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Concrete with Aalborg cement and variable fly ash content

COIN Project report 56 – 2015

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FA: Technical performance

SP 3.1 Crack free concrete structures

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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 restrained thermal dilation and autogeneous shrinkage. 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, experiments with two different concretes containing Aalborg cement and variable amount of fly ash have been carried out within the project. This was conducted as a supplement to the previous experiments with Norcem cements performed and reported earlier within the same COIN project.

This report contains 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 two 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 approximately linearly with increasing FA content.

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 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 will be implemented in the material data base for the temperature and stress calculation program Crack TeSt COIN.

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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 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.

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, two different concretes with Aalborg Rapid cement (CEM I 52,5 N LA) and varying amount of fly-ash, respectively 20 % and 33 % of binder, has been tested for mechanical properties. This report presents the results from the test programme conducted on these two concrete qualities.

2 Experimental programme, mix design and material characteristics

2.1 General

This chapter describes the experimental mechanical test programme, including mix design of the different concrete qualities. 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, two different concrete mixes were investigated for mechanical properties. The experimental programme is given in **Error! Reference source not found.**.

Table 2-1: Experimental programme Aalborg cement with different FA replacements

				Aalborg 20FA M40	Aalborg 33FA M40
Tensile strength and E-modulus	100×100×600	prisms	No. of spec.	12	12
			Test age	2, 7, 28, 90	2, 7, 28, 90
Tensile splitting strength	Ø100×200	cylinders	No. of spec.	12	12
			Test age	2, 7, 28, 90	2, 7, 28, 90
Compressive strength	100×100	cubes	No. of spec.	12	12
			Test age	2, 7, 28, 90	2, 7, 28, 90
E-modulus in compression	Ø100×200	cylinders	No. of spec.	9	9
			Test age	2, 7, 28	2, 7, 28

2.3 Mix design

Table 2-2 shows the mix design of the two different concretes. The percentage of fly ash referred to in the notation of the concretes is calculated by the formula:

$$\frac{FA}{FA+c+s} \cdot 100\ \% \qquad \textbf{Equation 2.1}$$

Table 2-2: Mix design of basic concretes

Materials [kg/m^3]	Aalborg 20FA M40	Aalborg 33FA M40
Cement, Aalborg Rapid	282.3	234.9
Fly ash, Aalborg B4	74.5	123.0
Micro silica, Elkem 920-D	14.9	14.9
Super plasticizer, Sika Visco Crete RMC-420	2.90	2.90
Sand 0-2 mm, Årdal	209.3	214.1
Sand 0-8 mm, Årdal	748.2	765.4
Stone 4-8 mm, Årdal	267.8	273.9
Stone 8-16 mm, Årdal	597.4	611.1
Total water content	162.3	162
$(w/(c + k_s \cdot s + k_{FA} \cdot FA))$[1]	0.4	0.4
s/c	5.3	6.4
f/c	26.3	52.4
Matrix volume [l/m^3]	326	326

---

[1] For these mixtures, the following k-values were used: $k_s = 2.0$ and $k_{FA} = 1.0$

2.4 Material characteristics

2.4.1 Cement

In these experiments a Portland cement; CEM I 52.5 N LA (Aalborg Rapid) was used. The specifications as provided by the manufacturer are given in Table 2-3.

Table 2-3: Cement specifications

Specifications	Aalborg Rapid 2012 - CEM I 52,5 N LA
Physical properties	
1-day strength	22 MPa
2-day strength	35 MPa
7-day strength	52 MPa
28-day strength	65 MPa
Setting time	135 minutes
Fineness	469 m^2/kg
Reflection (DIN 5033)	31 %
+90my	0.5%
+64	1.7%
-24	74%
-30	82.6%
Absolute density	3130 kg/m^3
Bulk density	1100 kg/m^3
Bogue composition	
C_3S	62 %
C_2S	13 %
C_3A	8 %
C_4AF	12 %
Chemicals	
SO_3	3.2 %
MgO	1.0 %
Na_2O	0.6 %
Cl^-	0.02 %
Loss on ignition (LOI)	2.6 %
Insoluble residue	0.7 %
Water-soluble Cr^{6+}	≤ 2

2.4.2 Admixtures

A polycarboxylate based super plasticizer, Sika ViscoCrete RMC-420, was used in both mixes. Specifications are listed in Table 2-4.

