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COIN Project report 55 – 2015

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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 fulfil this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

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

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

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

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

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Tor Arne Hammer
Centre Manager

Summary

One of the objectives of COIN's Focus Area 3.1 *Crackfree concrete structures* is to develop guidelines for recommended mix design for different types of structures subjected to restraint thermal and autogeneous dilation. FA 3.1 should develop further the theoretical and practical implications of crack control by stress calculation, aiming at full incorporation of the technology in the specification for civil engineering structures.

As part of this research, a test series of four different concretes, which has been named "COIN P3.1 series" has been carried out within the project. The intention was to investigate how replacing cement with an increasing amount of fly-ash would affect the development of the main mechanical characteristics for such concrete qualities.

The report gives a detailed description of the materials and the test methods used in the experimental programme, and presents the results from this mechanical test programme for the four concrete qualities in question.

The mechanical test programme covers fresh concrete properties; slump, density and air content, tested according to NS-EN 12350, Part 2, 6 and 7. Further, it covers testing of the following hardened concrete properties:

- Density and compressive strength, NS-EN 12390, Part 7 and 3
- Modulus of elasticity in compression (NS 3676), and tension
- Uniaxial tensile strength, SINTEF internal procedure 14-05-04-512
- Splitting tensile strength, NS-EN 12390-6
- Activation energy, NS 3656:1993
- Heat development, NS 3657

In general, it is shown that all the investigated properties; the final heat generated, the compressive strength, the tensile strength and the E-modulus decrease with increasing FA content approximately linearly.

The material models used for the heat development and the time dependence of the mechanical properties are described. Furthermore are the model parameters determined for all the investigated concretes. In general, the material models describe the test results very well. The model parameters are logically related to the FA content, and confirm previous experience. The calculated material model parameters are to be implemented for calculations in the data program Crack TeSt COIN.

The experimental programme is extended and the theoretical approach is further elaborated within COIN FA 3.1.

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1 Introduction

1.1 Background

Early age concrete cracking is caused by restrained volume changes (i.e. autogenous shrinkage and thermal dilation) in hardening concrete structures, and may be a serious threat to aesthetics, tightness and durability. For decades it has been well known that use of low heat cements, including slag and fly-ash, reduce the cracking risk at early ages. Today, materials as fly ash are frequently being used in a much broader range of cement types mainly due to environmental aspects. To prevent unwanted cracking in hardening concrete structures and to be able to predict the property development of new types of concrete with relatively high fly ash content, it is a need for updating the general knowledge continuously as materials are changing. In addition there are new calculation tools available which can utilise this knowledge.

To be able to follow up development of new cement and concrete types within the research topic "Crack assessment of early age concrete in large infrastructure projects", the experimental equipment in the Concrete Laboratory at NTNU and SINTEF has been expanded and modernized. The equipment used in the project consists mainly of a temperature-stress-testing machine (TSTM-system) and seven new free deformation rigs (FD-system).

1.2 Principal objectives and scope

One of the objectives of COIN's Focus Area 3.1 *Crackfree concrete structures* is to develop further the theoretical and practical implications of crack control by stress calculation, aiming at full incorporation of the technology in the specification for civil engineering structures.

To reach this goal, SINTEF's and NTNU's test equipment has been upgraded to deliver more efficient materials testing, which will be used to map the most relevant properties for the new materials. This will contribute to better understanding of the involved mechanisms and the role of the different material properties, which again will give more reliable and user-friendly calculation methods.

As part of this research, a test series of four different concretes, which has been named "COIN P3.1 series" has been carried out within the project. The intention was to investigate how partial replacement of cement with an increasing amount of fly-ash would affect the development of main mechanical characteristics for these concretes.

This report presents the results from a mechanical test programme and calculations of the belonging material model parameters for the COIN P3.1 series. These experiments are carried out to establish a material database for use in crack risk estimations. Results from testing in the TSTM-system, the FD-system and testing of other material variants will be reported separately.

2 Experimental programme, mix design and material properties

2.1 General

This chapter describes the experimental mechanical test programme, including mix design of the four concrete qualities of the COIN P3.1-series. The main characteristics of the materials used in the experiments are included. Mixing and casting procedures are described as well.

2.2 Experimental programme

As mentioned above, four basic concrete mixes were investigated for mechanical properties in the COIN P3.1 series. The experimental programme is given in Table 2-1.

	Tensile strength		**Tensile splitting strength**		**Compressive strength**		**E-modulus**	
	100×100×600 prisms		Ø100×200 cylinders		100×100 cubes		Ø100×200 cylinders	
	No. of spec.	Test age	No. of spec.	Test age	No. of spec.	Test age	No. of spec.	Test age
ANL Ref. (0 % Fly ash)	4	2, 28	6	2, 28	3	28	6	2, 28
ANL FA (20 % Fly ash)	4	2, 28	21	18h, 24h, 2, 3, 7, 14, 28	3	28	6	2, 28
ANL FA + 8FA (28 % Fly ash)	4	2, 28	6	2, 28	3	28	6	2, 28
ANL FA + 16FA (36 % Fly ash)	4	2, 28	6	2, 28	3	28	6	2, 28

Table 2-1: Experimental programme COIN P3.1

2.3 Mix design

Table 2-2 shows the mix design of the four basic concretes. The reference mix is made with a Portland cement CEM I 52.5 N “Norcem Anlegg" (ANL). The others are made with a Portland cement; CEM II / A-V 42.5 N “Norcem Anlegg FA” (ANL FA), see also Table 2-3 in the next chapter. The ANL FA cement contains 20 % Fly Ash. The amount of fly ash is expressed in % of the total binder content by the following formula:

$$\% \boldsymbol{FA} = \frac{\boldsymbol{FA_{add}} + \boldsymbol{FA_{cem}}}{\boldsymbol{cem} + \boldsymbol{FA_{add}}} \qquad \text{Equation 2.1}$$

The fly ash replaces clinker by 1:1 on weight-base when calculating the mass ratio, while the total volume of cement paste is kept constant. The present concretes are proportioned with a constant cement paste volume of 293 l/m^3.

	ANL ref	ANL FA	ANL FA + 8FA	ANL FA + 16FA
Material	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
Cement	374	367	325.6	285.5
Fly Ash in cement (FA_{cem})	0.0	73.4	65.1	57.1
Fly Ash added (FA_{add})	0.0	0.0	36.2	71.4
Silica Fume (SF)	18.7	18.3	18.1	17.7
Free water	164.5	161.4	159.2	156.9
Sand 0-8	939.5	939.5	939.5	939.5
Stone 8-16	887.5	887.5	887.5	887.5
Admixtures	2.06	2.02	1.79	1.57
v/b	0.40	0.40	0.40	0.40
k-factor cement	1.0	1.0	1.0	1.0
k-factor silica fume	2.0	2.0	2.0	2.0
k-factor fly ash	1.0	1.0	1.0	1.0
% FA	0.0	20.0	28.0	36.0
Cement paste volume	293	293	293	293

Table 2-2 Mix design of basic concretes

2.4 Material characteristics

2.4.1 Cement

In these experiments Portland cement; *CEM I 52.5 N, Norcem Anlegg* and Portland cement; *CEM II / A-V 42.5 N, Norcem Anlegg FA* was used. The specifications as provided by the manufacturer are given in Table 2-3. As the table shows, there are two different batches for each cement type, one batch used at SINTEF, and the other batch used at Norcem for activation energy tests.

	Specifications			
Physical properties	Norcem Anlegg EG1-10 CEM I 52,5 LA	Norcem Anlegg EG1-12* CEM I 52,5 LA	Norcem Anlegg FA TF3-11 CEM II / A-V 42,5N	Norcem Anlegg FA TZ1-12* CEM II / A-V 42,5N
1-day strength	18.6 MPa	19.8 MPa	12.1 MPa	16.4 MPa
2-day strength	29.7 MPa	32.3 MPa	21.5 MPa	25.6 MPa
7-day strength	46.6 MPa	48.3 MPa	33.7 MPa	40.2 MPa
28-day strength	56.0 MPa	63.2 MPa	-	56.4 MPa
Setting time	145 min	125 min	195 min	150 min
Fineness	382 m^2/kg	396 m^2/kg	370 m^2/kg	404 m^2/kg
+90my	0.5 %	0.0 %	0.07%	2.3 %
+64	1.7 %	1.0 %	1.34%	4.1 %
-24	74 %	74.1 %	75.4%	71.2 %
-30	82.6 %	82.6 %	83.3%	79.3 %
Specific weight	3160 kg/m^3	3160 kg/m^3	2980 kg/m^3	2980 kg/m^3
Fly ash	-	-	18.7 %	17.8 %
Loss on ignition (LOI)	2.02 %	2.15 %	1.30 %	1.13 %
Chemical composition				
SO_3	3.45 %	3.25 %	2.75 %	2.57 %
SiO_2	19.99 %	20.61 %	27.04 %	26.57 %
Al_2O_3	4.76 %	4.40 %	8.68 %	8.70 %
Fe_2O_3	3.72 %	3.53 %	4.60 %	4.42 %
CaO	62.90 %	63.24 %	52.73 %	53.55 %
MgO	1.99 %	1.73 %	1.94 %	1.71 %
P_2O_5	0.13 %	0.15 %	0.25 %	0.33 %
K_2O	0.45 %	0.45 %	0.72 %	0.64 %
Na_2O	0.30 %	0.32 %	0.42 %	0.33 %
Tot. Alkali (Na_2O-ekv)	0.60 %	0.62 %	0.90 %	0.75 %
Cl^-	0.024 %	0.030 %	0.024 %	-

Table 2-3: Cement specifications (used for testing of activation energy)***

2.4.2 Admixtures

2.4.2.1 Super plasticizer

A polycarboxylate based super plasticizer was used for all mixes.

2.4.3 Pozzolanic additions

2.4.3.1 Fly ash

The fly ash was supplied by Norcem. The composition and physical properties are listed in Table 2-4.

	LN-00021-2002.03.12
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
Karbon [%]	3.64
LOI [%]	4.08
SO_3 [%]	0.52
Blaine [m^2/kg]	388
Specific density [g/cm^3]	2.20
Sieve analysis	
24 [µm]	59.7
30 [µm]	66.3
64 [µm]	11.4
90 [µm]	5.4

Table 2-4 Fly ash specifications

2.4.3.2 Silica fume

In these experiments Elkem Micro silica Grade 920 Densified was used. Specifications are listed in Table 2-5.

	Declared values
SiO_2 [%]	> 85
H_2O [moisture content when packed, %]	< 3,0
Loss on ignition [%]	< 6,0
Specific surface [BET – m^2/gram]	> 15
Retained on 45 micron sieve [%]	< 10
Bulk density [when packed, kg/m^3]	500 - 700

Table 2-5: Specifications Elkem Micro silica 920 D

2.4.4 Aggregates

Each of the concrete mixes contained four fractions of aggregate; Årdal 0/2 mm, Årdal 0/8 mm Årdal 8/11 mm and Årdal 11/16 mm. Årdal aggregate is dominated by granite and gneiss, and has an expected E-modulus of 32 GPa.

Sieve analysis, see Figure 2-1, and humidity tests were performed before mixing.

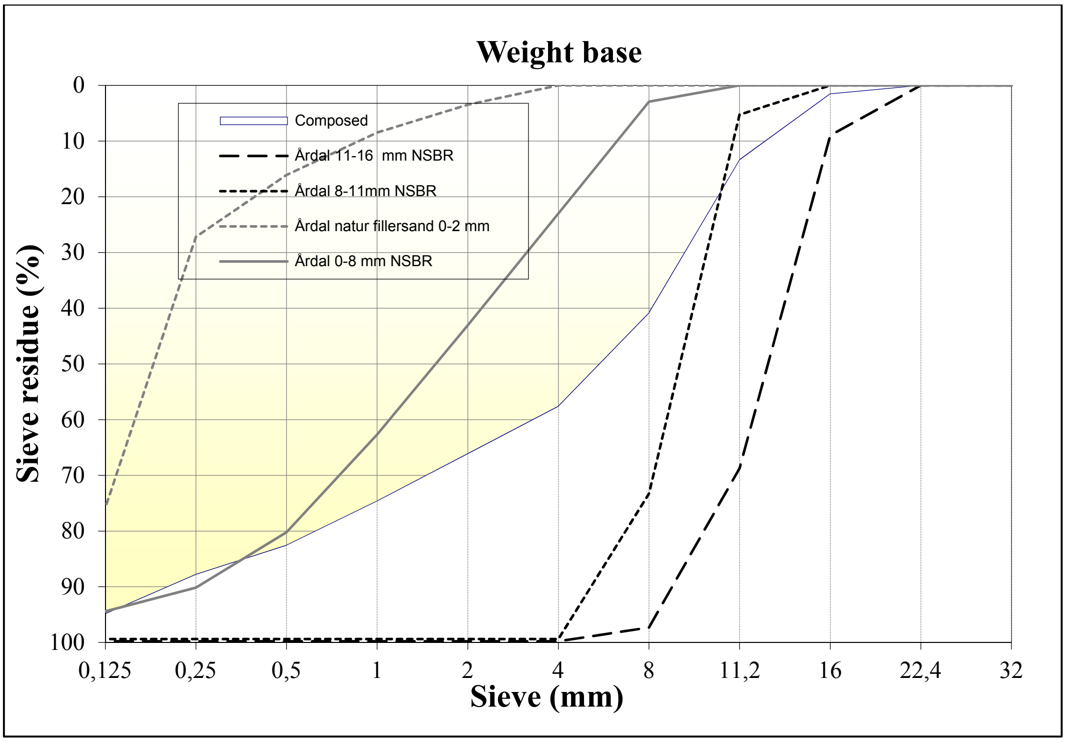

Figure 2-1: Sieve analyses aggregates

2.5 Mixing and casting

The concrete was mixed in an Eirich paddle mixer with a capacity of 50 litres. The batches were in total 35-55 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 were added within 30 sec.

Slump, air-content and density in the fresh concrete were measured directly after mixing, according to NS-EN 12390. Target slump was 170-200 mm.

3 Test procedures and equipment

3.1 General

This chapter describes the test methods used in the experimental programme for mechanical testing.

3.2 Fresh concrete properties

The following fresh properties were measured:

Density: NS-EN 12350-6:2009

Slump: NS-EN 12350-2:2009

Air content: NS-EN 12350-7:2009

3.3 Density and compressive strength

Density and compressive strength were measured on three reference cubes from each mix according to NS-EN 12390, Part 7 and Part 3 at 28 days age.

3.4 Modulus of elasticity

The modulus of elasticity in compression was determined according to NS 3676.

The procedure includes two preloading cycles:

1. Loading to 45 % of ultimate load. Resting period 90 sec. Unloading followed by a new 90 sec resting period.
2. Loading to 30 % of ultimate load. Resting period 60 sec. Unloading followed by a new 60 sec resting period.
3. Loading to 30 % of ultimate load. Resting period 90 sec. Unloading followed by a new 90 sec resting period.

The modulus of elasticity is determined from the unloading part of step 3 (including the subsequent 90 sec resting period), see Figure 3-1. The loading rate is 0.8 MPa/sec and 100 × 200 mm cylinders were used. The deformation was measured over the 100 mm mid-section, using 3 displacement transducers.

