture 3**
	Recipe [kg/m^3]	**Recipe [kg/m^3]**	**Recipe [kg/m^3]**
$(w/(c + k_s \cdot s + k_{FA} \cdot FA))$[1]	0.40	0.40	0.45
Cement	385	424	250
Silica fume	20	0	0
Fly ash	0	0	125
Total quantity of added water	180	180	148
Svelvik gravel 0/8	936	940	940
Svelvik gravel 8/16	312	314	314
Årdal gravel 16/24	589	591	591
Super plasticizer	3.0	3.0	5.0
s/c	5.2 %	-	-
f/c	-	-	50 %
f/b	-	-	30 %

Table 5: Recipes mixture 1, 2 and 3

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[1] For these mixtures, the following k-values were used: $k_s = 2.0$ and $k_{FA} = 0.4$

4 Test procedure and equipment

4.1 Mixing and casting

The concrete was mixed in an Eirich paddle mixer with a capacity of 50 litres. The materials were added according to the following procedure:

1.	Dry mixing	1 min
2.	Wet mixing	2 min
3.	Standstill	1 min
4.	Wet mixing	2 min

The admixtures were added in step 2, together with the mixing water. Water and admixtures are added within 30 sec.

Slump, air-content and density in the fresh concrete were measured directly after mixing.

From each mixture, two dilatation rig specimens of 100×100×500 mm for measuring autogenous deformation and one specimen in a 1 litre plastic bottle for measuring relative humidity were cast. One specimen of 100×100×500 mm was cast parallel to this at SINTEF's concrete laboratory for verification of the autogenous deformation results.

4.2 Dilatation rigs – Set-up and operational procedures, [6]

The set-up, see Figure 1 and 2, consists of rectangular cuboid moulds which measure 100×100×580 mm inside. The moulds are made of 10 mm thick steel plates.

The moulds were internally lined with a layer of adhesive plastic foil and two thin layers of plastic film. Talcum powder was applied between each layer to reduce friction. This makes it possible for the specimen to expand or shrink freely.

The length of the specimens will be 500 mm, and the remaining part of the mould is filled with a piece of extruded polystyrene on each short end. The piece of polystyrene has a whole for LVDTs. LVDT is a type of electrical transformer commonly used for measuring linear displacement. The LVDTs register deformation in the longitudinal direction on each short end of the specimens.

The transmitters are connected to each other with an independent Invar steel bar, and the transmitters are connected with the specimen with Invar pins which goes through the piece of polystyrene and into the specimen.

In addition, each mould is designed with two 6 mm copper pipes on three of the lateral surfaces. These are connected in series to a cooling/heating simulator (Julabo FP33). This is a temperature controlled bath with a pump which provides that a fluid circulates through the rig. Temperature can be regulated from a computer or by manually programming of the bath. In the present test series this simulator circulates water with a temperature of 19.5 ºC to control the temperature development in the concrete. The temperature can, however, be altered and more realistic temperature histories can be described and applied to the concrete specimen.

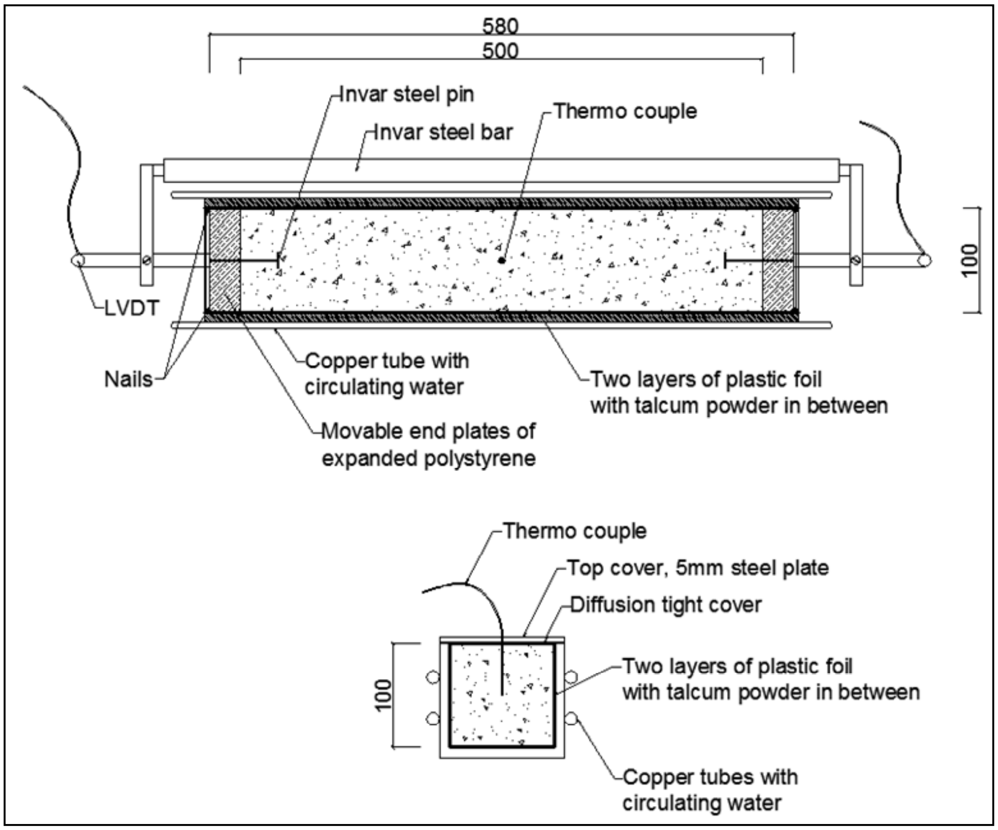

Figure 1: Dilation Rig

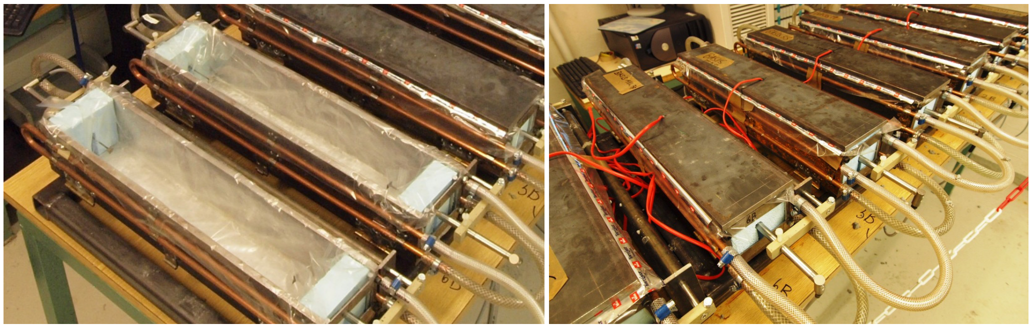

Figure 2: Moulds ready for casting and after covering of specimens

Concretes were cast into the moulds and compressed by hand, using a casting ladle. After compaction, the concrete surfaces were covered with plastic film, then an aluminium foil and detached a 5 mm thick steel plate to keep the plastic/aluminium foil sealing in place. A thermo couple was put centrically into each specimen through the top steel plate.

Once the hardening of the concrete was initiated, the piece of extruded polystyrene was liberated in the longitudinal direction by removing two nails on each short end of the mould. This was done to ensure freely movement of the specimens. At this time the LVDTs were reset as well.