Table 2-4: Specifications – Super-plasticizer

Properties	Declared values
Dry substance	(18 ± 1) %
Density	(1.04 ± 0.02) kg/l
pH-value	4.0 ± 1
Equivalent Na2O	< 0.7 % by weight
Chloride content	< 0.01 % by weight

2.4.3 Pozzolanic additions

Fly ash

The fly ash, Type B4 was supplied by Emineral, Denmark. The composition and physical properties are given in Table 2-5 (in Danish).

Table 2-5: Specifications Emineral Fly Ash, Type B4

Egenskab		**Metode**	**Krav i henhold til DS/EN 450-1:2007+A1**	**Emineral har for Type B4 supplerende deklareret**
Glødetab / Restkulstof (Kategori A) (1)		EN 196-2	> 0,0 - < 5,0 (7,0)	< 4,0 (4,0) *
Chlorid (Cl^-)		EN 196-2	< 0,10 (0,10)	< 0,02 (0,02) *
Svovlsyre anhydrid (SO_3)		EN 196-2	< 3,0 (3,5)	
Fri calciumoxid (Fri CaO)		EN 451-1	< 1,0 / < 2,5 (2,6)	
Reaktiv calciumoxid (Reakt CaO)		EN 197-1(8)	< 10,0 (11,0)	
Finhed + 0,045 mm (Kategori N)		EN 451-2	< 40 (45)	
- variation			Dekl.værdi ± 10 % (± 15) % -point	(4)
Aktivitetsindeks	28 døgn	EN 196-1	> 75 (70) %	
	90 døgn		> 85 (80) %	
Volumenbestandighed (hvis krævet) (2)		EN 196-3	< 10 (10,0) mm	
Partikel densitet		EN 196-6	Dekl.værdi ± 200 (± 225) kg/m^3	2300 kg/m^3
Reaktivt silicium dioxid (Reakt SiO_2) (4)		EN 197-1	> 25 (22)	
Sum SiO_2 / Al_2O_3 / Fe_2O_3 (4) (5)		EN 196-2 (6)	>70 (65)	
Total alkali ($Na_2O_{ækv}$) (4) (5)		EN 196-2	< 5,0 (5,5)	
Magnesium oxide (MgO) (5)		EN 196-2	<4,0 (4,5)	
Opløseligt fosfat (P_2O_5) (5)		Annex C (7)	< 100 (110) mg/kg	
Afbindingstid (5)		EN 196-3	< 100 % test cement x 2	

Noter:

Ubenævnte værdier er i masseprocent.

Kravværdier er statistiske værdier; grænseværdi for enkeltværdier er angivet i parentes.

(1) Emineral bestemmer restkulstof i stedet for glødetab, med anvendelse af LECO- eller ELTRA-udstyr. Glødetab/restkulstof for kategori A er mellem 0,0 masse- % og 5,0 masse- %, med en grænseværdi for e masse- %

Ved leverancer fra ELK er det oplyste restkulstofindhold et beregnet gennemsnit af siloens indhold min oplyses ved henvendelse til Emineral

(2) Volumenbestandighed bestemmes kun når indholdet af fri CaO er mellem 1,0 og 2,5% -point.

(3) Middelværdien målt over en given periode.

(4) Værdier for disse egenskaber oplyses på forlangende.

(5) Disse egenskaber kræves kun bestemt for flyveaske fremstillet ved samforbrænding iht. DS/EN 450-1.

(6) Prøvningsmetoden er modificeret som angivet i DS/EN 450-1, pkt. 5.2.1.

(7) Annex C i DS/EN 450-1.

(8) Bestemmes kun når indholdet af CaO er >10,0 masse- %

Silica fume
In these experiments Elkem Micro silica Grade 920 Densified was used. Specifications are listed in Table 2-6.

Table 2-6: Specifications Elkem Micro silica 920 D

	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

2.4.4 Aggregates

Each of the concrete mixes contained three sand fractions; Årdal 0/2 mm, Årdal 0/8 mm Årdal 4/8 mm, and one fraction of stone; Årdal 8/16 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 measurement of moisture content in the sand were performed before mixing.