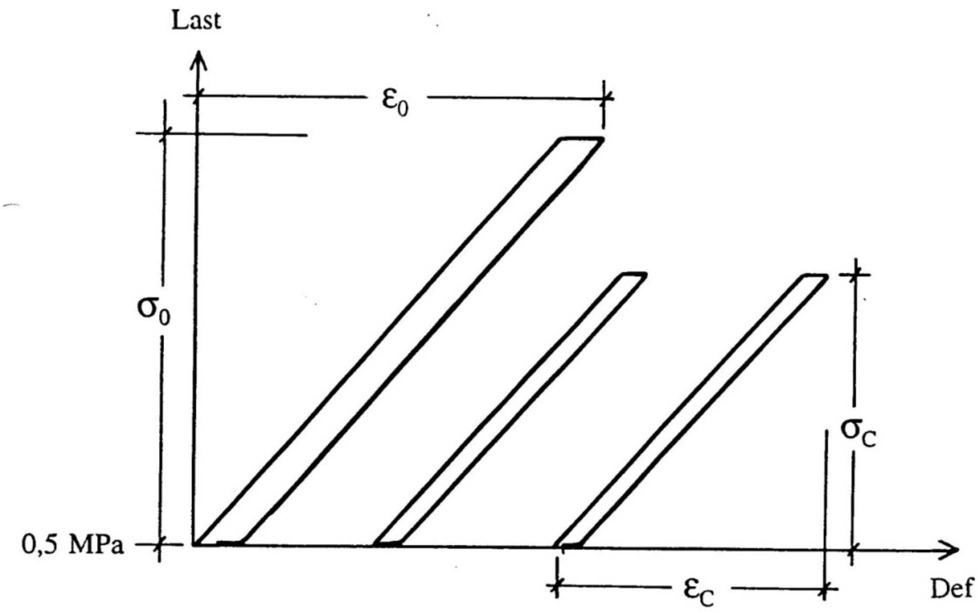

Figure 3-1: Testing cycles and calculation of E-modulus

The E-modulus was also calculated with the values measured in the uniaxial tensile test, see section 3.5, where failure load, deformation and the area of the cross section is measured and the E-modulus is calculated with the following formula:

$$E = \frac{\sigma_{40} - \sigma_{10}}{\varepsilon_{40} - \varepsilon_{10}} \qquad \text{Equation 3.1}$$

where σ and ε are the stress and strain values at a load levels corresponding to 10 % and 40 % of the failure load.

3.5 Tensile strength

The tensile strength was determined both directly by applying a uniaxial tensile load to prisms (100×100×600 mm), and indirectly by splitting cylinder specimens (Ø100×200 mm).

In the uniaxial tensile test, or direct pull test, the tensile forces are applied at the ends of the specimen by gripping devices. This method has been used for several years as the standard method for uniaxial tensile strength determination at SINTEF/NTNU and is described in the SINTEF internal procedure KS 14-05-04-511.

An advantage with the uniaxial tensile tests is the possibility for measuring the deformation in the loading direction and thus the ultimate strain and the E-modulus in tension.

The deformation during the test is measured with two displacement transducers placed on the opposite sides of the prisms. The strain rate was approximately $100x10^{-6}$ /min. The modulus of elasticity in tension was calculated from the load-deformation curve as mentioned in section 3.4, see also Figure 3-2.

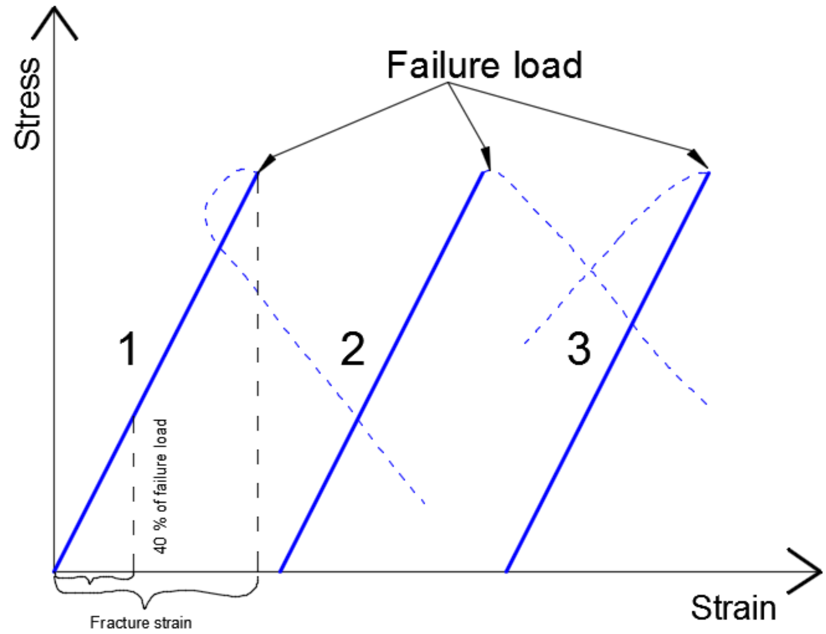

Figure 3-2: Interpretation of load / strain curves of tensile strength for three test specimens

The tensile splitting strength test was performed according to NS-EN 12390-6. A concrete cylinder specimen is laid horizontally between the loading platens of the testing machine and compressed along two opposite generatrices. Strips of comparatively soft material (wood) are placed between the specimen and the platens of the machine. The load is applied until the specimen splits, normally along a vertical diameter.

The tensile splitting strength at failure, f_{ts}, is found as:

$$f_{ts} = \frac{2P}{\pi DL} \qquad \text{Equation 3.2}$$

where; *P* = failure load, *D* = cylinder diameter, and *L* = length.

3.6 Temperature sensitivity

The temperature sensitivity constants in the maturity expression, A and B, describe the temperature influence on the development of the different mechanical properties, see section 5. The procedure to determine these two parameters in the rate of reaction function is described in NS 3656:1993. The development of strength at three different temperatures shall be measured, and in the present experimental series, which were performed at Norcem's laboratory, the strength development was determined at 5, 20 and 35 °C.

Based upon the measured strength values and the temperature development, the constants A and B are determined by iterative calculations according to the procedure described in Chapter 5.3.

3.7 Heat development

The heat development was measured by a semi-adiabatic calorimeter ("curing box"). This is a well-insulated box for a concrete sample of 15 litres. The temperature development in the concrete is measured and converted to heat development as a function of maturity.

The heat development was measured with three temperature loggers in each curing box; two Testo 176 T4 loggers, and one Pico logger. The reason for this was to test the new Testo 176 T4 loggers, and compare the individual results with the traditional Pico logger. The room temperature was only measured with the Pico logger.

In the calculations the heat loss to the environment is compensated for by assuming that the heat flow out of the box is proportional to the temperature difference between the concrete and the environment. The proportionality coefficient is called "heat loss coefficient", and can be measured or calculated. The method is standardized and described in NS 3657.

The method and calculation of results are also described in SINTEF internal procedure KS 14-05-04-525.

For these experiments, the curing box was stored in a 38 °C climatic chamber for 15 days. This is a procedure which reduces the heat loss to the surroundings and therefore improves the accuracy of the method.

4 Test results

4.1 Fresh concrete properties

Table 4-1 lists the measured fresh concrete properties of all mixes performed in the mechanical test programme.

Mix	ID	Casting date	Density [kg/m^3]	Slump [mm]	Air content [%]
ANL Ref.	MEK 001-1	2011-10-18	2399	190	2.5
ANL FA	MEK 002-1	2011-10-18	2404	210	2.4
ANL FA	MEK 002-2	2011-10-11	2409	205	2.1
ANL FA + 8FA	MEK 003-1	2011-10-19	2379	210	2.5
ANL FA + 16FA	MEK 004-1	2011-10-19	2376	230	2.1

Table 4-1: Fresh concrete properties

4.2 Mechanical properties

4.2.1 Density and compressive strength

The average compressive strength at 28 days age (f_c) for each concrete quality is given in Table 4-2. Figure 4-1 shows how the compressive strength changes when the Fly ash content is increased.

Mix	ID	Compressive strength [MPa]	Density [kg/m^3]
ANL Ref.	MEK 001-1	80.3	2438.0
ANL FA	MEK 002-1	68.8	2468.0
ANL FA	MEK 002-2	71.2	2442.0
ANL FA + 8FA	MEK 003-1	65.7	2420.0
ANL FA + 16FA	MEK 004-1	53.6	2421.0

Table 4-2: Average compressive strength for each concrete quality

From Table 4-2 and Figure 4-1 it is seen that the compressive strength decreases with increasing amount of fly ash. The fly ash replaces the cement by 1:1. A fly ash content of 36 % leads to a strength reduction of about 30 % at 28 days.

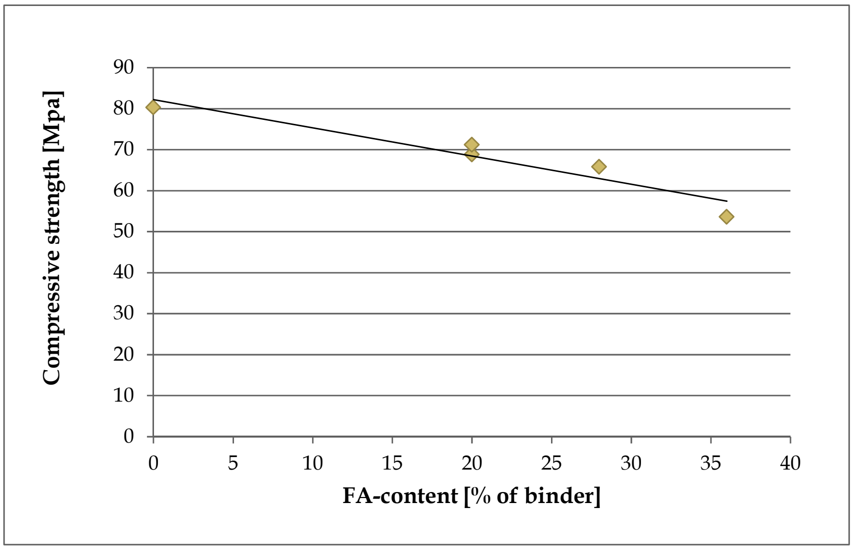

Figure 4-1: Compressive strength related to FA-content

4.2.2 Tensile strength

The tensile strength of the concretes was measured both with the splitting tensile strength test and the uniaxial tensile strength test as described in Chapter 3.5. The results from the splitting tensile strength tests are given in Table 4-3, Figure 4-2 and Figure 4-3, while the results from the uniaxial tensile strength are given in Table 4-4, Figure 4-4 and Figure 4-5.

Concrete age [days]		0.75	1	2	3	7	14	28
Mix	**ID**	**Tensile splitting strength [MPa]**						
ANL Ref.	MEK 001-1			3.69				5.07
ANL FA	MEK 002-1	1.17	1.86	2.72	3.1	3.43	3.71	4.59
ANL FA + 8FA	MEK 003-1			2.32				4.1
ANL FA + 16FA	MEK 004-1			1.97				3.72

Table 4-3: Results, splitting tensile strength

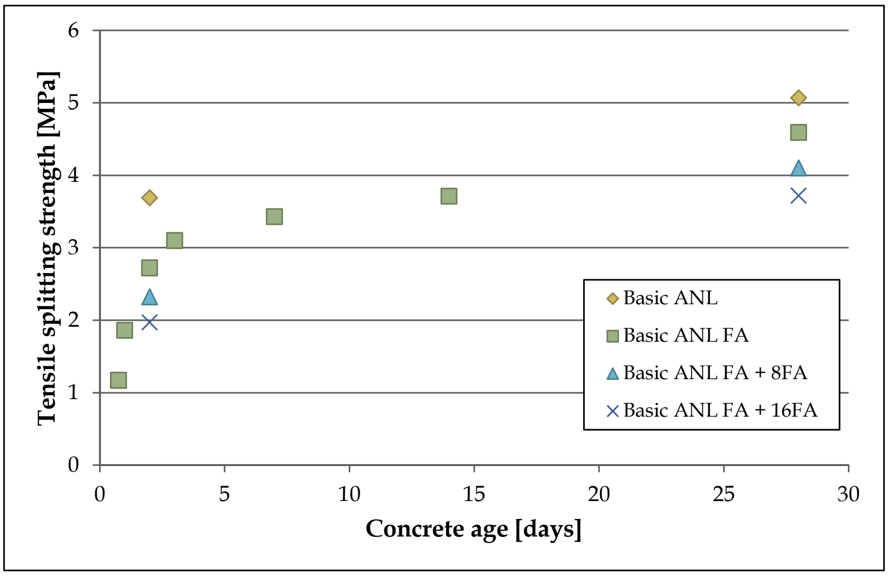

Figure 4-2: Tensile splitting strength as a function of concrete age at testing

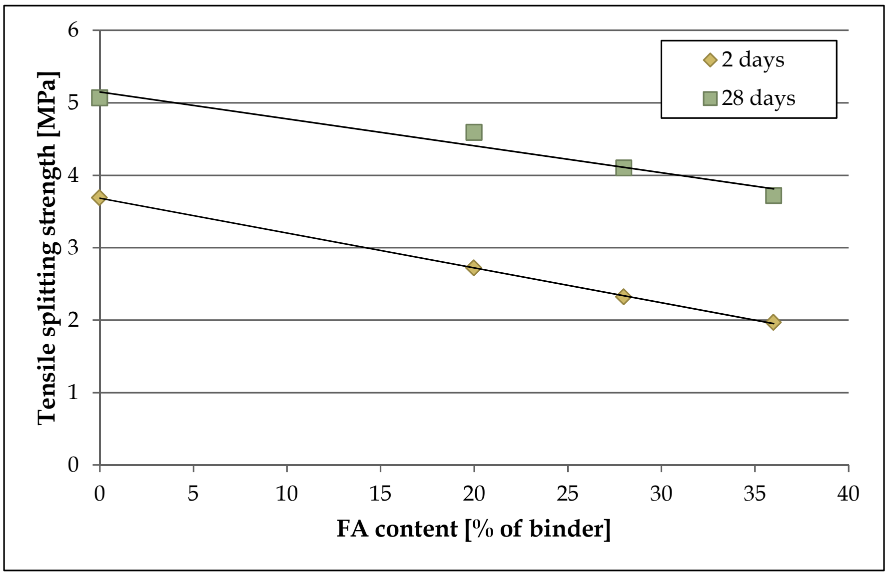

Figure 4-3: Tensile splitting strength related to FA content

From the trend line in Figure 4-3 it is seen that a FA content of 36 % implicates a splitting tensile strength reduction after 28 days of about 27 %. Correspondingly, it is seen from Figure 4-5 that 36 % FA leads to a reduction in uniaxial tensile strength of about 18 %.

In general, it is expected that the influence of FA content is stronger on the compression strength than on the tensile strength due to the nonlinear relation between these parameters;

$$f_{ct} = \alpha(f_{ck})^n, \quad n < 1.0 \qquad \text{Equation 4.1}$$

This topic is further discussed in Chapter 5.