The rig stood in a conditioning room which was set to hold 20 °C and 50 % relative humidity. Instruments for measuring temperature and relative humidity in the room were used to record the conditions in the room.

4.3 Control measurements

For verifications of the test results in the dilation rigs, an extra 100×100×500 mm specimen was cast from each mixture. This was tested in SINTEFs concrete laboratory according to procedure KS 14-05-04-117, which describes a method for measuring drying shrinkage of hardened concrete, but in this case the specimens were sealed to measure autogenous deformation.

For this method, the concrete was cast into moulds with special measurement studs (20 mm) placed centrically in each short-end. The concrete was filled into the mould in two layers, and each layer was compacted by hand, using a casting ladle. Extra attention is paid around corners, along edges and around the knobs during compaction.

The surface of the prisms were covered with plastic and stored in the laboratory at 20 ± 4°C until demoulding at an age 22 ± 2 hours. The specimens were then sealed in plastic and aluminium foil to avoid external drying and marked with ID and an arrow to indicate which end should point upwards when measuring the length. One must also make sure that the knobs are fixed to the specimens.

The prisms were stored in a conditioning room at 20 ± 2 °C and 50 % relative humidity. Length and weight of the specimens were measured at 1, 5, 8, 11 and 20 day's age.

The following exception from the procedure was made to achieve approximately equal conditions for the control prisms as for the specimens in the dilation rig:

- The specimens were not stored in water for 7 days before placing in the conditioning room. Instead, they were placed directly in the room after demoulding and packing.

4.4 Relative humidity in concrete, [7]

From each mixture a specimen was cast in a closed plastic bottle (1 litre Nalgene bottle) for measuring relative humidity (% RH) in the concrete parallel to the deformation and temperature measurements, see Figure 3.

A plastic tube with a diffusion open tape in the bottom was cast into each bottle. The end of the tube was approximately 6.5 cm down in the specimen. Afterwards the bottles were sealed with a perforated lid, in such a way that the pipe went through. Putty was used to seal the top of the pipes carefully.

% RH was measured with a Vaisala HM44 Concrete Humidity Measurement System. In addition to measuring relative humidity, the sensors also measure temperature inside the specimens. The following accuracy for the sensors are given by the producer(the sensors are calibrated at delivery);

0-90 % RF → ± 2 % RF
90-100 % RF → ± 3 % RF
Accuracy at 20 °C → ± 0.4 °C

Before each measurement, the tube sealing was removed, and the sensors were immediately placed into the plastic tubes. They were left in the tubes 30 minutes before the RH-values were recorded. According to the producer, 30 minutes is a minimum time period to ensure that RH has stabilized. It was also argued that there is a certain risk of drifting of the sensors if they are exposed to high values of relative humidity for a longer period. Because of this, the sensors were removed after each measurement. The specimens were stored in 20 °C and 50 % RH climate during the test period.

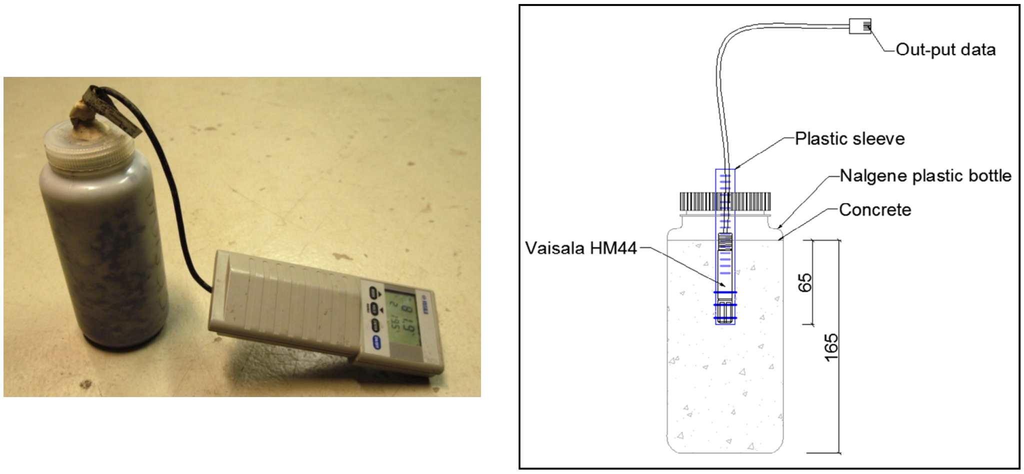

Figure 3: Specimen for RH-measurements

To verify the measured RH-values, the Vaisala sensors were calibrated a few times during the test period. The calibration is performed in sealed containers with different salt solutions inside. Depending on the salt used, the air above the salt solution will reach a certain relative humidity at a certain temperature. The calibration equipment is shown in Figure 4, and data for the selected salt solutions are given in Table 6. The calibration was performed at 23 ± 0.5 °C and 50 ± 2 % RH.

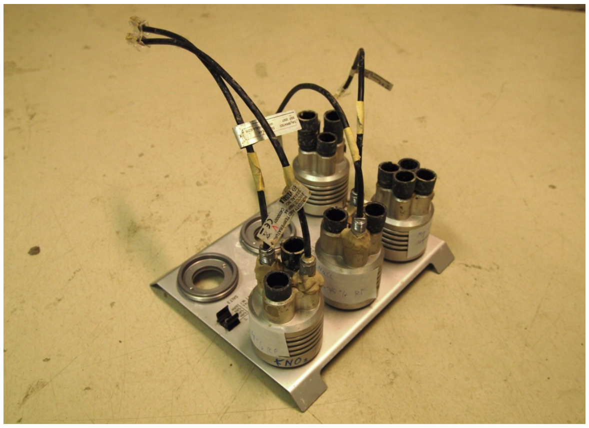

Figure 4: Equipment for calibrating Vaisala sensors

Solid phase	% Humidity at Specified Temperatures			
	10 °C	20 °C	25 °C	30 °C
KNO_3	95	93	92.5	91
NaCl	76	75.7	75.3	74.9
K_2SO_4	98	97	97	96

Table 6: Humidity at specified temperatures for selected salt solutions

5 Test results

5.1 Curing conditions

The rig was placed in a conditioning room which was planned to hold 20 °C and 50 % RH. However, a stable temperature and humidity level was not achieved. The room temperature was held with an accuracy of 20 ± 2 °C, with a deviation after approximately 120 hours when the conditioning system was out of function during the weekend. RH was held at 50 ± 15 %. Work will continue to improve the stability. Variations in the relative humidity did probably not affect the concrete much, since the prisms were stored in closed system. However, the temperature variations will influence the measured deformations because the LVDT's are placed outside the specimens and are exposed to a temperature history which differs from the concrete.

Figure 5 shows measured values for concrete temperatures inside the specimens as well as temperature and relative humidity in the room during the test period of 480 hours. Figure 5 shows variations of the concrete temperature from 19.5 °C for mixture 2 to 20.5 °C for mixture 3. The thermo couples were not calibrated in the experiment, and this may explain the variations in temperature between the three mixtures. For future experiments a calibration of the thermo elements should be done.