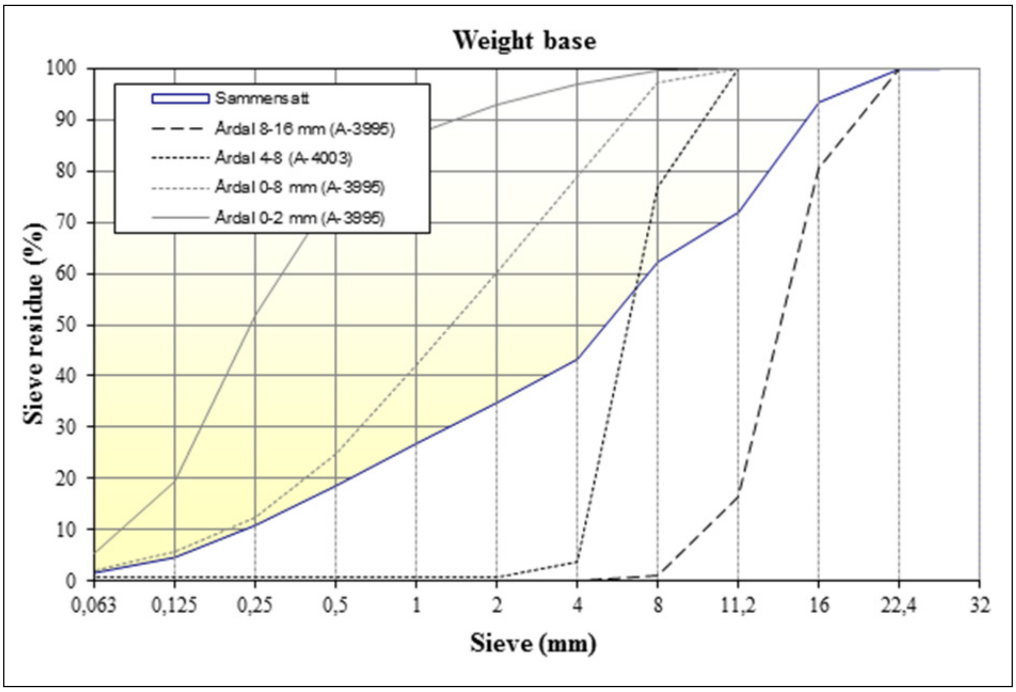

Figure 2-1: Sieve analyses aggregates

The moisture content in the sand was measured to be:

- Årdal 0/2 mm: 6.5 %
- Årdal 0/8 mm: 3.5 %
- Årdal 4/8 mm: 0.2 %

2.5 Mixing and casting

The concrete was mixed in an Eirich paddle mixer with a capacity of 800 litres. The batches were in total 250 litres. The materials were added according to the following procedure:

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

50 % of the admixtures were added together with mixing water in step 2. There were 1-2 minutes of mixing after addition of the super plasticizer. After standstill, the flow was adjusted to a slump of 200 ± 10 mm with the remaining super plasticizer.

Slump, air-content and density in the fresh concrete were measured directly after mixing, according to NS-EN 12390. The 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 NS-EN 12350

The following fresh properties were measured:

Density: NS-EN 12350-6:2009

The density is determined by compacting the concrete into a rigid and watertight container of known volume and mass and then the weight of the container with its content is measured. The density is calculated from the formula:

$$D = \frac{m_2 - m_1}{V}$$ **Equation 3.1**

where

D=density of the fresh concrete, m_1 = is the mass of the empty container, m_2 = mass of the container completely filled with concrete, V = volume of the container.

Slump: NS-EN 12350-2:2009

Air content: NS-EN 12350-7:2009

3.3 Compression strength

Compressive strength was measured on cubes (100×100 mm) according to NS-EN 12390-3.