Concrete age [days]		2	28
Mix	**ID**	**Uniaxial splitting strength (MPa]**	
ANL Ref.	MEK 001-1	2.80	3.92
ANL FA	MEK 002-2	2.42	3.09
ANL FA + 8FA	MEK 003-1	2.01	3.38
ANL FA + 16FA	MEK 004-1	1.66	3.16

Table 4-4: Results, uniaxial tensile strength

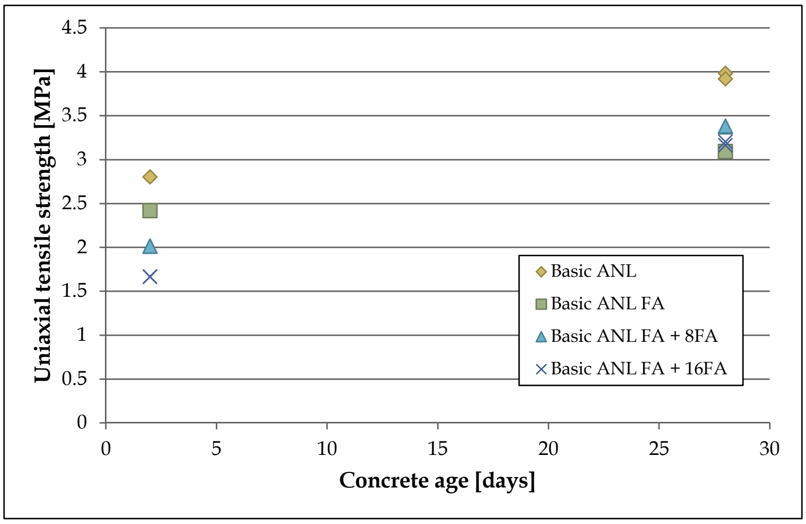

Figure 4-4: Uniaxial tensile strength as a function of age at loading

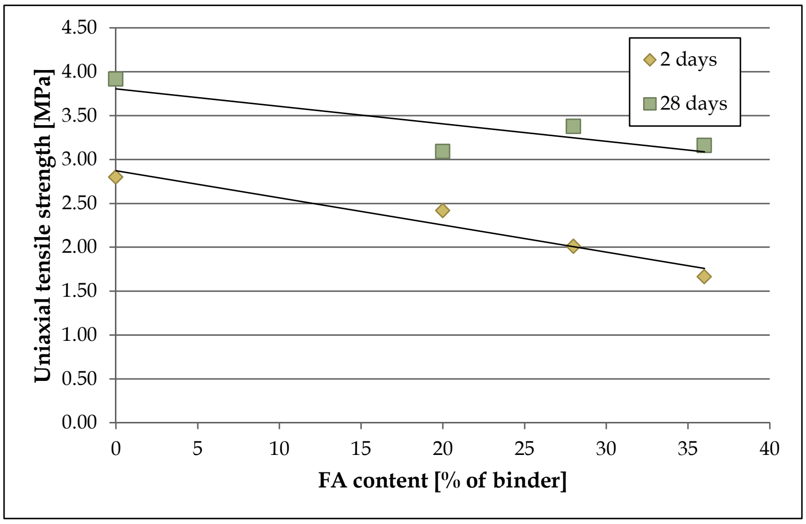

Figure 4-5: Uniaxial tensile strength related to FA content

4.2.3 Uniaxial Strength versus splitting strength

The splitting tensile tests were conducted on 100×200 mm cylinders while the uniaxial strength tests were conducted on 100×100×600 mm prisms. If a linear regression analysis is applied, the following relation between tensile (f_t) and splitting strengths (f_{ts}) is found, see Figure 4-6:

$$f_t = 0{,}65 \cdot f_{ts} + 0{,}52 \qquad \text{Equation 4.2}$$

[Kanstad et al., 2003] obtained the relation $f_t = 0{,}79x + 0{,}53$ in a previous investigation where about 85 parallel tests were carried out. This relation is also included in Figure 4-6. The two relations show that the difference between the splitting and the uniaxial tensile strength is larger for the current FA concretes than for the previous test series.

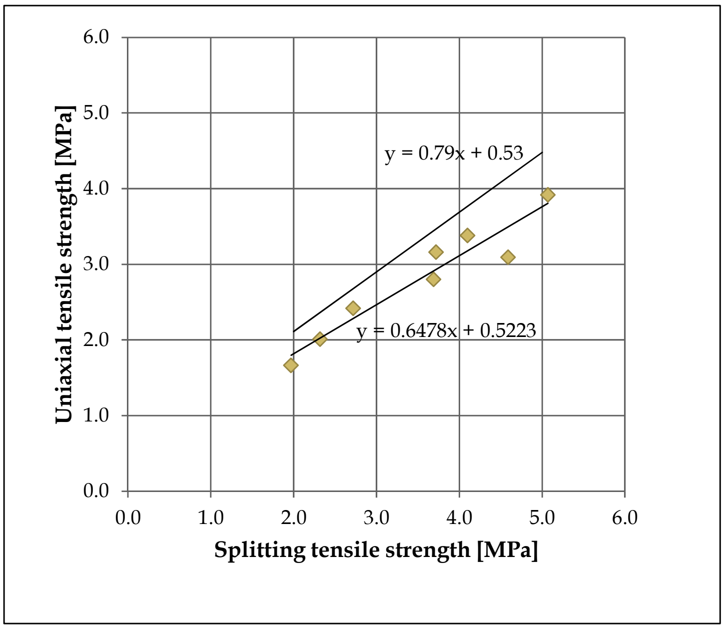

Figure 4-6: Uniaxial tensile strength versus splitting tensile strength.

4.2.4 Modulus of elasticity

The modulus of elasticity was measured and calculated both in compression tests and in uniaxial tensile tests. These results are presented in Table 4-5 and Figure 4-7 to Figure 4-10. Results from the two test methods are later compared in Chapter 0.

Concrete age [days]		2	28	2	28
Mix	ID	NS 3676 [GPa]		Uniaxial test [GPa]	
ANL Ref.	MEK 001-1	25.25	30.8	27.0	*
ANL FA	MEK 002-2	22.45	30.2	25.5	30.9
ANL FA + 8FA	MEK 003-1	21.4	26.9	23.0	28.5
ANL FA + 16FA	MEK 004-1	19.55	27.8	21.9	27.8

Table 4-5: Modulus of elasticity from compression test and uniaxial tensile stress test

** Deformation measurement failed and E-modulus could not be calculated.*

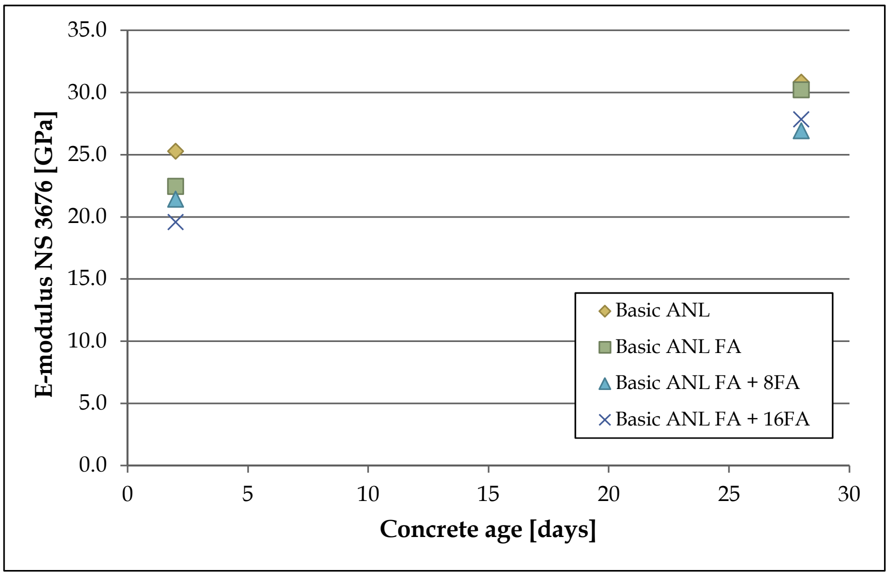

Figure 4-7: Modulus of elasticity in compression according to NS 3676

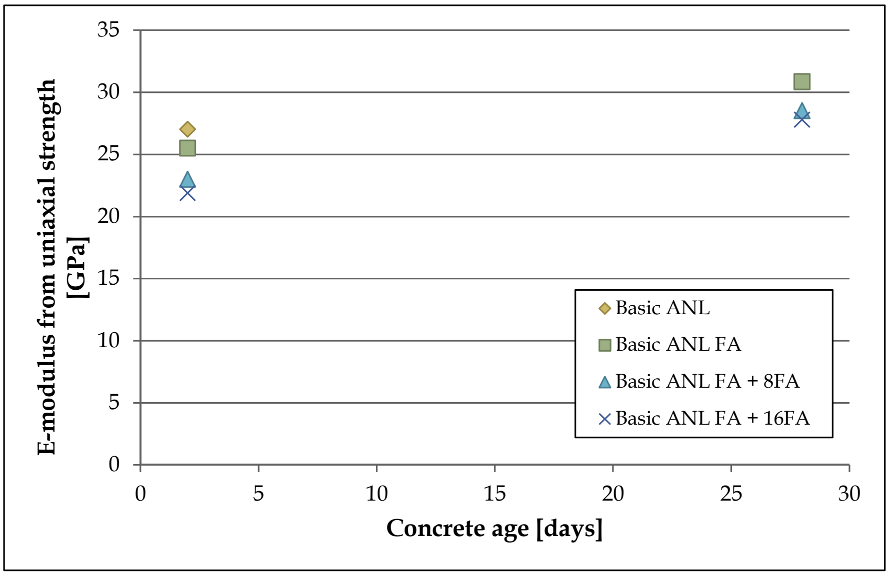

Figure 4-8: Modulus of elasticity from the uniaxial tensile strength test

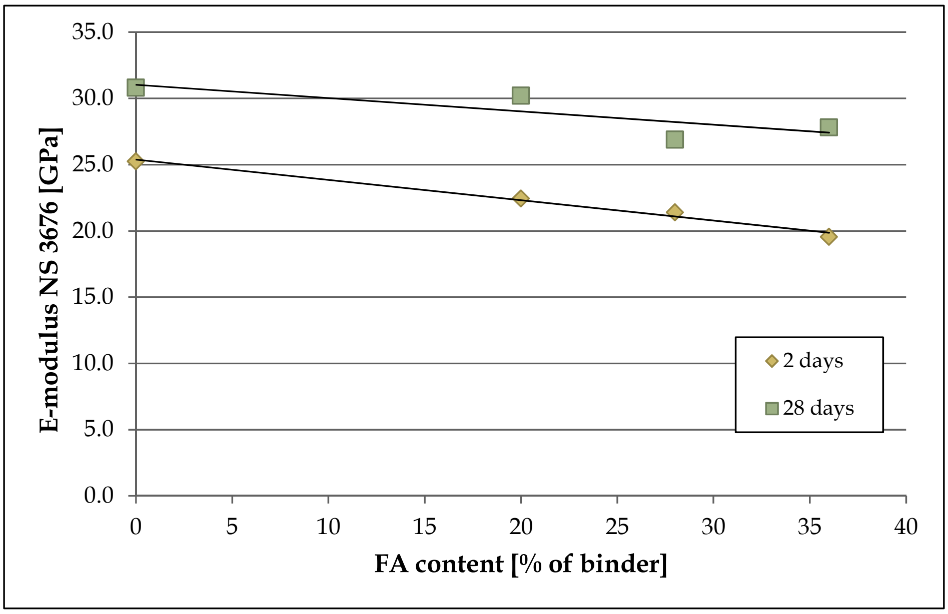

Figure 4-9: E-modulus related to FA content, NS 3676

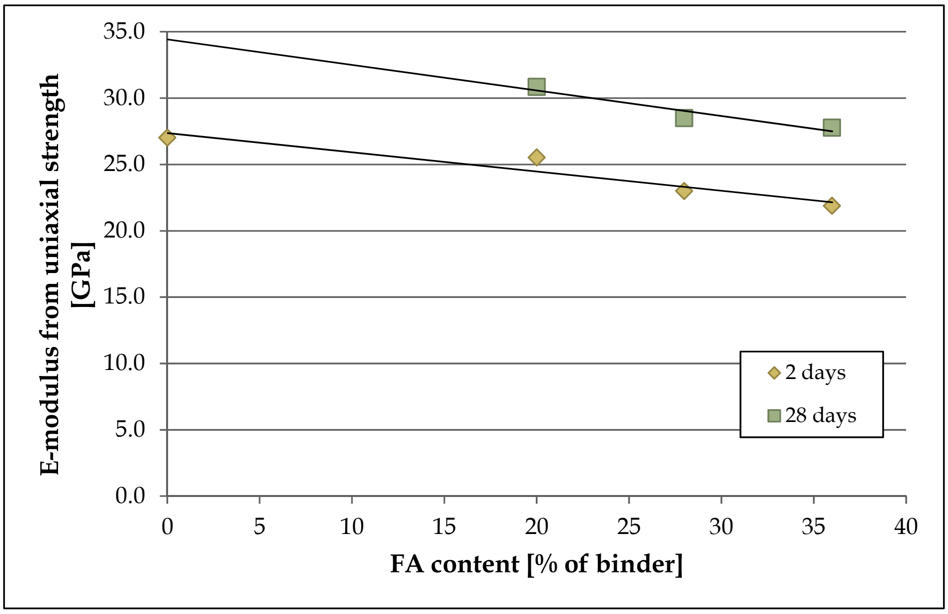

Figure 4-10: E-modulus related to FA content, uniaxial tensile strength

Due to test failure, the E-modulus for 28 days for ANL Ref. could not be calculated. However, the trend lines in Figure 4-10 indicate that the 28 days E-modulus for ANL Ref. is expected to be approximately 33.7 GPa. The 28 days E-modulus for ANL Ref. was therefore set to 33.7 GPa prior to the material model fitting presented in Chapter 5.

The trend line in Figure 4-9 indicates that 36 % FA content leads to a reduction in the 28 days compressive E-modulus of about 11 %.

4.2.5 Modulus of elasticity in compression versus modulus of elasticity in tension

If a linear regression analysis is applied, the following relation between modulus of elasticity in tension and compression is found, see Figure 4-11:

$$E_t = 0{,}81 \cdot E_c + 6.37 \qquad \text{Equation 4.3}$$

[Kanstad et al., 2003] concluded in a previous investigation that there was no significant difference between the E-modulus test results obtained in tension or compression. The results in the present investigation confirm, however, the findings of [Guomin et al, 2012], who in comparison of compressive and tensile creep concluded that the instantaneous deformations (per unit stress) in tensile are slightly smaller than in compression.

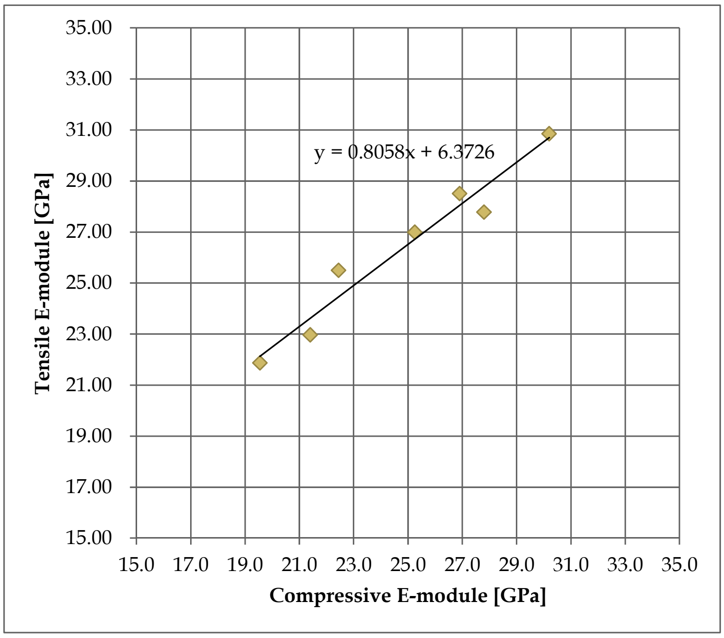

Figure 4-11: Modulus of elasticity in compression versus tension

4.3 Compressive strength for temperature sensitivity calculations

The rate of reaction was determined by measuring the compressive strength on 100 × 100 mm cubes that were stored in water baths at three different temperatures; 5, 20 and 35 °C. The cubes were tested at up to eight different ages between 0 and 28 days. The compressive strength was measured according to NS-EN 12390-3. The results from the experiment are given in Table 4-6, as an average of two tested specimens. The results are presented as strength versus age in Figure 4-12 to Figure 4-18. As mentioned earlier, the compressive strength tests for temperature sensitivity calculations were performed at Norcem. Figure 4-17 includes all the results for the 20 °C temperature, and it is seen that the 28 days strength is 5-10 MPa higher than the other compressive strength results performed at NTNU/SINTEF (shown previously in Figure 4-1). The relative influence of the FA content is however approximately the same. The difference is most likely because two different cement batches were used, see section 2.4.1.