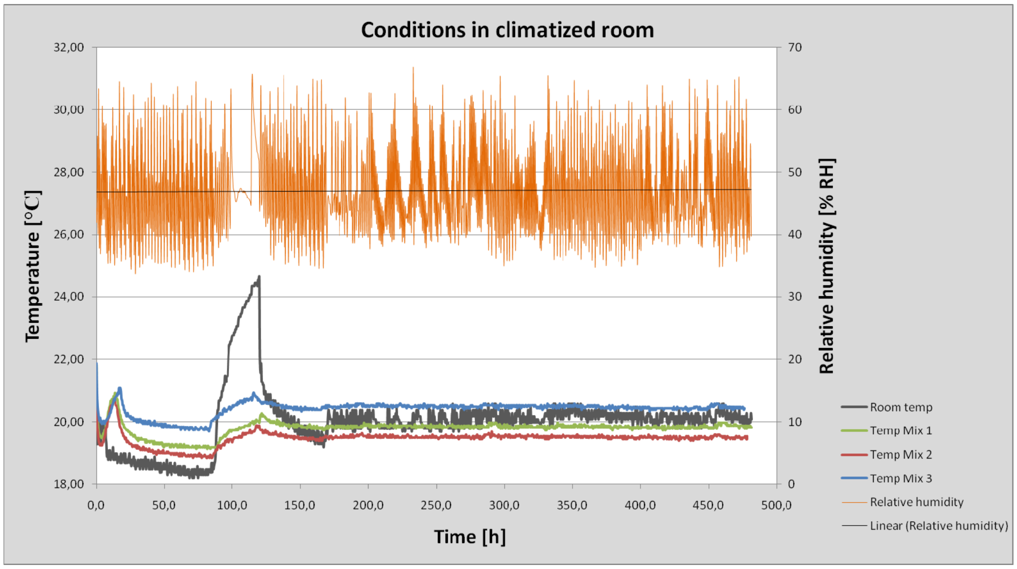

Figure 5: Temperature and relative humidity in the conditioning room

5.2 Fresh concrete properties

The results from testing of the fresh concrete are given in Table 7. Time after addition of water is given in parenthesis. Fresh properties were not the main issue for these tests, and no further comments are included in this report.

Fresh concrete	**Mixture 1**	**Mixture 2**	**Mixture 3**
Slump [mm]	210 (10 min)	210 (13 min)	250 (12 min)
Slump Flow [mm]	-	-	620 (12 min)
Air-content [%]	2.8 (20 min)	1.7 (23 min)	0.9 (22 min)
Density[kg/m^3]	2430 (18 min)	2460 (21 min)	2450 (20 min)

Table 7: Fresh concrete properties

5.3 Relative humidity

Table 8 to 10 show the results from the RH-measurements (calibrated values) inside the plastic bottles for Mixture 1-3. The values are also shown in Figure 6, together with the temperature curves from the dilation rig.

Concrete age		Sensor No.	RH in concrete	Temperature [°C]
[h]	[days]		[%]	
121	5	14	74.2	21.9
144	6	14	80.5	19.4
169	7	14	83.6	18.8
482	20	6	67.5	19.3
488	20	6	69.0	20.1

Table 8: % RH Mixture 1 (silica fume)

Concrete age		Sensor No.	RH in concrete	Temperature [°C]
[h]	[days]		[%]	
120	5	6	80.5	22.0
141	6	6	84.7	19.5
166	7	6	86.7	18.9
479	20	1	(52.5)[2]	19.4
485	20	1	(54.5)[2]	19.7

Table 9: % RH Mixture 2 ("reference")

Concrete age		Sensor No.	RH in concrete	Temperature [°C]
[h]	[days]		[%]	
117	5	1	88.5	22.0
139	6	1	90.0	19.5
164	7	1	92.0	19.0
477	20	2	92.0	19.4
483	20	2	92.0	19.5

Table 10: % RH Mixture 3 (Fly ash)

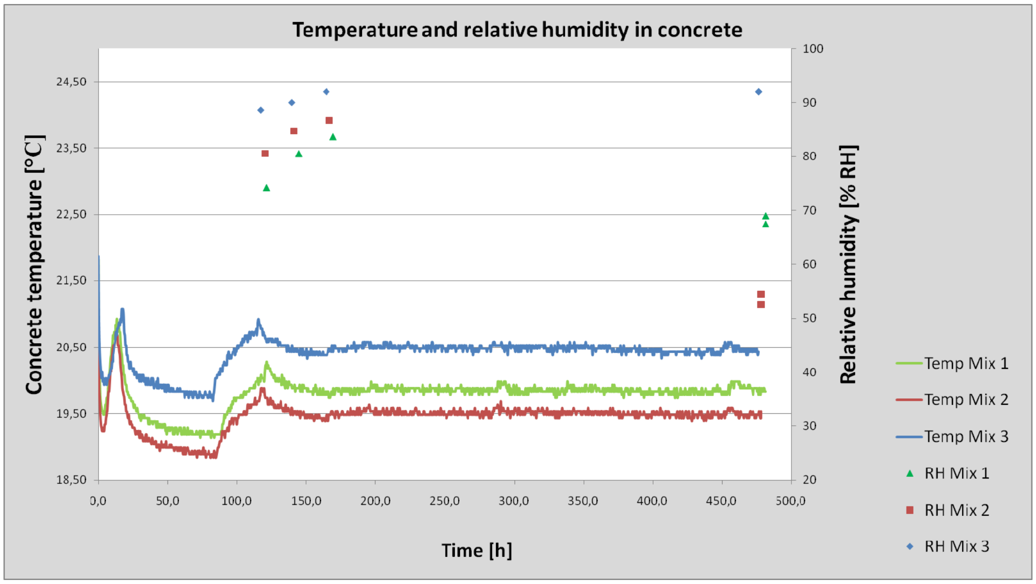

Figure 6: Relative humidity and temperature in Mixture 1, 2 and 3

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[2] The calibrated values had large deviation from non-calibrated values for this individual test. The reason for this is unknown and the values might not be reliable.

As can be seen in the tables 8 to 10 and in figure 6, mixture 3 deviated from the other two mixes by maintaining a high value of relative humidity during the whole test period. The deviating behaviour of Mix 3 is probably due to the added fly-ash. Fly ash retards the heat development in the concrete, as well as the hardening process. The self-desiccation of the concrete thus slows down, contributing to a higher relative humidity for a longer period.

Both mixture 1 and 2 had a clear decrease of % RH towards the end of the test period, which was larger than expected. Experiments on similar concretes with Standard FA cement and v/c=0.4 have shown a decrease from 97 to 89 % RH during the first 20 days [8]. That gives an 8 % decrease, while the values for mixture 1 and 2 indicate a 15 to 30 % reduction in % RH during the 20 days test period, which is extraordinary large.

The values also indicate that there is an increase of % RH in the beginning of the test period for all mixes. This is not in agreement with experience from previous experiments and common knowledge. % RH normally starts at a high value, and decreases as the concrete hardens. This error can be related to the increase in room temperature between 90 and 100 hours, see figure 5. The temperature increase did not last long enough for the concrete to stabilize on a higher temperature. Thus, the sensors, which were stored in the room, held a temperature of approximately 4 °C higher than the average concrete temperature. When inserting the sensors (24 °C) into the specimens (20 °C), it might have lead to a heating of the cavity in the concrete, and further resulting in lower RH-value measurements.