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

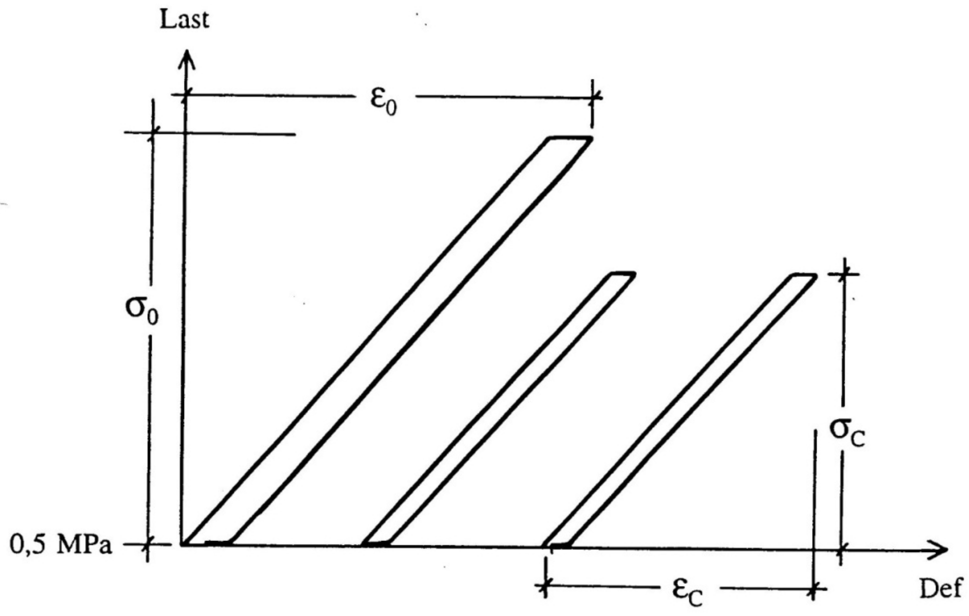

Figure 3-1: Testing cycles and calculation of E-modulus

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:

$$E = \frac{\sigma_{40} - \sigma_{10}}{\varepsilon_{40} - \varepsilon_{10}} \qquad \text{Equation 3.2}$$

where σ and ε are the stress and strain values at 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 in the tensile forces are applied on the ends of specimens by gripping devices. Clamping forces are applied at two positions on each grip. This method has been used for several years as the standard for uniaxial tensile strength determination at SINTEF/NTNU and is described in the SINTEF internal procedure KS 14-05-04-511.

An advantage with 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 is approximately $100x10^{-6}$/min. The modulus of elasticity in tension is calculated from the load-deformation curve, between 10 % and 40 % of the failure load as described above, see Figure 3-2.

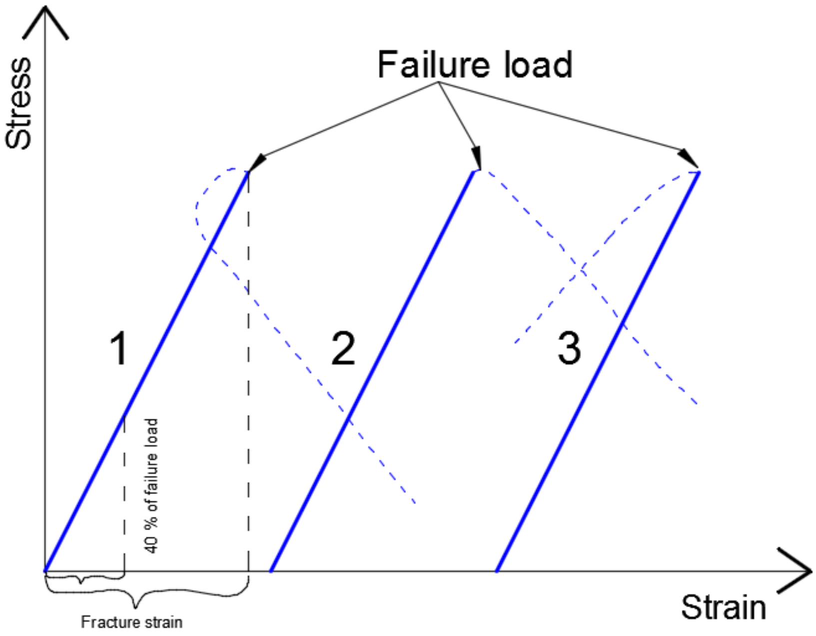

Figure 3-2: Interpretation of load / strain curves of tensile strength

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 a 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: $f_{ts} = \frac{2P}{\pi DL}$ **Equation 3.3**

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. 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, 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 5.3.1.

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.

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 9 days. This is a procedure which reduces the heat loss to the surroundings and therefore improves the accuracy of the method.