ANL Ref.					
5 °C		20 °C		35 °C	
Age [d]	MPa	Age [d]	MPa	Age [d]	MPa
1	3.7	0.5	6.3	0.25	6.3
1.5	10.4	0.67	11.1	0.33	13
2	18.9	1	25.2	0.5	26.4
3	32.1	2	41	0.67	32.2
4	41.2	3	52.2	1	40.2
5	48.6	7	65.1	2	50.3
7	56.8	28	84.8	4	61.7
28	70.7	90	89.4	28	72.3
-	-	364	92.9	-	-
ANL FA					
5 °C		20 °C		35 °C	
Age [d]	MPa	Age [d]	MPa	Age [d]	MPa
1	4.4	0.5	6.6	0.25	7.2
1.5	12	0.67	14.9	0.33	15.4
2	18.3	1	23.6	0.5	21.2
4	34.8	2	36.6	0.67	25.5
5	36.5	3	43.1	1	32.6
7	48.1	7	51	2	42.3
28	66.7	28	79.3	4	56.1
-	-	90	94.2	28	81.4
-	-	364	98.2	-	-
ANL FA + 8FA					
5 °C		20 °C		35 °C	
Age [d]	MPa	Age [d]	MPa	Age [d]	MPa
1	2.9	0.5	5.6	0.25	4.2
1.5	9	0.67	12.5	0.33	12.8
2	14.5	1	20.3	0.5	19.8
3	21.6	2	32.3	0.67	24.7
4	29.3	3	38.5	1	29.6
5	35.2	7	49.6	2	38.3
7	38.7	28	78.9	4	55.2
28	61.3	90	95.6	28	80.3
-	-	364	100.3	-	-
ANL FA + 16FA					
5 °C		20 °C		35 °C	
Age [d]	MPa	Age [d]	MPa	Age [d]	MPa
1	2.1	0.5	3.8	0.25	3
1.5	7	0.67	7.6	0.33	8.8
2	10.8	1	15.5	0.5	15.7
3	18.3	2	25	0.67	18.7
4	21.7	3	30.7	1	23
5	26.7	7	40.4	2	32.6
7	31.9	28	66.9	4	46
28	47.7	90	83	28	77.4
-	-	364	94.1	-	-

Table 4-6: Test results compressive strength at different temperatures

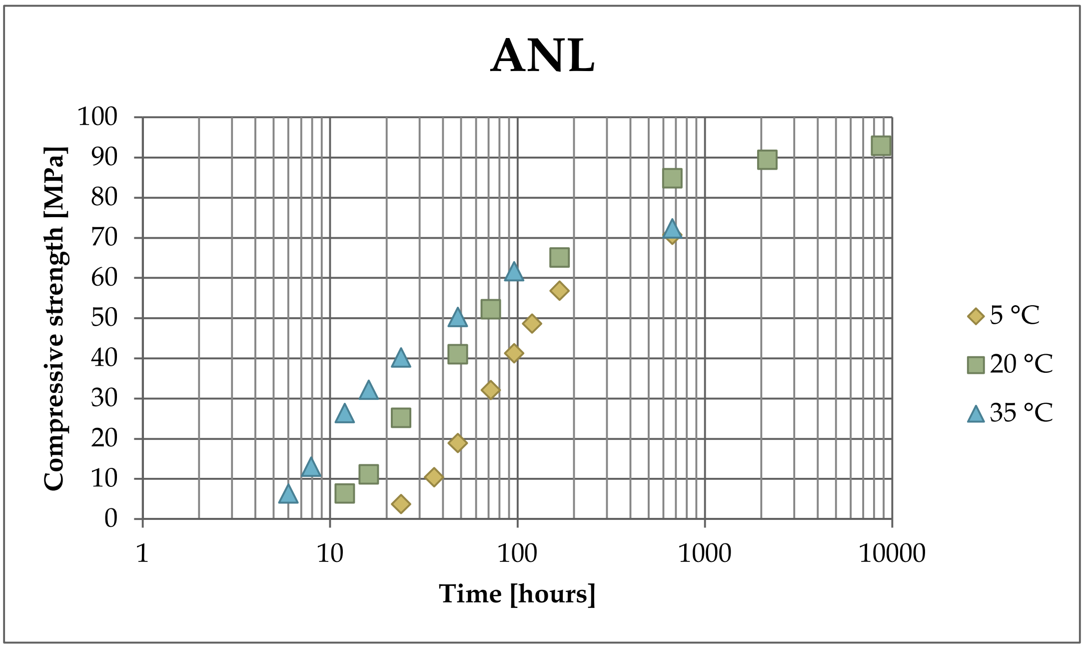

Figure 4-12: Strength development, ANL Ref.

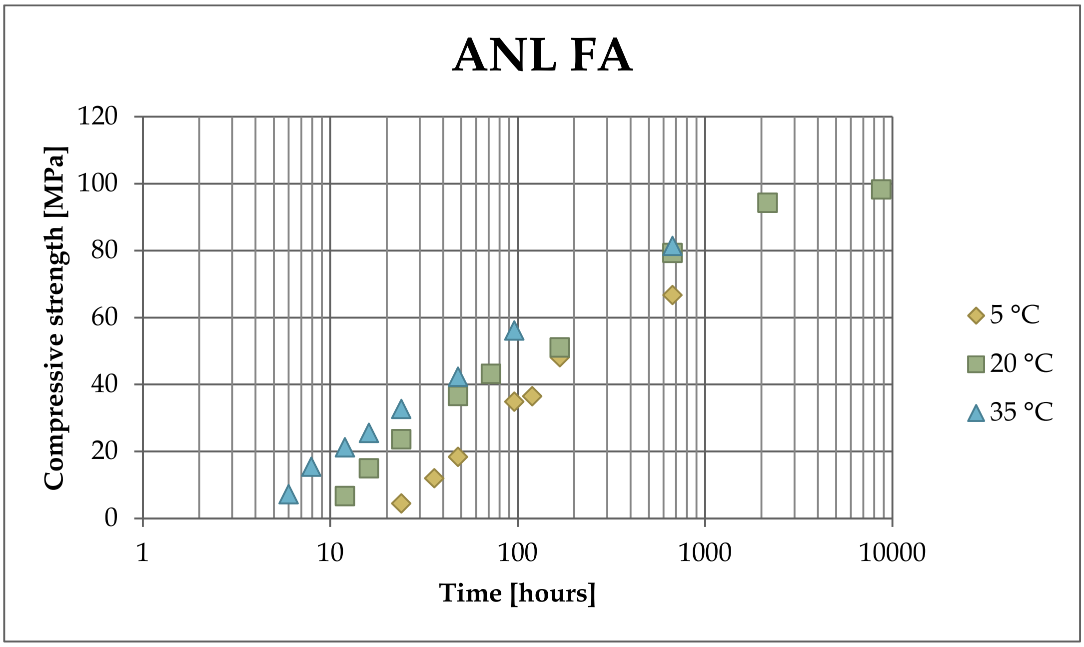

Figure 4-13: Strength development, ANL FA

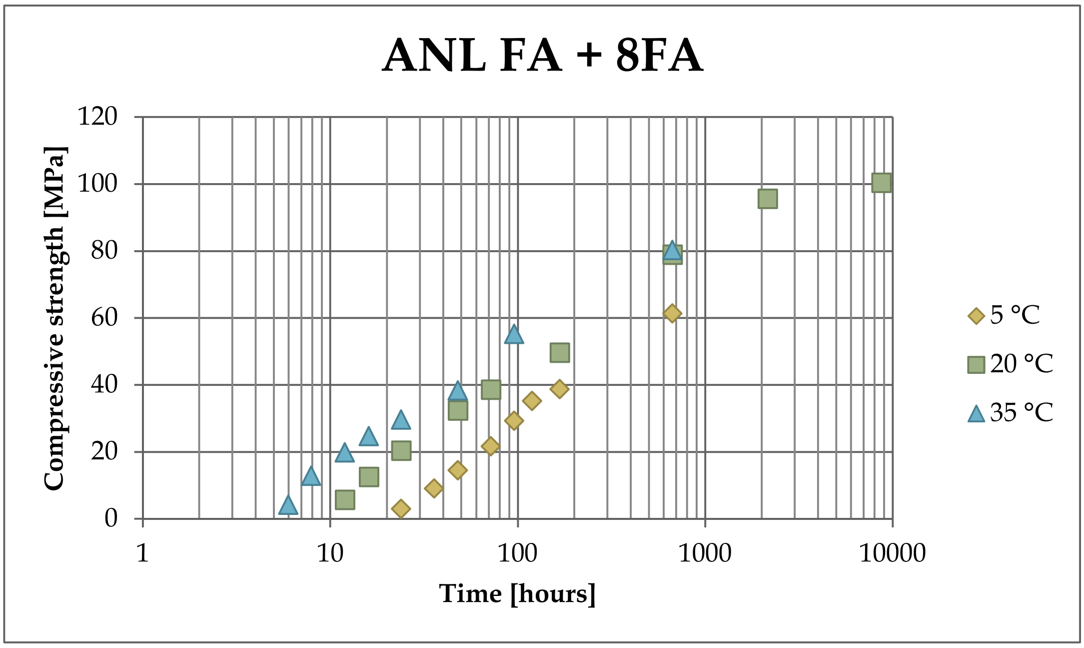

Figure 4-14: Strength development, ANL FA + 8FA

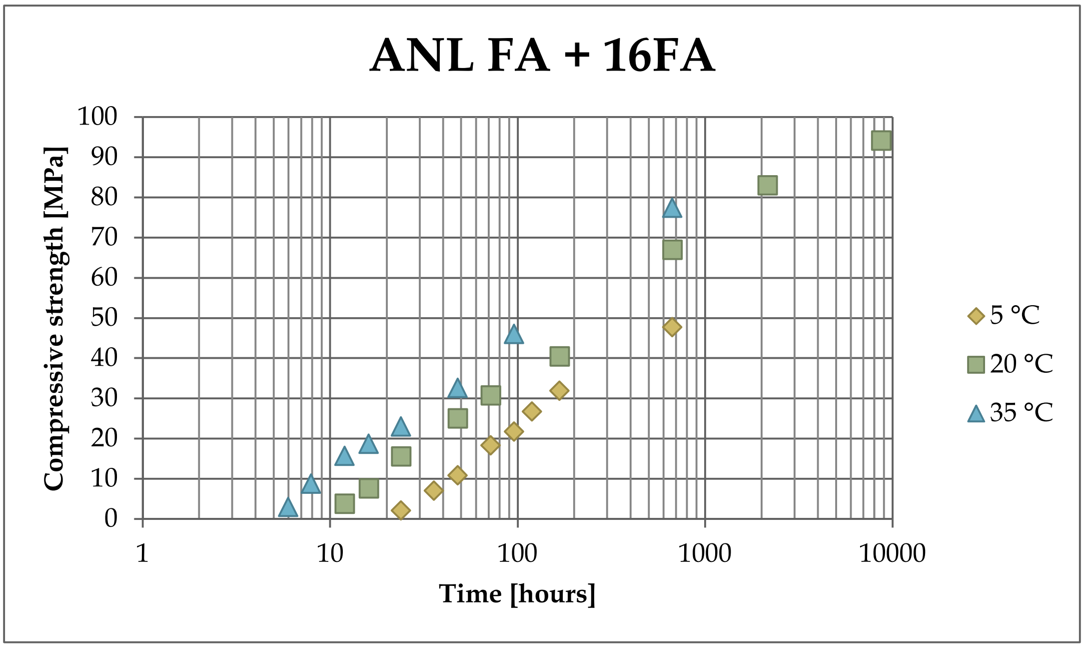

Figure 4-15: Strength development, ANL FA + 16FA

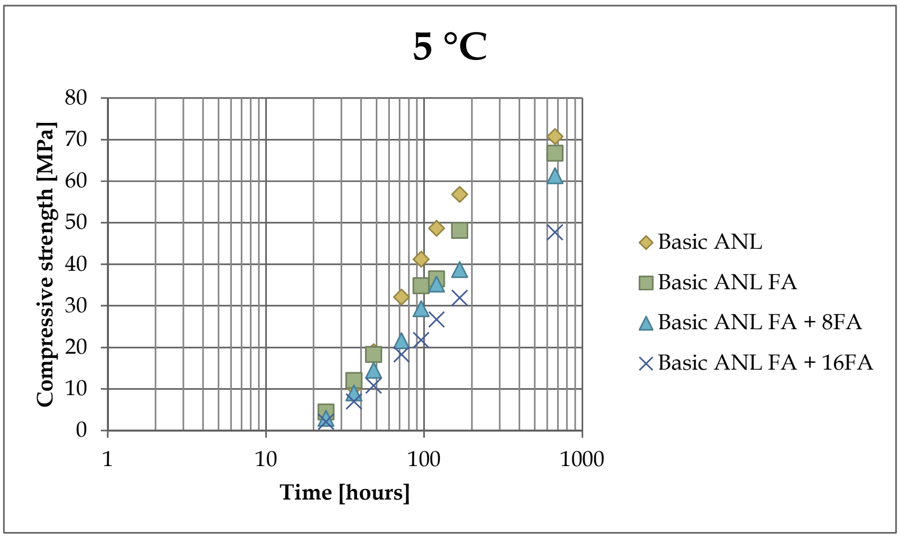

Figure 4-16: Strength development - All concrete qualities, 5 °C

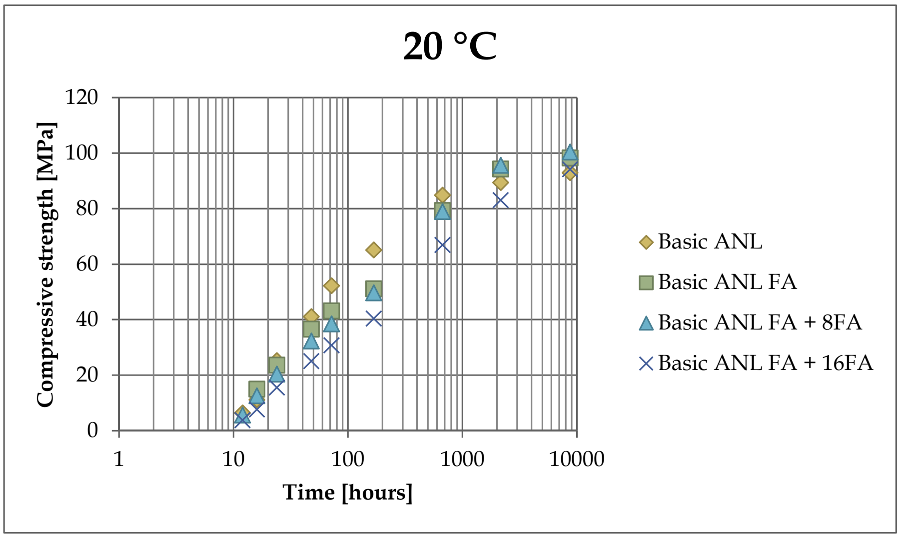

Figure 4-17: Strength development - All concrete qualities, 20 °C

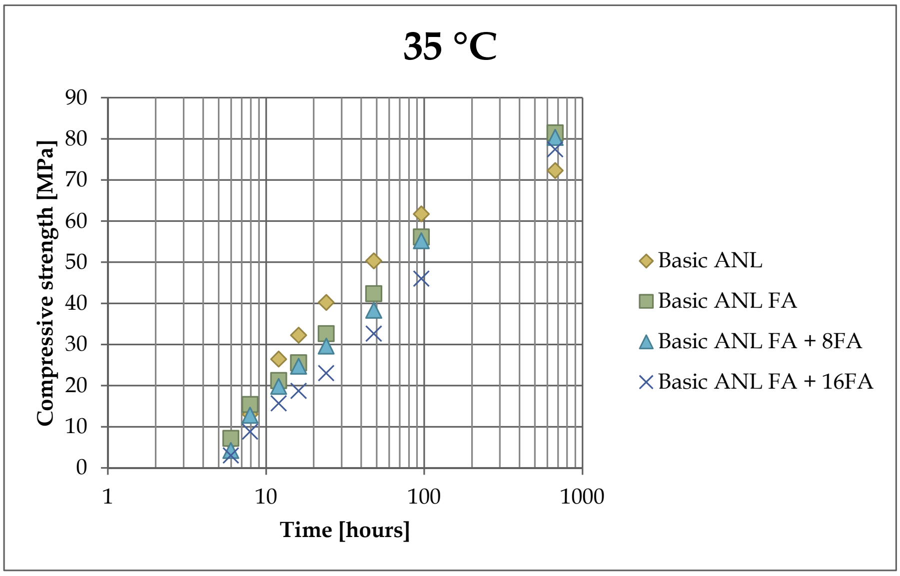

Figure 4-18: Strength development - All concrete qualities, 35 °C

4.4 Heat development

Figure 4-19 shows the measured temperatures with the two Testo loggers (left) and the Pico logger (right), while Figure 4-20 shows the results from one of the Testo loggers and the Pico logger.