In this experiment, the relative humidity was recorded after storing the sensors in the specimens for 30 minutes. According to the producer, this should be enough. However, experience from other experiments and unpublished work has shown that the sensors must be left in the specimens for 4-6 days for the relative humidity to stabilize. This might be because the concrete surface in the hole is exposed to some drying when inserting or removing the sensors. The concrete needs time to compensate for this drying and restore a relative humidity in the small hole which should be representative for the whole specimen. The values measured after 30 minutes might be 5-10 % lower than the values measured after 6 days. According to the Swedish council of construction industry, RBK [9], measurements with Vaisala sensors should not occur until 12 hours after installation for v/c > 0.4 and 48 hours for v/c < 0.4. This is in agreement with experience from this project.

The values in the last column of the tables 8 to 10 are temperatures measured inside the specimens with the Vaisala sensors. These values show some variations between the three mixtures at the same measuring point, but this is most likely related to calibration of the sensors and not temperature differences between the three specimens.

For further experiments the sensors should be left in the specimens during the whole test period, and only removed for short periods when calibration is necessary. In addition, control measurements of RH on crushed specimens put on glass tubes should be performed at specific time intervals on parallel specimens. Unpublished results have shown that the RH-values for crushed concrete can be 2-6 % higher, depending on the v/b-ratio. In addition, the sensors should be calibrated with regard to temperature together with the calibration of relative humidity.

5.4 Autogenous deformation, [10]

Defining the setting time zero for a certain concrete is one of the main issues when it comes to understanding autogenous deformation in concrete. Earlier experiments have shown that the parameter time zero, t_0, is difficult to detect through indirect methods such as early heat liberation, $t_{Q=12kJ}$. Setting according to heat is experienced to be around 2-3 hours earlier than setting according to semi-adiabatic tests in e.g. a TSTM rig. An appropriate t_0 for stress calculations has shown to be the point in time where the TSTM has developed 1/10 of the maximum compressive strength during the heating period.

Earlier experiments where t_0 was determined in a TSTM rig showed that t_0 increased from 13 hours to 15 hours when the fly ash content increased from 0 to 35 %. Silica fume (Mix 1) has been shown to shorten t_0. If this is taken into consideration in these experiments performed in the dilation rig, one can assume the following time zero for the three mixtures:

Mixture 1	$t_0 =$ 9 hours
Mixture 2	$t_0 =$ 11 hours
Mixture 3	$t_0 =$ 13 hours

The deformation measurements in the dilation rigs were initiated 5-6 hours after casting. This is long before final set and therefore the "semi-plastic" phase is part of the first hours of all curves. The average autogenous deformation results for each of the three mixtures are shown in Figure 7. Further, the values for the SINTEF reference prisms are included. Concrete temperature and RH-values are plotted on the secondary axis.

Figure 7: Autogenous deformation and % RH – Mixture 1, 2 and 3

When the measured strains are gathered in Figure 7, it seems that the autogenous shrinkage was largest for mixture 3 which contains a large amount of fly-ash. This is not in agreement with general knowledge and is due to the unclear definition of the time zero for measurement start. The general knowledge is that concrete containing FA develops less autogenous shrinkage than other concrete.

If it is assumed that t_0 = 9 hours for all three mixtures, the development will be as shown in Figure 8.

Figure 8: Autogenous deformation, t_0 = 9 hours

Figure 9 shows curves where t_0 is set to 9, 11 and 13 hours for Mixture 1, 2 and 3, respectively. This probably gives a more correct picture of the development of autogenous deformation. However, regardless of time zero, the results show that Mixture 3 has the highest autogenous deformation the first 20 hours.

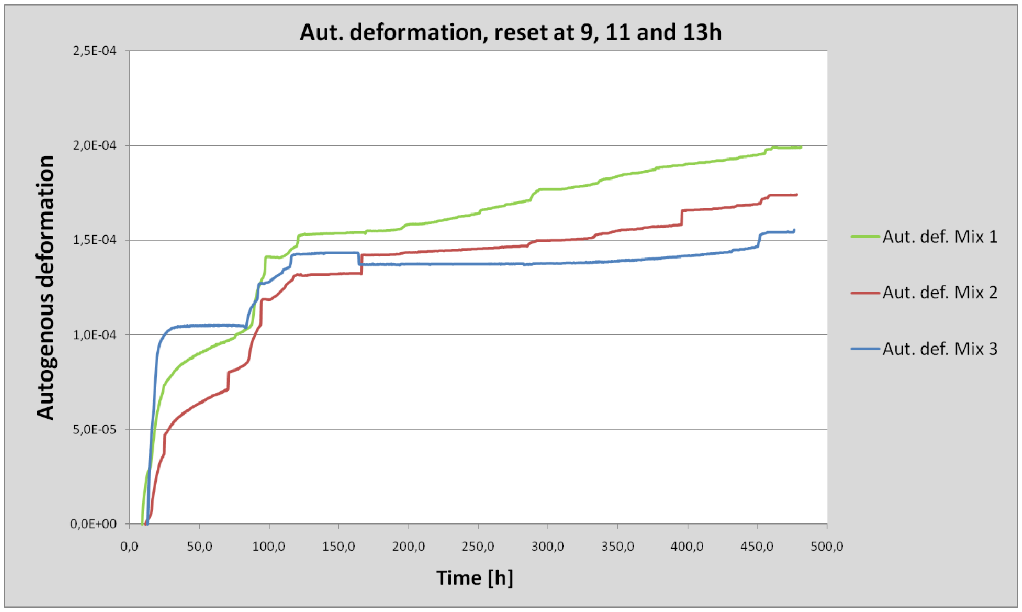

Figure 9: Autogenous deformation, t_0 = 9, 11 and 13 hours

The first measurements for the SINTEF reference prisms were performed after 24 hours. For comparison, the starting-point for the control prism curves is set to be the 24h-value for the corresponding Dilation rig curve. This is shown in Figure 10.

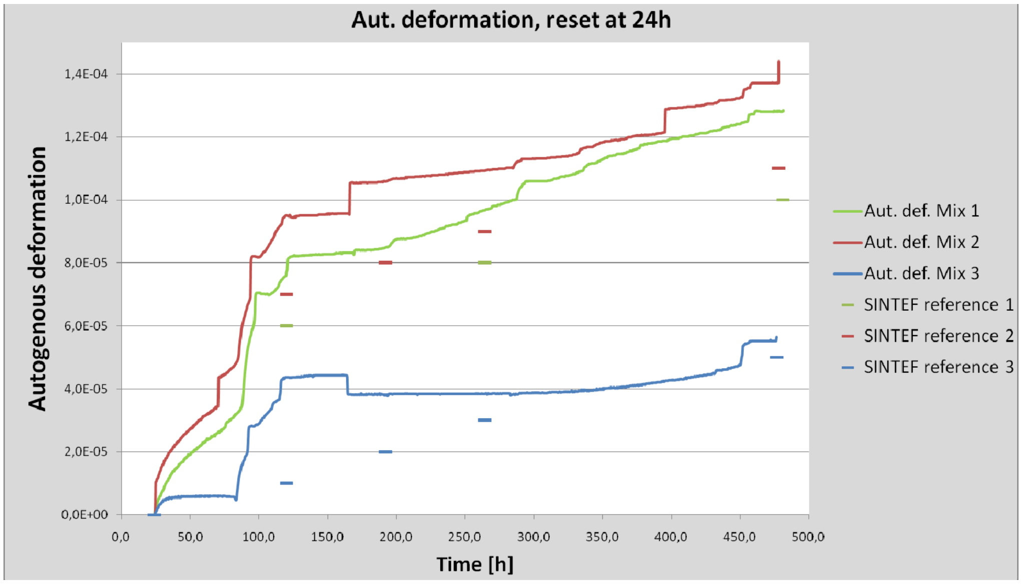

Figure 10: Autogenous deformation, t0 = 24 hours, comparison with SINTEF reference

When the strain development after 1 day is compared, it is seen that fly-ash concrete has the lowest shrinkage. While mixture 1 has approximately $170 \cdot 10^{-6}$ after 3 weeks, mixture 2 has $140 \cdot 10^{-6}$ while mixture 3 has only $60 \cdot 10^{-6}$. This means that the fly ash concrete might be less vulnerable to shrinkage cracking than the two other mixtures.