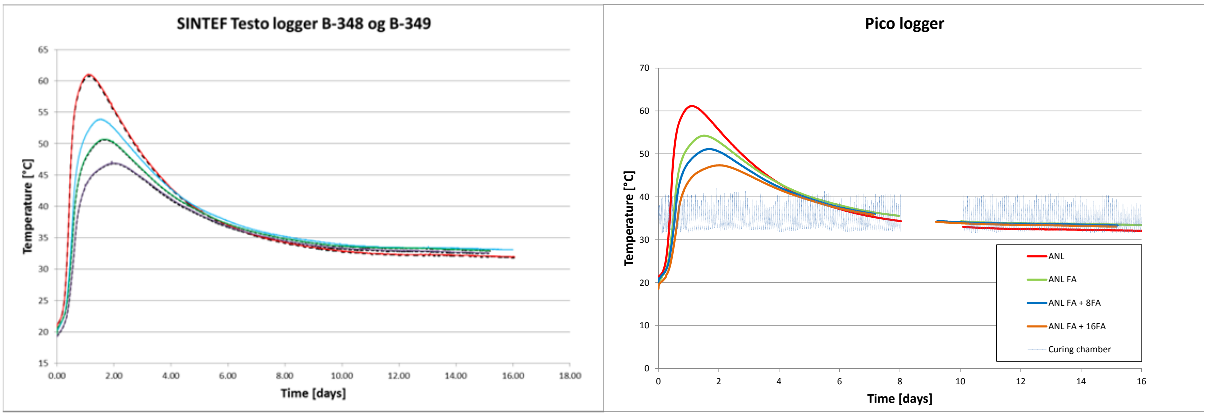

Figure 4-19: Correspondance between Testo and Pico loggers

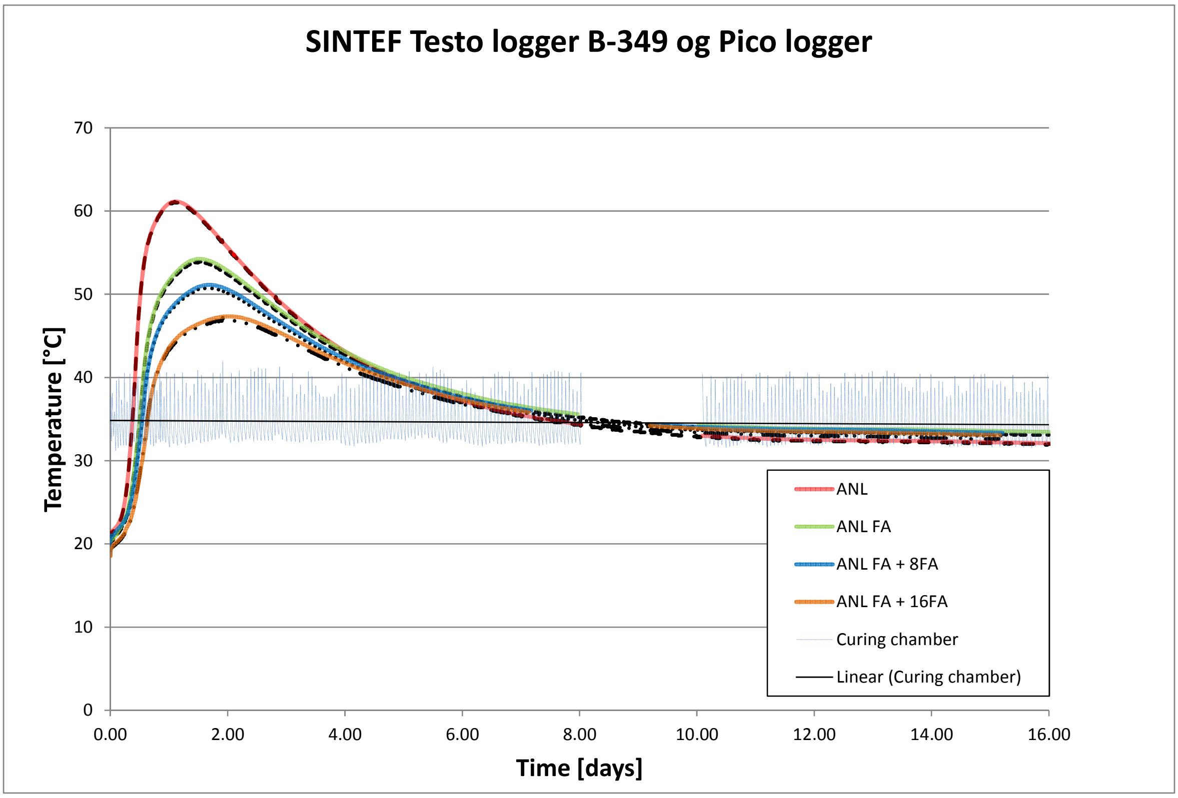

Figure 4-20: Heat development measured with Testo logger and Pico logger

Due to some unknown reason, the computer controlling the Pico logger turned off after approximately eight days. This was noticed two days later, and the system was turned back on. This explains the gap in the measuring data from the Pico logger. There was also failure on one channel for Testo logger B-348. The figures show that the correspondence between the three loggers was very good, but anyhow, for security reasons, it can be useful to use more than one temperature measurement system in case of failure.

Calculation of results are performed with an excel sheet developed by Sverre Smeplass, according to the descriptions in SINTEF's internal procedure KS 14-05-04-138.

Table 4-7 gives the guiding values for choosing a suitable *dQ/dm* for different maturity ranges and increasing amount of fly ash. At a high maturity range (150-300 mh), *dQ/dM* (heat intensity) is assumed to increase by an increasing fly ash content, because the fly ash contribute to a slower hydration and heat development. Further, a bisection of *dQ/dM* is assumed within a maturity range of 50 mh from 150-300 mh [Smeplass S, 2001]. This has been verified for CEM I by testing. For the other concretes in the present experiments, these values have been estimated, based on previous experience. To reduce the uncertainty of the calculations, the latest matuity range possible should be choosen.

Maturity range (m)	150-200	200-250	250-300	300-350
CEM I	0.100	0.050	0.025	0.01250
CEM I + 10 % FA	0.150	0.075	0.0375	0.01887
CEM I + 20 % FA	0.200	0.100	0.050	0.02500
CEM I + 30 % FA	-	0.150	0.075	0.03750
CEM I + 40 % FA	-	-	0.100	0.05000

Table 4-7: Guiding values for choosing *dQ/dm* with increasing maturity range and fly ash content

The input parameters used in the calculations and the results are given in Table 4-8 and Table 4-9. The results are also illustrated in Figure 4-21 - Figure 4-26.

Concrete mix	ANL Ref.	ANL FA	ANL FA + 8FA	ANL FA + 16FA
Concrete parameters				
Temp. trans. coeff.	0.0230	0.0209	0.0234	0.0251
Density	2395	2385	2377	2377
Heat capacity (fresh)	1.01	1.01	1.01	1.01
Heat capacity (hardened)	1.01	1.01	1.01	1.01
Cement content	395	387	382	377
Set time	7.0	8.8	9.3	10.2
A - set time	31482	31487	32958	37023
B - set time	296	197	273	0
A - hydration	31482	31487	32958	37023
B - hydration	296	197	273	0
Adia. start temperature	20	20	20	20
Temp. trans. Coeff.				
dQ/dm	0.0125	0.050	0.075	0.100
m>	300	250	250	250
m<	350	300	300	300
Heat function				
m-limit	370	345	330	320
Heat development at 300 mh [kJ/kg cem]	342.6	284.5	269.9	246.2
R^2	0.9701	0.9677	0.9672	0.9768
ΣD_Q	16983	11139	12907	16165

Table 4-8: Input parameters and results from calculations of heat development

Heat polygon							
ANL Ref.		*ANL FA*		*ANL FA + 8FA*		*ANL FA + 16FA*	
[mh]	[kJ/kg cem]	[mh]	[kJ/kg cem]	[mh]	[kJ/kg cem]	[mh]	[kJ/kg cem]
0,0	0	0,0	0	0,0	0	0,0	0
4,2	5	3,4	5	5,5	5	7,6	5
5,9	10	6,9	10	8,3	10	9,4	10
7,6	20	9,0	20	10,2	20	11,3	20
9,4	40	11,3	40	12,7	40	14,2	40
10,8	60	13,3	60	15,0	60	17,0	60
12,2	80	15,3	80	17,2	80	19,7	80
13,6	100	17,1	100	19,5	100	23,5	100
14,9	120	19,2	120	23,1	120	31,1	120
16,5	140	22,7	140	29,5	140	42,3	140
18,6	160	28,3	160	39,5	160	61,5	160
21,6	180	36,9	180	54,0	180	86,4	180
25,9	200	50,0	200	72,1	200	115,5	200
32,9	220	66,8	220	94,2	220	157,2	220
43,1	240	88,1	240	130,8	240	243,3	240
56,8	260	124,1	260	204,2	260	314,6	247
87,3	290	222,9	280	300,4	270		
125,1	310	343,0	285				
199,9	330						
387,4	345						

Table 4-9: Reference heat [kJ/kg cem] and corresponding maturity [h]

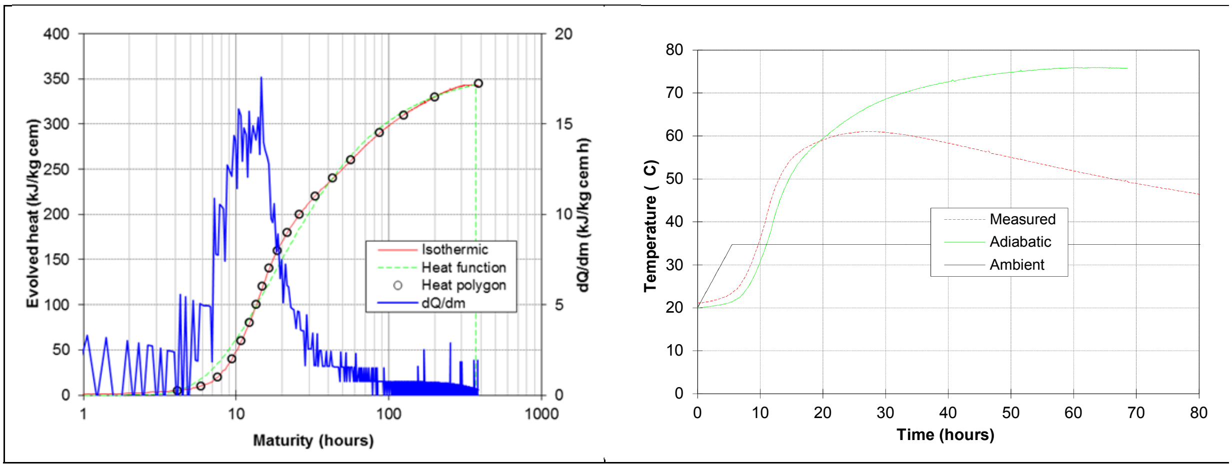

Figure 4-21: Heat development, ANL Ref.

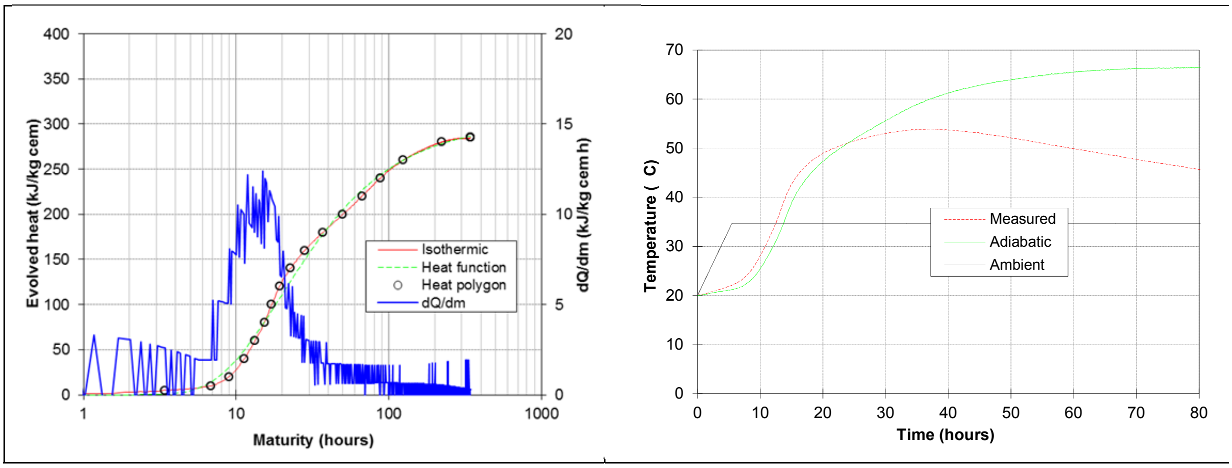

Figure 4-22: Heat development, ANL FA

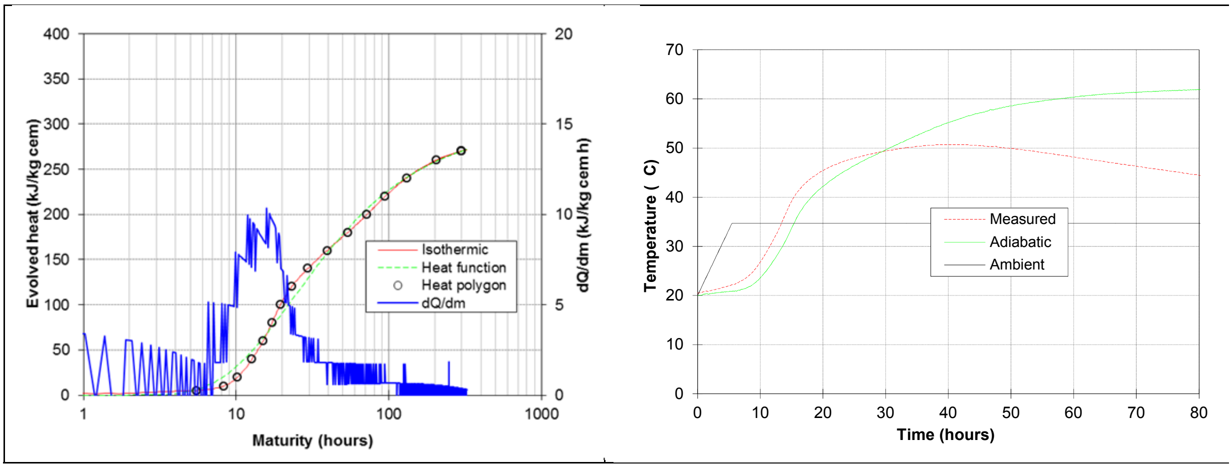

Figure 4-23: Heat development, ANL FA + 8FA

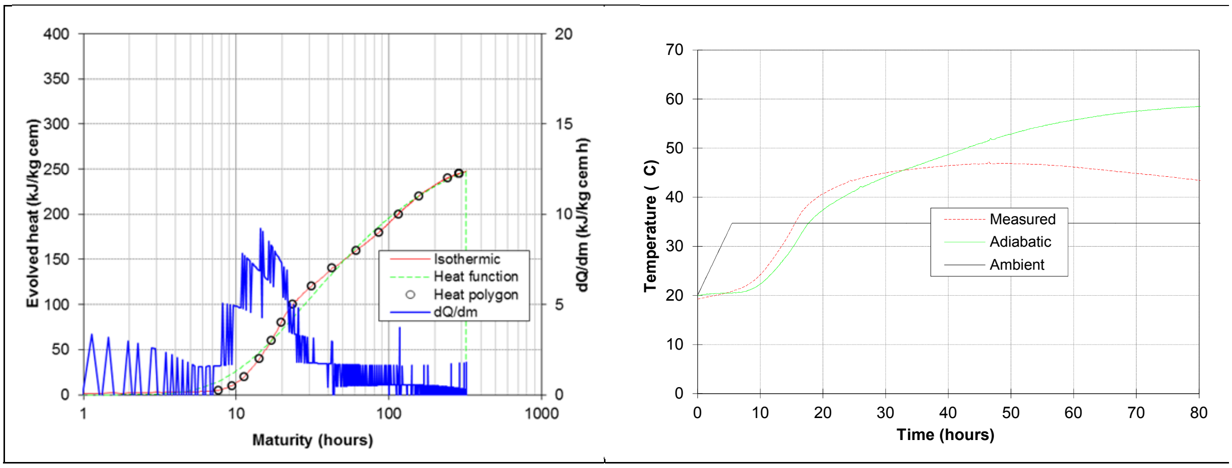

Figure 4-24: Heat development, ANL FA + 16FA

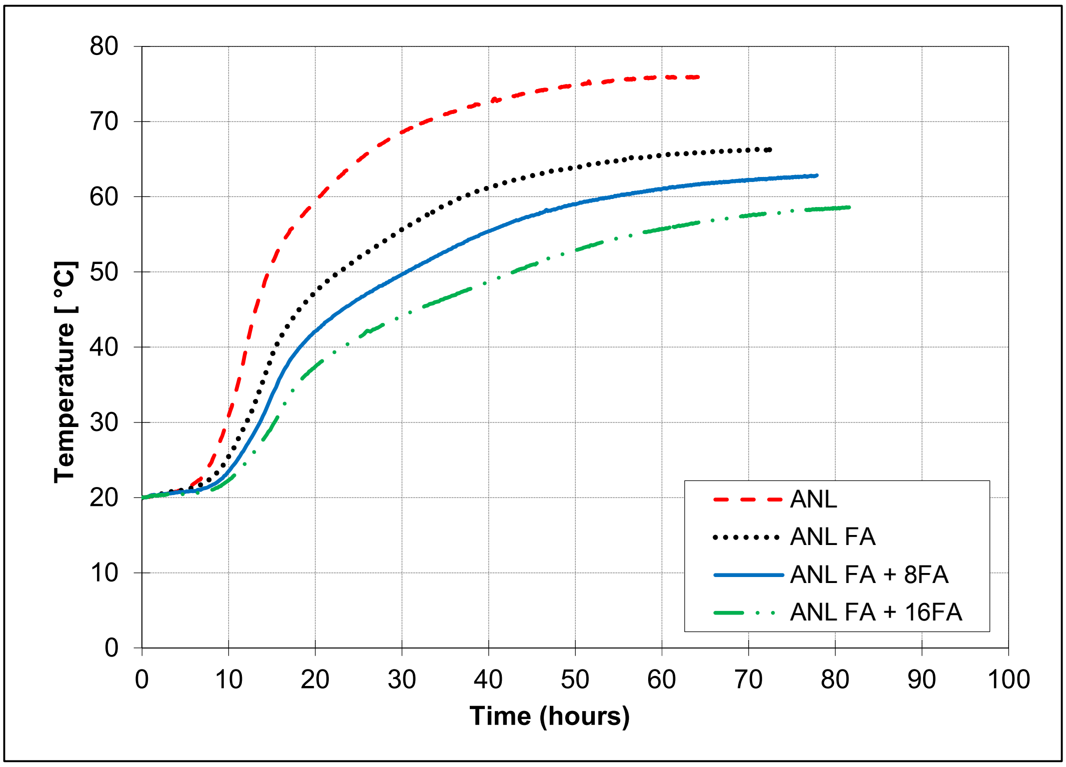

Figure 4-25: Temperature development versus time – All concrete qualities

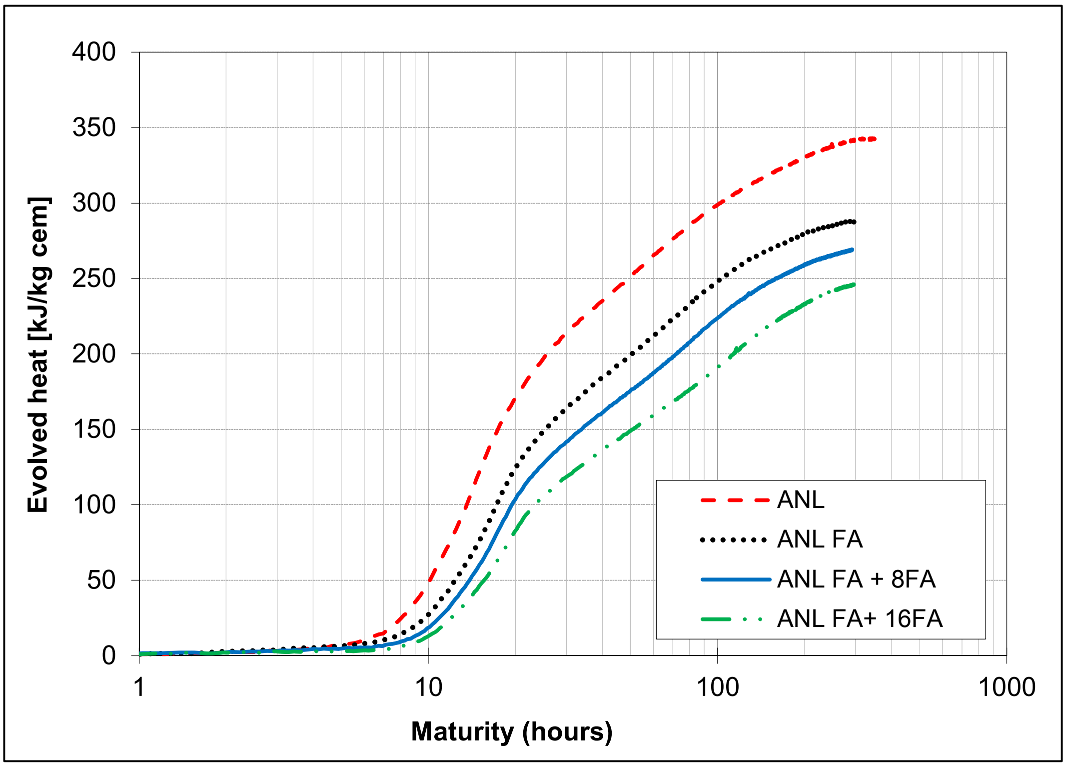

Figure 4-26: Evolved heat versus maturity – All concrete qualities

As can be seen from Figure 4-25, the temperature reduction is about proportional to the replacement of clinker by FA. [Bjøntegaard et al., 2012] also show reduced temperatures with increased FA content, allthough not proportional.

5 Material model parameters

5.1 General

The present section gives a description of the models used for heat development, compressive- and tensile strength development, as well as the modulus of elasticity development. The description of the material models is followed by a presentation of the determined model parameters, as well as an explanation of the procedures by which they were found. Finally, the model parameters for use in CrackTeSt COIN are summarized in Section 5.4.

5.2 Material models

5.2.1 Heat development

The concrete's heat development is described by the following model.

$$Q = W_c \cdot e^{\left(-\lambda_1 \cdot \ln\left(1+\frac{t_e}{t_1}\right)\right)^{-\kappa_1}}$$ Equation 5.1

where $Q(t_e)$ is the heat generation as a function of maturity time t_e, Q_∞ is the final heat after "infinite" time as well as a curve fitting parameter, together with τ og α

5.2.2 Compressive strength, tensile strength and modulus of elasticity

Compressive strength, tensile strength and E-modulus are modelled by the following modified version of CEB-FIP MC 1990 [Kanstad et. al, 2003] and [Bjøntegaard, 2011]:

$$X(t_e) = X(28) \cdot \left\{ exp\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_e - t_0}} \right) \right] \right\}^n$$ Equation 5.2

where $X(t_e)$ is the mechanical property as a function of maturity t_e. $X(28)$ is the property at 28 days, s and n are curve-fitting parameters, and t_0 is the maturity time when the properties are assumed to start to develop [Bjøntegaard, 2011]

Hence, the equations describing the compressive strength, tensile strength and E-modulus, respectively, are as follows;

$$f_c(t_e) = f_{c28} \cdot \left\{ e^{\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_e - t_0}} \right) \right]} \right\}^{n_c}$$ where n_c=1 Equation 5.3

$$f_t(t_e) = f_{t28} \cdot \left\{ e^{\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_e - t_0}} \right) \right]} \right\}^{n_t}$$ Equation 5.4

$$E_c(t_e) = E_{c28} \cdot \left\{ e^{\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_e - t_0}} \right) \right]} \right\}^{n_E}$$ Equation 5.5

5.3 Determination of model parameters

5.3.1 Temperature sensitivity, model parameters A and B

Compressive strength tests on specimens cured in 5 °C, 20 °C or 35 °C were performed for the four given concretes as described in Section 3.6.

The maturity time t_e is defined as;

$$t_e = \sum_t e^{\frac{E_T(T_i)}{R} \cdot \left(\frac{1}{293} - \frac{1}{273+T_i}\right)} \cdot \Delta t_i \qquad \text{Equation 5.6}$$

where E_T is the activation energy; $E_T = A + B(20-T_i)$ for $T < 20\,^{o}$C, and $E_T = A$ for $T > 20^{o}$C. R is the gas constant

By using the method of least squares, the isothermal (20 °C) compressive strength test results for each concrete were fitted to the compressive strength model, Equation 5.3. The activation energy model parameters *A* and *B* for the given concretes were determined by minimizing the deviations between the obtained isothermal model line (20 °C) and the results from the 5 °C and 35 °C tests. The results are presented in Table 5-1.

Table 5-1: Activation energy model parameters

Concrete	*A*	*B*
ANL Ref.	31482	296
ANL FA	31487	197
ANL FA + 8FA	32958	273
ANL FA + 16FA	37023	0

It is seen from Table 5-1 that the constant *A*, which represents the concrete temperature sensitivity, is increasing with increasing FA content. The same trend was also seen in [Bjøntegaard et. al, 2012], where there was a clear tendency of increased *A*-value for the two highest FA-dosages ($ANL_{mod}20\%FA$ and $ANL_{mod}35\%FA$). It was expected that the temperature sensitivity constant *B*, which represents the temperature sensitivity for T < 20 °*C*, would be decreasing with increasing FA content [Bjøntegaard et. al, 2012]. This was also the case for the current test series, except that ANL FA + 8FA deviates from the trend with a higher B value than ANL FA. However, the differences are small, see Table 5-1.

5.3.2 Compressive strength

After obtaining the activation energy model parameters *A* and *B* for the given concretes, the final compressive strength models with its belonging fitting parameters, f_{c28}, *s* and t_0, were determined by the following procedure; First, t_0 was found by fitting the compressive strength test results for *T* = 20 ^{o}C to the previously described modified CEB-FIP model code formulation, Equation 5.3, by using the method of least squares and a Solver add-in in Excel VBA. Further, f_{c28} and *s* were found by fitting the compressive strength test results for all temperatures (5, 20 and 35 ^{o}C) to the modified CEB-FIP model code formulation, Equation 5.3, by using the method of least squares and Excel VBA. The results are presented in Table 5-2 and in Figure 5-1 - Figure 5-5. The agreement between the model and the experimental results is reasonably good, and nearly as expected based on previous experience with these models.

The concrete set time, t_0, determined by the described procedure, agrees well with the compressive strength development for all four concretes, Figure 5-6. However, Table 5-2 shows that t_0 decreases with increasing FA-content. Setting time determined by heat development, t_{12kJ}, shows the opposite trend. The latter is expected due to previous experience. The heat development measurements give the most trustworthy setting time development, and in addition, these measurements are performed in the same laboratory and from the same batch as the tensile strength–, and E-modulus tests. It is therefore decided to proceed the current parameter determination for tensile strength and E-modulus with t_0 based on the setting time determined from heat development, t_{12kJ}. A previously found correlation between t_0 and t_{12kJ} is used; $t_0 = t_{12kJ} + 1.8$ hours [Bjøntegaard, et al., 2000], and the results are presented in Table 5-2.

Table 5-2: Model parameters for the compressive strength, and t_0 evaluation

Concrete	*Compressive strength tests*			*Semi-adiabatic heat calorimeter tests*	
	f_{c28}	s	t_0	t_{12kJ}	$t_0 = t_{12kJ} + 1.8$
	[Mpa]	-	*[hours]*	*[hours]*	*[hours]*
ANL Ref.	78.8	0.200	8.9	7.0	8.8
ANL FA	77.8	0.257	7.5	8.8	10.6
ANL FA + 8FA	77.1	0.295	7.5	9.3	11.1
ANL FA + 16 FA	67.9	0.356	7.0	10.2	12.0

As it can be seen from Table 5-2, the model parameter *s* is increasing with increasing FA content. This means that, increasing FA content leads to a reduction of the rate of compressive strength development, Figure 5-5. Also in [Bjøntegaard et. al, 2012], the model parameter *s* was found to be increasing with increasing FA-content.