Considering the results from the new dilation rigs and the SINTEF standard method, the agreement is very good; all final results are within limits of $\pm 25 \cdot 10^{-6}$ (micro strains). This confirms the first experiments with the new rigs.

As can be seen in figure 7 to 10, the curves are not very smooth. They include some jumps which are not related to material behaviour. This can be explained by external influence on the rig, i.e. temperature increase or touching of the rig, or because of internal friction and holding of the LVDTs. For later experiments actions should be taken to reduce this.

Approximately 80 hours after casting, accelerated strain development (contraction) seemed to occur in all the specimens in the new test rig. Corresponding behaviour was not seen in the specimens for the SINTEF method. The explanation may be due to the uncontrolled variation in room temperature seen in figure 5. The concrete is isothermal while the measuring equipment is affected by the room climate.

6 Conclusions

The procedure for measuring relative humidity in “fresh” concrete is still under development, and there are great uncertainties attached to the presented results. The relatively irregular results are related to the test procedure, and the results can not be regarded as reliable. However, these experiments have been an important step on the road to find a reliable test procedure to measure relative humidity in concrete.

Because of the difficulties with the RH-measurements mentioned above, it is impossible to draw any conclusions on the relation between relative humidity and autogenous deformation in concrete at this stage.

If we study the strain development beyond 1 day, it is seen that fly-ash concrete has the lowest shrinkage. The same is valid if one assumes t_0 = 9, 11 and 13 hours for the three mixtures.

For later experiments a method for determine setting time zero must be used. In addition to the TSTM method mentioned in chapter 5, a temperature criterion can be used; t_0 can be determined according to a 2 °C/12kJ criteria + 2 hours by use of a calorimeter [11].

The agreement between the SINTEF test method and the results from the new dilation rigs seems to be rather good. If one exclude the apparent increase of shrinkage at the point in time where the room temperature increases, the autogenous deformation measured with the two test methods gives overall a reasonably good correspondence. The present results have pointed out the need for further work on test set-ups and climate control.

7 Recommended further research

For further research, focus should be aimed towards the following topics:

- Develop a criterion for the zero-point for deformation curves for example according to the temperature criteria 2 °C/12kJ criteria + 2 hours.
- Work to improve the climatic conditions in the test room to get a more stable temperature to avoid the T-disturbance of the LVDTs.
- Increase the conditioning room RH to reduce the RH-difference between specimens and air.
- Work to improve the reliability of the relative humidity measurements to be able to map the relation between autogenous deformation and % RH.
- Investigate and map the influence of the concretes temperature history on autogenous deformation.
- Perform experiments to measure the long time deformation development, for instance during 6 months.

8 Acknowledgement

The new Dilation Rigs could not have been developed and built without good support from and co-operation with all the contributors in this COIN Project 3.1. We want to thank NTNU, SINTEF, Skanska, The Norwegian Public Roads Administration, Unicon and Norcem for participating. Special thanks to Ove Loraas and Steinar Seehuus at NTNU who have produced the rig, and to Lars Haugan, SINTEF, who was responsible for pilot tests and initialisation of the tests described in this report.

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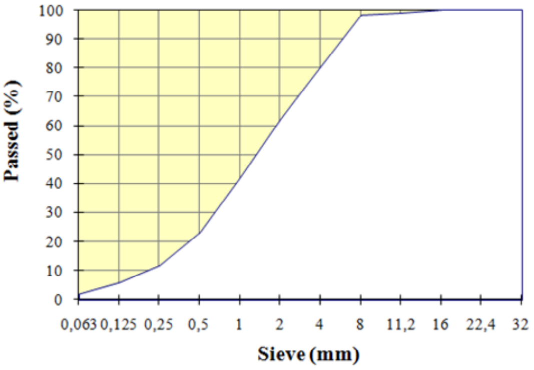
Appendix A1

Aggregate – Fraction I

Type:	Svelvik 0/8
Date:	2009-10
FM =	3,29

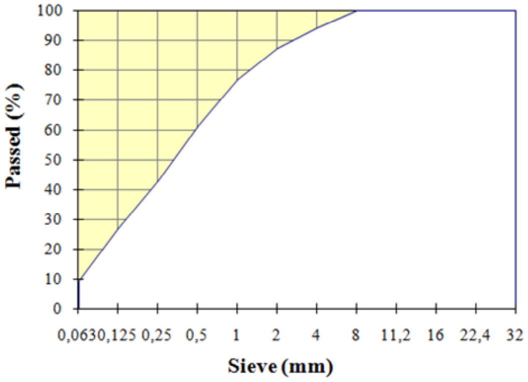
Sieve	Sieve residue (g)		Sieve residue (%)	Passed (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	10,5	10,5	1,0	99,0
8	17,5	17,5	1,7	98,3
4	195,7	195,7	19,6	80,4
2	378,1	378,1	37,8	62,2
1	579	579	57,8	42,2
0,5	768,2	768,2	76,7	23,3
0,25	881,6	881,6	88,1	11,9
0,125	940,3	940,3	93,9	6,1
0,063	980,0	980,0	97,9	2,1
Bottom	1001	1001		



Aggregate – Fraction II

Type:	Svelvik 8/16
Date:	2009-10
FM =	1,74

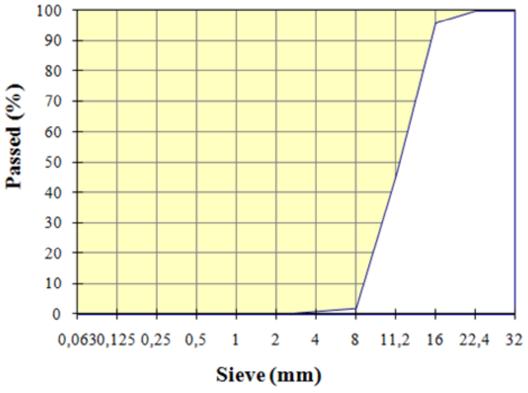
Sieve	Sieve residue (g)		Sieve residue (%)	Passed (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	0	0	0,0	100,0
4	29,2	28,8	5,8	94,2
2	63,9	62,4	12,7	87,3
1	115,4	115	23,1	76,9
0,5	191,9	193,4	38,6	61,4
0,25	282,6	285,1	56,9	43,1
0,125	362	364	72,8	27,2
0,063	449	454	90,6	9,4
Bottom	498	499		