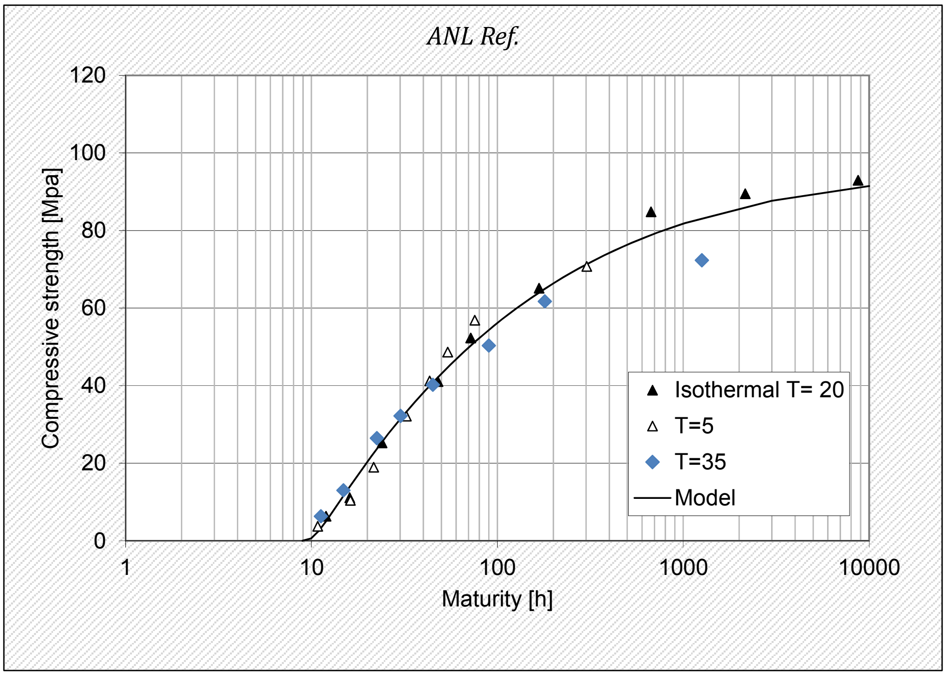

Figure 5-1: Strength versus maturity (logarithmic scale) ANL Ref.

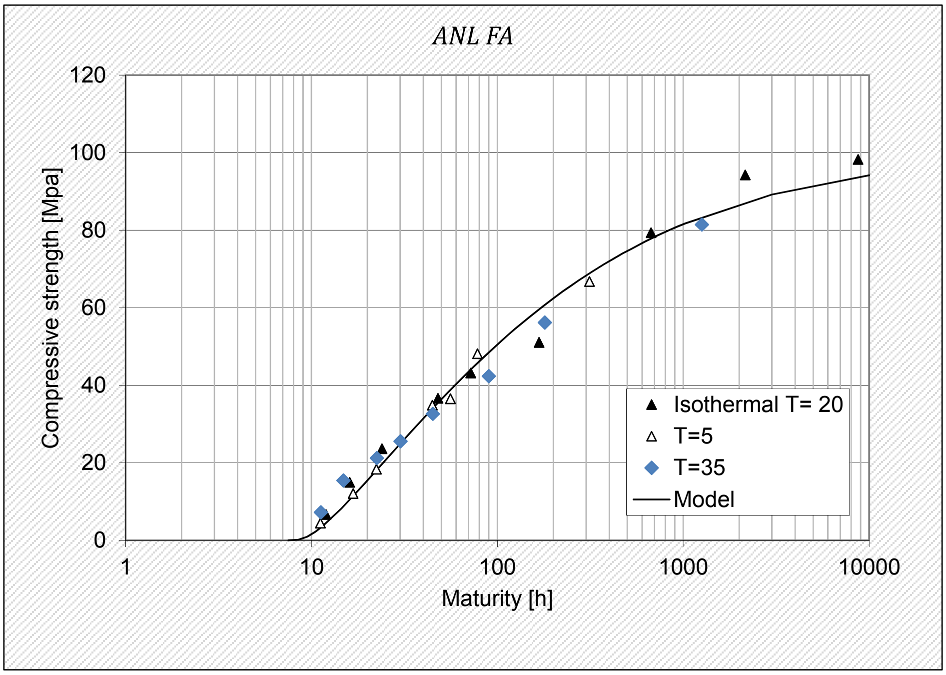

Figure 5-2: Strength versus maturity (logarithmic scale) ANL FA

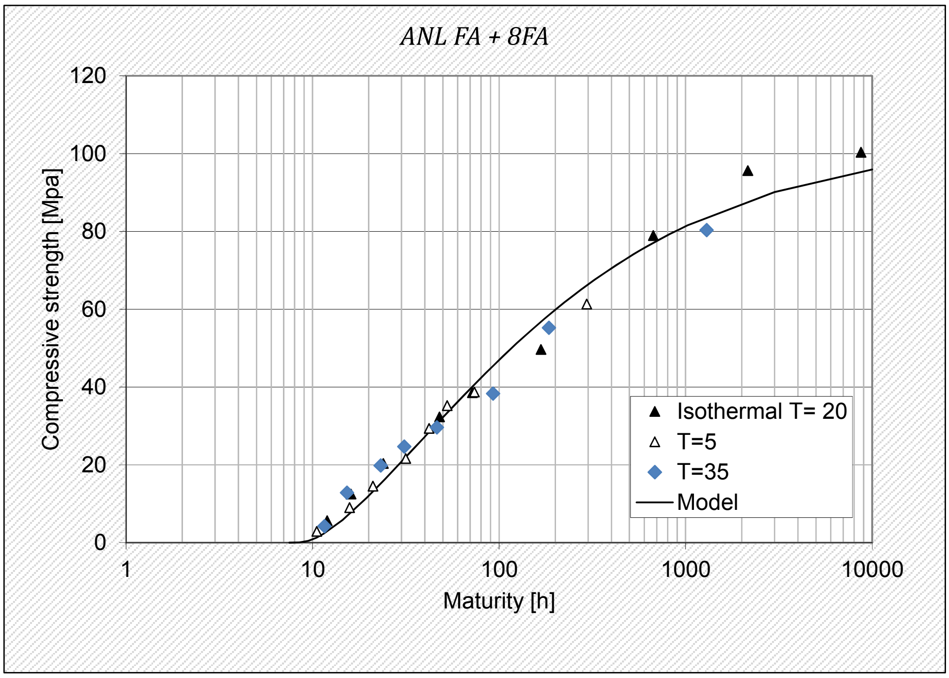

Figure 5-3: Strength versus maturity (logarithmic scale) ANL FA + 8FA

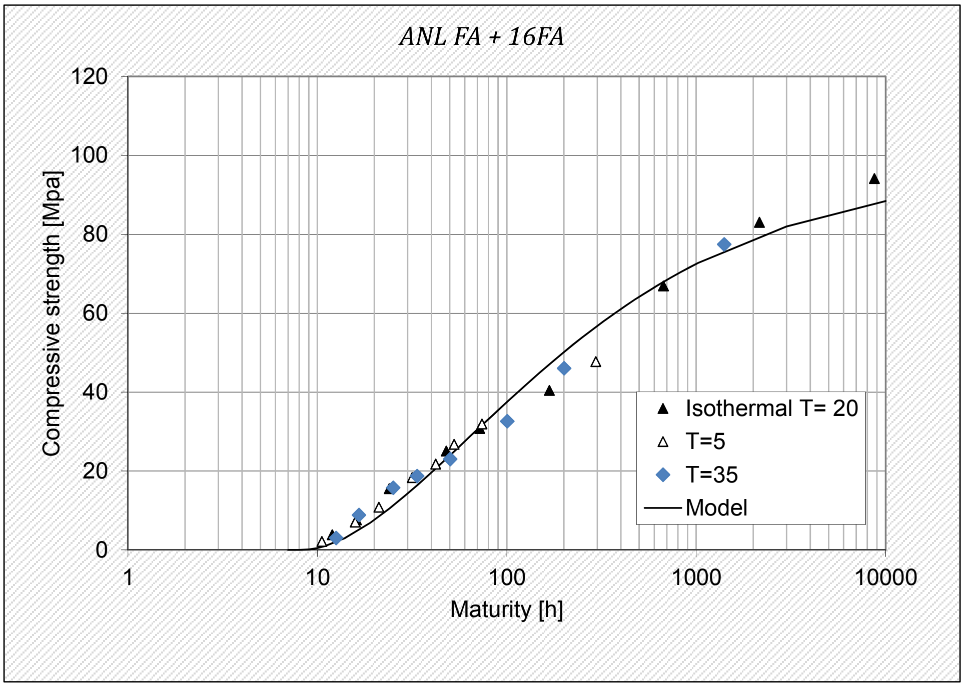

Figure 5-4: Strength versus maturity (logarithmic scale) ANL FA + 16FA

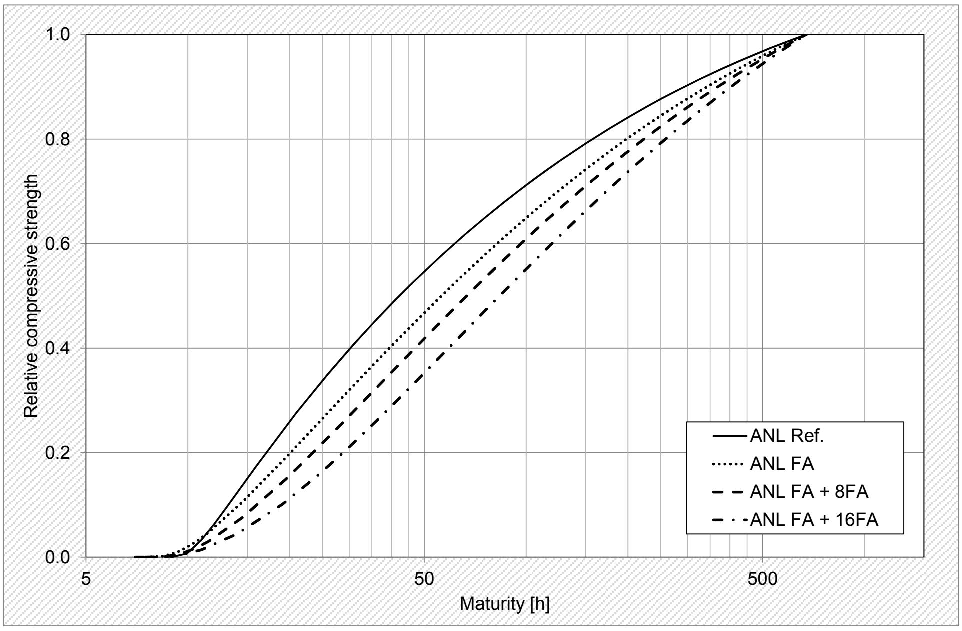

Figure 5-5: Relative compressive strength development

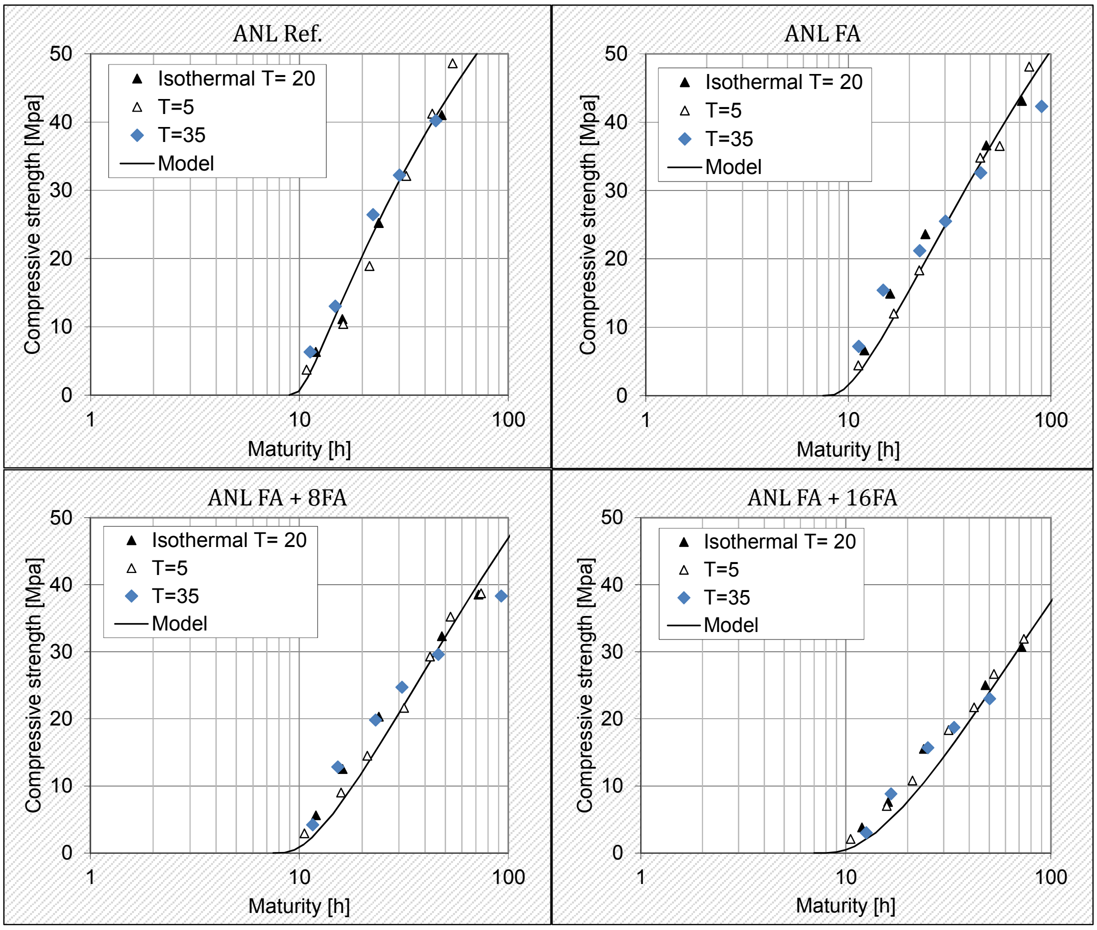

Figure 5-6: Setting time t_0 versus compressive strength development

5.3.3 Tensile strength

The concretes ANL Ref., ANL FA + 8FA and ANL FA + 16FA were tested at 2 and 28 days, while the concrete ANL FA was subjected to 7 tests within the timespan 0.75 – 28 days. All tensile splitting test results are adjusted to uniaxial test results by the linear relation found in Chapter 4.2.3. Due to the limited number of performed tensile strength tests for three of the given concretes, the determined tensile strength at 28 days was fixed to the tensile strength test results at 28 days, t_0 was set according to Section 5.3.2, while the fitting parameter n_t was found by fitting the remaining tensile strength test results to the previously described modified CEB-FIP model code formulation, Equation 5.4, by using the method of least squares and a Solver add-in in Excel VBA.

The results are presented in Table 5-3, as well as in Figure 5-7 - Figure 5-8.