Aggregate – Fraction III

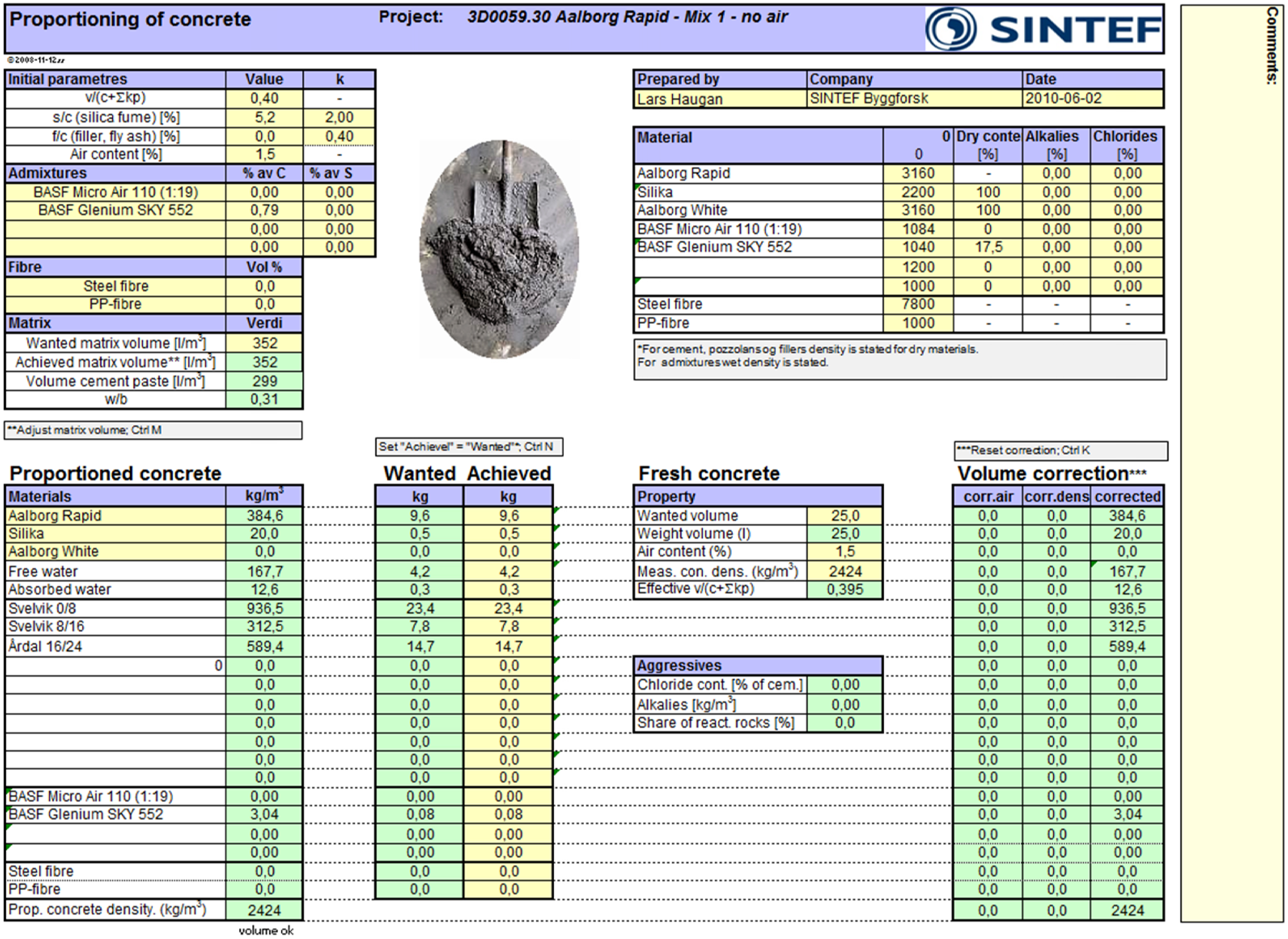
Type:	Årdal 16/24
Date:	2008-11-21
FM =	6,51

Sieve	Sieve residue (g)		Sieve residue (%)	Passed (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	3	5	4,0	96,0
11,2	55	54	54,5	45,5
8	98	98	98,0	2,0
4	99	99	99,0	1,0
2	100	100	100,0	0,0
1	100	100	100,0	0,0
0,5	100	100	100,0	0,0
0,25	100	100	100,0	0,0
0,125	100	100	100,0	0,0
0,063	100	100	100,0	0,0
Bottom	100	100		



Appendix A2

Mixture 1



Comments:

Proportioning of concrete

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Project: *3D0059.30 Aalborg Rapid - Mix 1 - no air*

SINTEF

Initial parametres	Value	k
v/(c+Σkp)	0,40	-
s/c (silica fume) [%]	5,2	2,00
f/c (filler, fly ash) [%]	0,0	0,40
Air content [%]	1,5	-
Admixtures	**% av C**	**% av S**
BASF Micro Air 110 (1:19)	0,00	0,00
BASF Glenium SKY 552	0,79	0,00
	0,00	0,00
	0,00	0,00
Fibre	**Vol %**	
Steel fibre	0,0	
PP-fibre	0,0	
Matrix	**Verdi**	
Wanted matrix volume [l/m³]	352	
Achieved matrix volume** [l/m³]	352	
Volume cement paste [l/m³]	299	
w/b	0,31	

**Adjust matrix volume; Ctrl M

Prepared by	Company	Date
Lars Haugan	SINTEF Byggforsk	2010-06-02

Material	0 0	Dry conte [%]	Alkalies [%]	Chlorides [%]
Aalborg Rapid	3160	-	0,00	0,00
Silika	2200	100	0,00	0,00
Aalborg White	3160	100	0,00	0,00
BASF Micro Air 110 (1:19)	1084	0	0,00	0,00
BASF Glenium SKY 552	1040	17,5	0,00	0,00
	1200	0	0,00	0,00
	1000	0	0,00	0,00
Steel fibre	7800	-	-	-
PP-fibre	1000	-	-	-

*For cement, pozzolans og fillers density is stated for dry materials.
For admixtures wet density is stated.

Set "Achieved" = "Wanted"; Ctrl N

***Reset correction; Ctrl K

Proportioned concrete / **Wanted** / **Achieved** / **Volume correction*****

Materials	kg/m³	Wanted kg	Achieved kg	corr.air	corr.dens	corrected
Aalborg Rapid	384,6	9,6	9,6	0,0	0,0	384,6
Silika	20,0	0,5	0,5	0,0	0,0	20,0
Aalborg White	0,0	0,0	0,0	0,0	0,0	0,0
Free water	167,7	4,2	4,2	0,0	0,0	167,7
Absorbed water	12,6	0,3	0,3	0,0	0,0	12,6
Svelvik 0/8	936,5	23,4	23,4	0,0	0,0	936,5
Svelvik 8/16	312,5	7,8	7,8	0,0	0,0	312,5
Årdal 16/24	589,4	14,7	14,7	0,0	0,0	589,4
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	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
BASF Micro Air 110 (1:19)	0,00	0,00	0,00	0,0	0,0	0,00
BASF Glenium SKY 552	3,04	0,08	0,08	0,0	0,0	3,04
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
Steel fibre	0,0	0,0	0,0	0,0	0,0	0,0
PP-fibre	0,0	0,0	0,0	0,0	0,0	0,0
Prop. concrete density. (kg/m³)	2424			0,0	0,0	2424