Table 5-3: Model parameters for the tensile strength

Concrete	f_{t28} *[Mpa]*	n_t
ANL Ref.	3.86	0.484
ANL FA	3.29	0.509
ANL FA + 8FA	3.28	0.508
ANL FA + 16FA	3.05	0.486

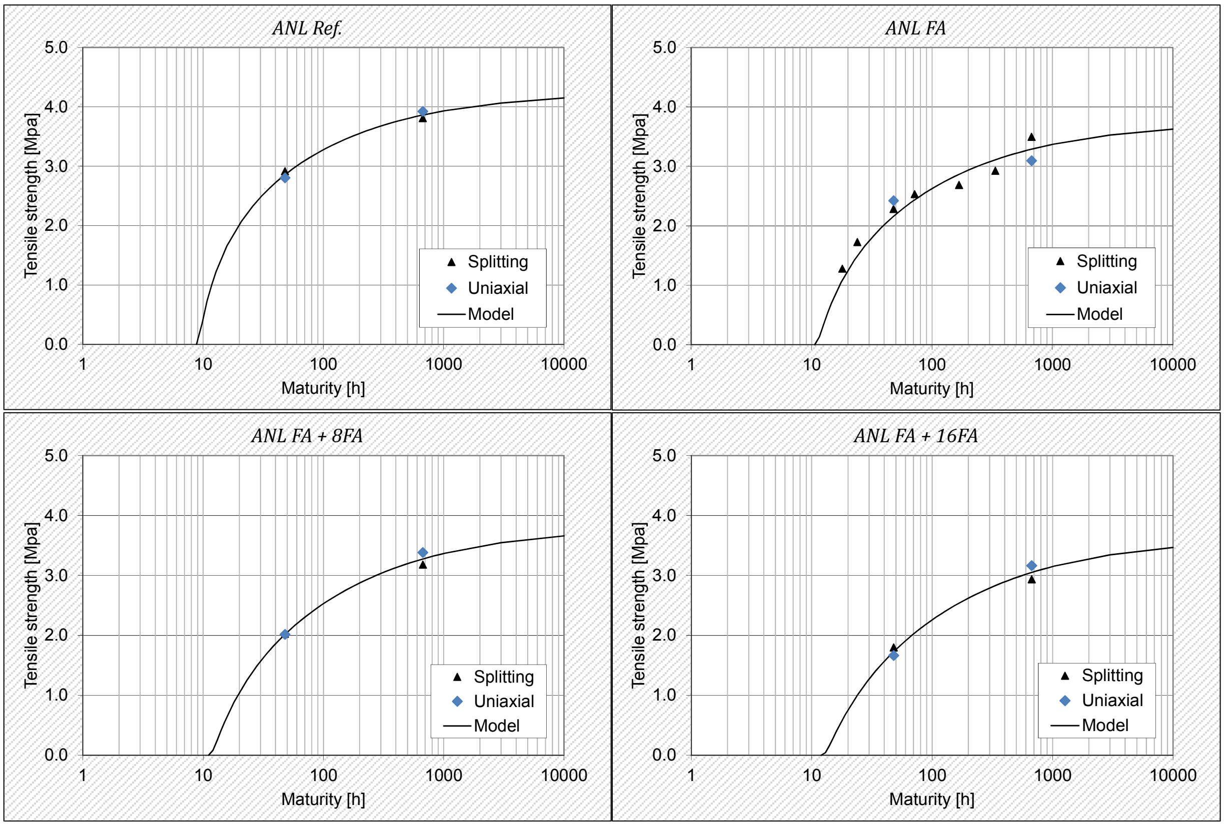

Figure 5-7: Tensile strength development. All tensile splitting test results are adjusted to uniaxial test results by the linear relation found in Chapter 4.2.3.

It is seen from Table 5-3 that the tensile strength decreases with increasing FA content, while n_t lies within the same range as found in [Kanstad et al., 2003]. Table 5-3 also shows very similar tensile strenght model parameter values for the concretes ANL Ref. and ANL FA. The model parameters found for ANL FA are based on considerable more test results than the other concretes.

Figure 5-8 presents the relative tensile strength development for the given concretes. It can be seen from the figure that there is a small reduction of the rate of tensile strength development with increasing FA content.

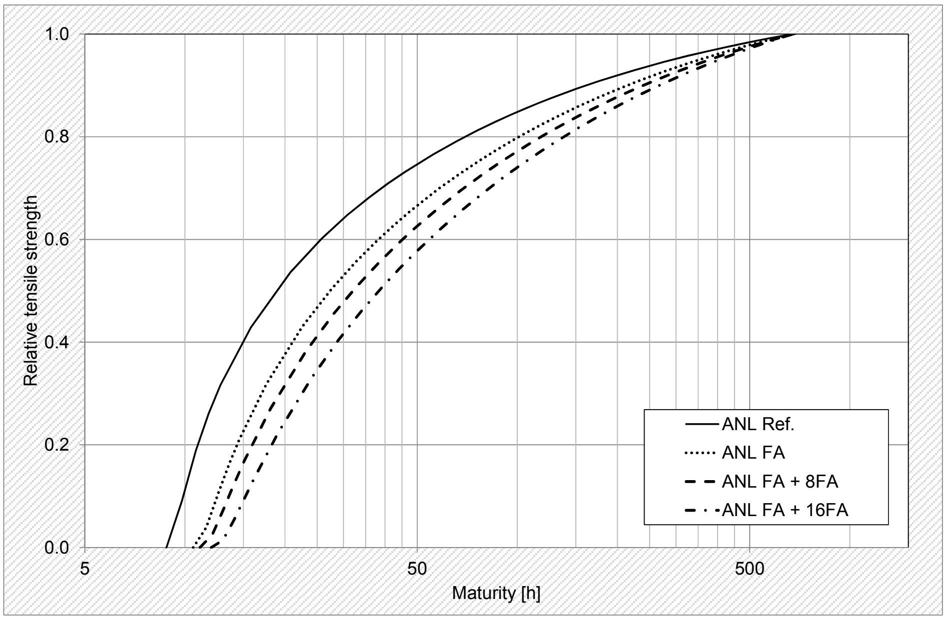

Figure 5-8: Relative tensile strength development

5.3.4 Modulus of elasticity

The model parameters describing the development of the elastic modulus were determined in the following way; for all given concretes, the E-modulus at 28 days was set to the E-modulus test result at 28 days and t_0 was set according to Section 5.3.2. Further, the fitting parameter n_E was found by fitting the test results at 2 days to the previously described modified CEB-FIP model code formulation, Equation 5.5, by using the method of least squares and a Solver add-in in Excel VBA. All compressive E-modulus test results are adjusted to tensile test results by the linear relation found in Chapter 0.

The results are presented in Table 5-4, as well as in Figure 5-9 - Figure 5-10.

Table 5-4: Model parameters for the E-modulus

Concrete	E_{28} [Gpa]	n_E
ANL Ref.	32.25	0.338
ANL FA	30.55	0.294
ANL FA + 8FA	27.70	0.232
ANL FA + 16FA	27.80	0.252

The 28 days E-modulus achieved for the given concretes, Table 5-4, seems to be slightly lower than E-moduli found in previous work as [Bjøntegaard et al., 2012] and [Kanstad et al., 2003]. The achieved values for n_E are for all given concretes lower than the default value n_E = 0.37 which was established by [Kanstad et al., 2003].

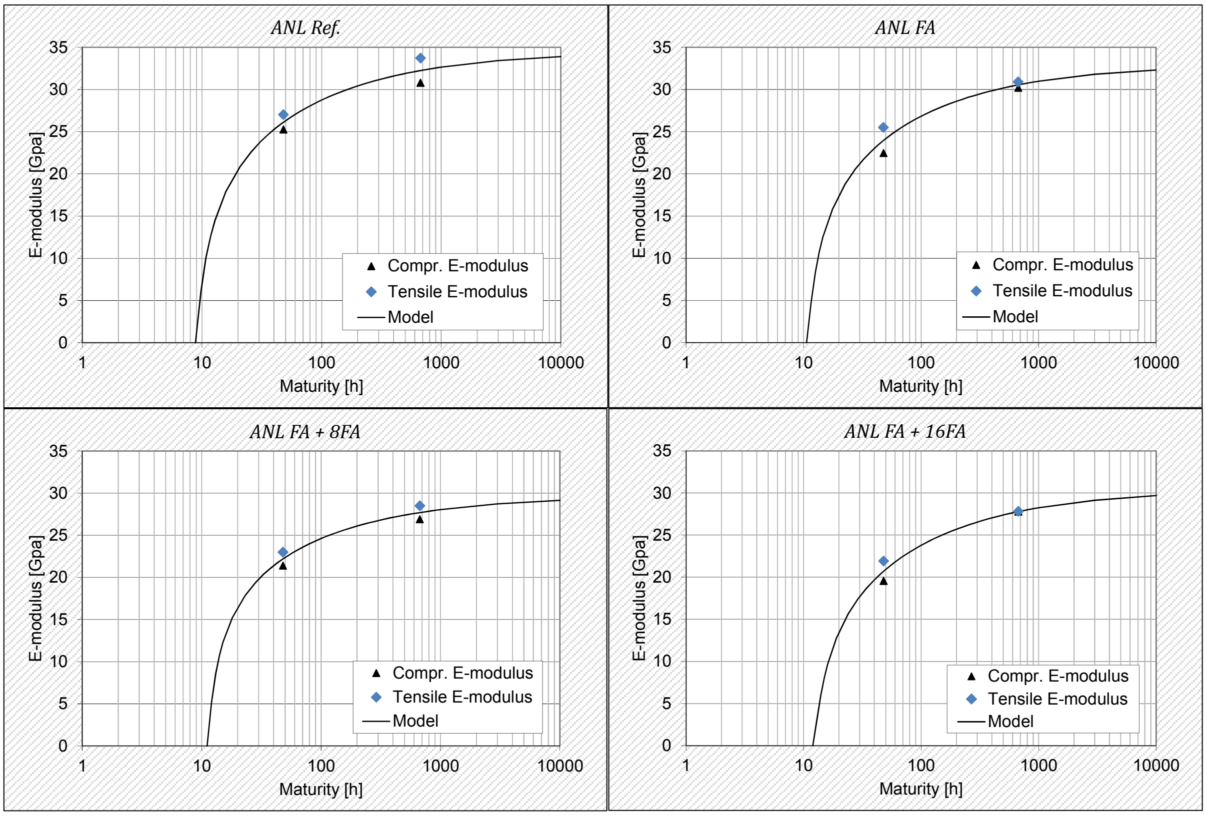

Figure 5-9: E-modulus development. All compressive E-modulus test results are adjusted to tensile test results by the linear relation found in Chapter 0.

Figure 5-10 presents the relative development of the E-modulus for the given concretes. It can be seen from the figure that, with exception from ANL FA +16FA, there is a small reduction of the rate of E-modulus development with increasing FA content.

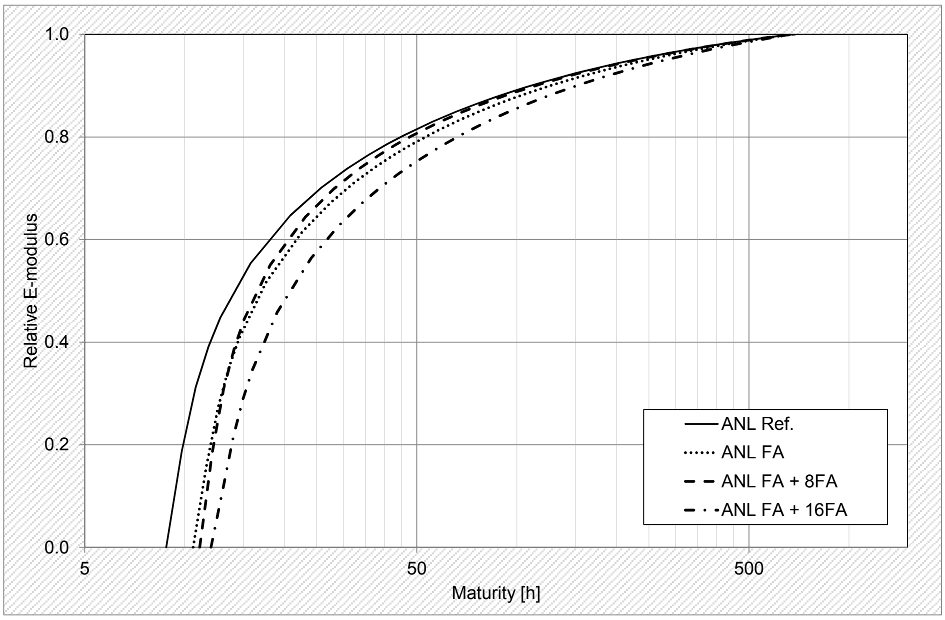

Figure 5-10: Relative E-modulus development, logarithmic scale

5.4 Model parameters for use in CrackTeSt COIN - Summary

Based on the present test series, the following model parameters for use in the CrackTeSt COIN program have been determined according to the procedures described in Chapter 5.3:

Model parameters for the activation energy;

Concrete	*A*	*B*
ANL Ref.	31482	296
ANL FA	31487	197
ANL FA + 8FA	32958	273
ANL FA + 16FA	37023	0

Model parameters for the compressive strength;

Concrete	f_{c28} [Mpa]	s -	t_0 [hours]
ANL Ref.	78.8	0.200	8.8
ANL FA	77.8	0.257	10.6
ANL FA + 8FA	77.1	0.295	11.1
ANL FA + 16FA	67.9	0.356	12.0

Model parameters for the tensile strength;

Concrete	f_{t28} [Mpa]	n_t
ANL Ref.	3.86	0.484
ANL FA	3.29	0.509
ANL FA + 8FA	3.28	0.508
ANL FA + 16FA	3.05	0.486

Model parameters for the E-modulus;

Concrete	E_{28} [Gpa]	n_E
ANL Ref.	32.25	0.338
ANL FA	30.55	0.294
ANL FA + 8FA	27.70	0.232
ANL FA + 16FA	27.80	0.252

6 Conclusions

A test series of four different concretes has been carried out within COIN's Focus Area 3.1 *Crack Free concrete structures*, and the test series has been named «COIN P3.1 series». The intention was to investigate how replacing cement with an increasing amount of fly-ash would affect the development of main mechanical characteristics for these concretes.

The current report presents the results from a mechanical test programme investigating the mechanical properties of young concrete for the COIN P3.1 series. Results from corresponding tests in the TSTM-system and FD-system will be reported separately.

In general, it is shown that all the investigated properties; the final heat generated, the compressive strength, the tensile strength and the E-modulus decrease approximately linearly with increasing replacement of cement clinker by fly ash. For instance, it is shown that 36% FA content leads to a 14 % compressive strength reduction at 28 days. The corresponding reductions in tensile strength, E-modulus and final heat are 21 %, 14 % and 19 % respectively. Since the rate of the hydration reactions decrease with increasing FA content, the differences are larger at lower ages.

A linear relation between uniaxial and splitting tensile strength is determined. This relation show larger differences between the two tests methods than determined previously.

The E-modulus determined from the uniaxial tensile strength test is slightly larger than the values determined from the standard compressive test.

In general, the material models describe the test results very well. The model parameters are logically related to the FA content, and confirm previous experience.

7 Recommended further research

The test series and model parameter determination are carried out to establish a material database for use in crack risk estimations of concrete at early ages. Corresponding test series should also be carried out for other material variants and for other cement replacing materials as slag.

A second, corresponding investigation with an Aalborg Rapid cement is presently being carried out.

The general validity and further work to establish default values or “range” of expected values should be investigated. This will make it possible to simplify future test programs.

The relations between the 28 days values of the compressive strength, the tensile strength and the E-modulus should be compared to the relations used in Eurocode 2 and FIB Model Code 2010. It would be interesting to see if the existing relations in the codes also hold for FA concretes (low heat concretes).

8 Acknowledgement

The report is based on the work performed in COIN - Concrete Innovation Centre (www.coinweb.no) - which is a Centre for Research based Innovation, initiated by the Research Council of Norway (RCN) in 2006. COIN has an annual budget of NOK 25 mill, and is financed by RCN (approx. 40 %), industrial partners (approx 45 % of which ¼ is cash) and by SINTEF and NTNU (in all approx 15 %). The Centre is directed by SINTEF, with NTNU as a research partners and with the present industrial partners: Aker Solutions, Norcem, Norwegian Public Roads Administration, Rescon Mapei, Skanska, Spenncon, Unicon, Veidekke and Weber Saint Gobain.

The new FD-system and upgrading of the TSTM-system 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 with their priceless contribution to production and maintenance of the rigs, and to the students Belen P. Fernandez and Juan Morales who have done a great job with the mechanical test programme.

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