volume ok

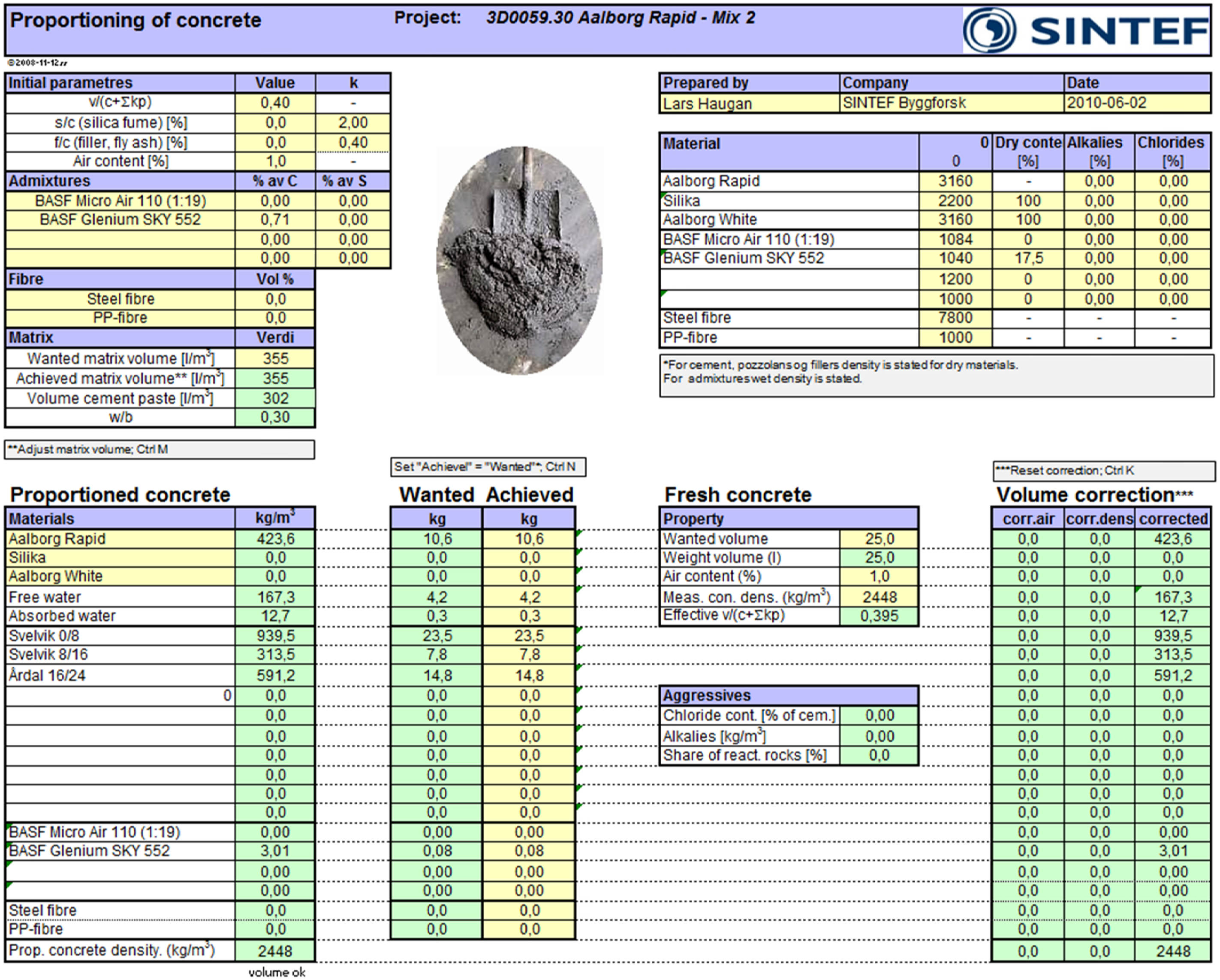
Fresh concrete

Property	
Wanted volume	25,0
Weight volume (l)	25,0
Air content (%)	1,5
Meas. con. dens. (kg/m³)	2424
Effective v/(c+Σkp)	0,395

Aggressives	
Chloride cont. [% of cem.]	0,00
Alkalies [kg/m³]	0,00
Share of react. rocks [%]	0,0

Mixture 2

Comments:



Proportioning of concrete **Project:** *3D0059.30 Aalborg Rapid - Mix 2*

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Initial parametres	Value	k
v/(c+Σkp)	0,40	-
s/c (silica fume) [%]	0,0	2,00
f/c (filler, fly ash) [%]	0,0	0,40
Air content [%]	1,0	-
Admixtures	**% av C**	**% av S**
BASF Micro Air 110 (1:19)	0,00	0,00
BASF Glenium SKY 552	0,71	0,00
	0,00	0,00
	0,00	0,00
Fibre	**Vol %**	
Steel fibre	0,0	
PP-fibre	0,0	
Matrix	**Verdi**	
Wanted matrix volume [l/m³]	355	
Achieved matrix volume** [l/m³]	355	
Volume cement paste [l/m³]	302	
w/b	0,30	

**Adjust matrix volume; Ctrl M

Prepared by	Company	Date
Lars Haugan	SINTEF Byggforsk	2010-06-02

Material	0 0	Dry conte [%]	Alkalies [%]	Chlorides [%]
Aalborg Rapid	3160	-	0,00	0,00
Silika	2200	100	0,00	0,00
Aalborg White	3160	100	0,00	0,00
BASF Micro Air 110 (1:19)	1084	0	0,00	0,00
BASF Glenium SKY 552	1040	17,5	0,00	0,00
	1200	0	0,00	0,00
	1000	0	0,00	0,00
Steel fibre	7800	-	-	-
PP-fibre	1000	-	-	-

*For cement, pozzolans og fillers density is stated for dry materials.
For admixtures wet density is stated.

Set "Achieved" = "Wanted"; Ctrl N

***Reset correction; Ctrl K

Proportioned concrete		**Wanted**	**Achieved**	**Volume correction*****		
Materials	**kg/m³**	**kg**	**kg**	**corr.air**	**corr.dens**	**corrected**
Aalborg Rapid	423,6	10,6	10,6	0,0	0,0	423,6
Silika	0,0	0,0	0,0	0,0	0,0	0,0
Aalborg White	0,0	0,0	0,0	0,0	0,0	0,0
Free water	167,3	4,2	4,2	0,0	0,0	167,3
Absorbed water	12,7	0,3	0,3	0,0	0,0	12,7
Svelvik 0/8	939,5	23,5	23,5	0,0	0,0	939,5
Svelvik 8/16	313,5	7,8	7,8	0,0	0,0	313,5
Årdal 16/24	591,2	14,8	14,8	0,0	0,0	591,2
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	0,0	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
BASF Micro Air 110 (1:19)	0,00	0,00	0,00	0,0	0,0	0,00
BASF Glenium SKY 552	3,01	0,08	0,08	0,0	0,0	3,01
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
Steel fibre	0,0	0,0	0,0	0,0	0,0	0,0
PP-fibre	0,0	0,0	0,0	0,0	0,0	0,0
Prop. concrete density. (kg/m³)	2448			0,0	0,0	2448

volume ok

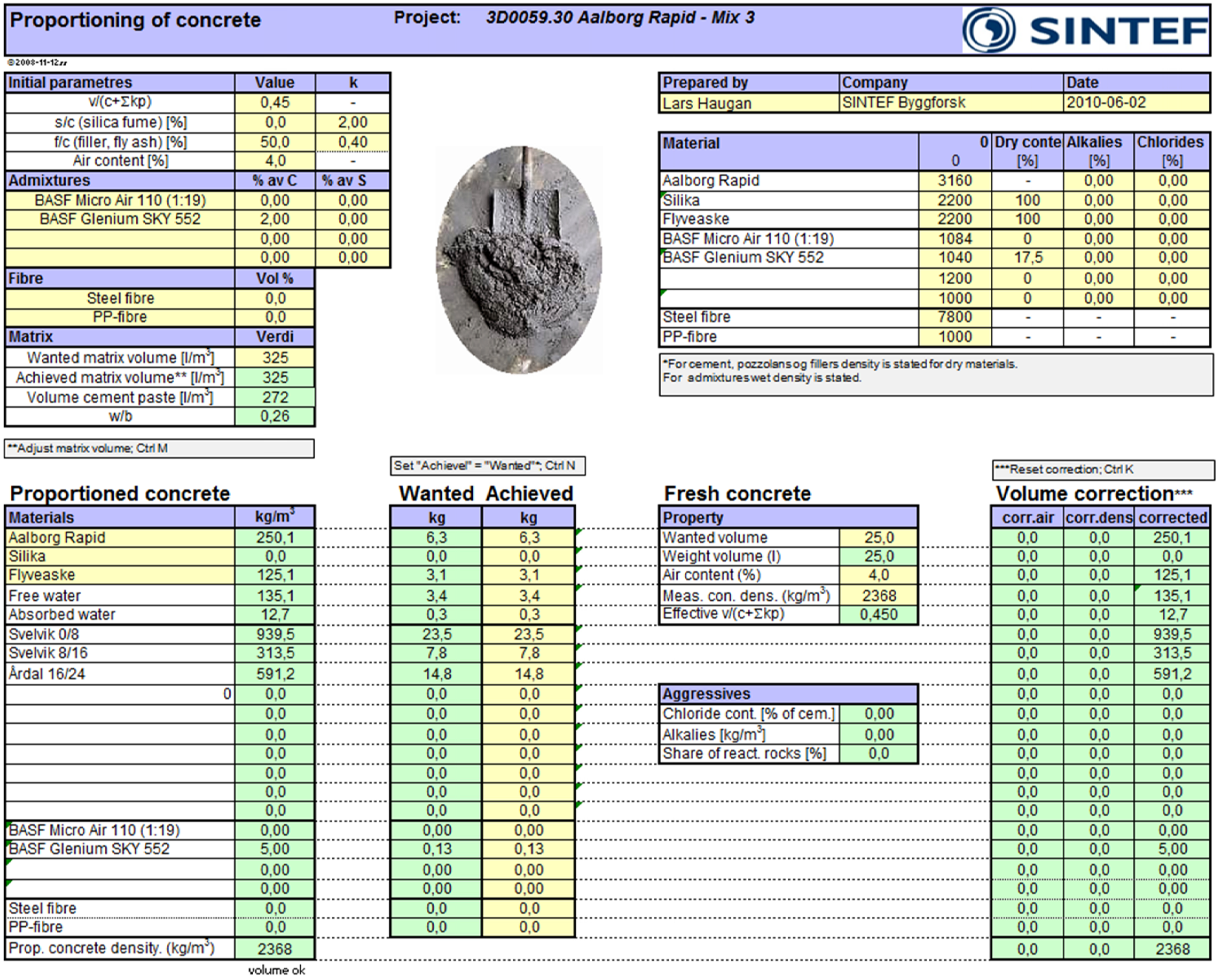
Fresh concrete

Property	
Wanted volume	25,0
Weight volume (l)	25,0
Air content (%)	1,0
Meas. con. dens. (kg/m³)	2448
Effective v/(c+Σkp)	0,395

Aggressives	
Chloride cont. [% of cem.]	0,00
Alkalies [kg/m³]	0,00
Share of react. rocks [%]	0,0

Mixture 3

Comments:



Proportioning of concrete **Project: *3D0059.30 Aalborg Rapid - Mix 3*** SINTEF

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Initial parametres	Value	k
v/(c+Σkp)	0,45	-
s/c (silica fume) [%]	0,0	2,00
f/c (filler, fly ash) [%]	50,0	0,40
Air content [%]	4,0	-
Admixtures	**% av C**	**% av S**
BASF Micro Air 110 (1:19)	0,00	0,00
BASF Glenium SKY 552	2,00	0,00
	0,00	0,00
	0,00	0,00
Fibre	**Vol %**	
Steel fibre	0,0	
PP-fibre	0,0	
Matrix	**Verdi**	
Wanted matrix volume [l/m^3]	325	
Achieved matrix volume** [l/m^3]	325	
Volume cement paste [l/m^3]	272	
w/b	0,26	

**Adjust matrix volume; Ctrl M

Prepared by	Company	Date
Lars Haugan	SINTEF Byggforsk	2010-06-02

Material	0 0	Dry conte [%]	Alkalies [%]	Chlorides [%]
Aalborg Rapid	3160	-	0,00	0,00
Silika	2200	100	0,00	0,00
Flyveaske	2200	100	0,00	0,00
BASF Micro Air 110 (1:19)	1084	0	0,00	0,00
BASF Glenium SKY 552	1040	17,5	0,00	0,00
	1200	0	0,00	0,00
	1000	0	0,00	0,00
Steel fibre	7800	-	-	-
PP-fibre	1000	-	-	-

*For cement, pozzolans og fillers density is stated for dry materials.
For admixtures wet density is stated.

Set "Achieved" = "Wanted"; Ctrl N

***Reset correction; Ctrl K

Proportioned concrete

Materials	kg/m^3
Aalborg Rapid	250,1
Silika	0,0
Flyveaske	125,1
Free water	135,1
Absorbed water	12,7
Svelvik 0/8	939,5
Svelvik 8/16	313,5
Årdal 16/24	591,2
0	0,0
	0,0
	0,0
	0,0
	0,0
	0,0
	0,0
BASF Micro Air 110 (1:19)	0,00
BASF Glenium SKY 552	5,00
	0,00
	0,00
Steel fibre	0,0
PP-fibre	0,0
Prop. concrete density. (kg/m^3)	2368

volume ok

Wanted kg	Achieved kg
6,3	6,3
0,0	0,0
3,1	3,1
3,4	3,4
0,3	0,3
23,5	23,5
7,8	7,8
14,8	14,8
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
0,00	0,00
0,13	0,13
0,00	0,00
0,00	0,00
0,0	0,0
0,0	0,0

Fresh concrete

Property	
Wanted volume	25,0
Weight volume (l)	25,0
Air content (%)	4,0
Meas. con. dens. (kg/m^3)	2368
Effective v/(c+Σkp)	0,450

Aggressives	
Chloride cont. [% of cem.]	0,00
Alkalies [kg/m^3]	0,00
Share of react. rocks [%]	0,0

Volume correction***

corr.air	corr.dens	corrected
0,0	0,0	250,1
0,0	0,0	0,0
0,0	0,0	125,1
0,0	0,0	135,1
0,0	0,0	12,7
0,0	0,0	939,5
0,0	0,0	313,5
0,0	0,0	591,2
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	0,00
0,0	0,0	5,00
0,0	0,0	0,00
0,0	0,0	0,00
0,0	0,0	0,0
0,0	0,0	0,0
0,0	0,0	2368

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