4 Results

4.1 Fresh concrete properties

Table 4-1 lists the fresh properties of the two mixes in the mechanical test programme.

Table 4-1: Fresh concrete properties

Concrete	Casting date	Density [kg/m^3]	Slump [mm]	Air content [%]
Aalborg 20FA M40	2012-12-05 10:00	2360	195	1.6
Aalborg 33FA M40	2012-12-05 13:20	2400	210	1.8

4.2 Mechanical properties

4.2.1 Density and compressive strength

The average compressive strength development (f_c) and measured density for both concrete qualities are given in Table 4-2. Figure 4-1 shows the strength development for both concretes during 90 days.

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

Age	2 days		7 days		28 days		90 days	
Concrete	Density [kg/m^3]	f_c [MPa]	Density [kg/m^3]	f_c [MPa]	Density [kg/m^3]	f_c [MPa]	Density [kg/m^3]	f_c [MPa]
Aalborg 20FA M40	2.43	40.9	2.42	66.7	2.42	92.7	2.41	101.4
Aalborg 33FA M40	2.42	28.6	2.42	50.6	2.41	78.7	2.43	94.0

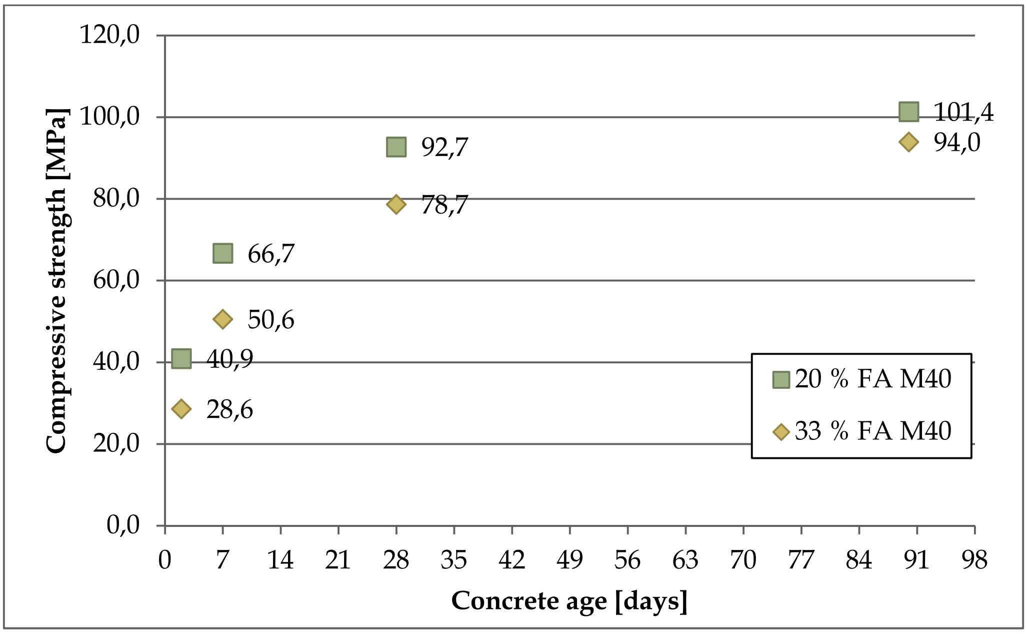

Figure 4-1: Compressive strength development

4.2.2 Tensile strength

The tensile strength of the concretes was measured both with a splitting tensile strength test and a uniaxial tensile strength test. The results from the splitting tensile strength tests are given in Table 4-3, together with the measured densities for those specimens. Figure 4-2 shows the strength development in the splitting tensile test during 90 days. The results from the uniaxial tensile strength are given in Table 4-4 and **Figure** 4-3.

Table 4-3: Results splitting tensile strengt

Age	2 days		7 days		28 days		90 days	
Concrete	Density [kg/m^3]	f_t [MPa]	Density [kg/m^3]	f_t [MPa]	Density [kg/m^3]	f_t [MPa]	Density [kg/m^3]	f_t [MPa]
Aalborg 20FA M40	2.43	3.24	2.44	4.31	2.44	4.70	2.44	5.81
Aalborg 33FA M40	2.42	2.81	2.41	3.47	2.43	5.07	2.43	5.14

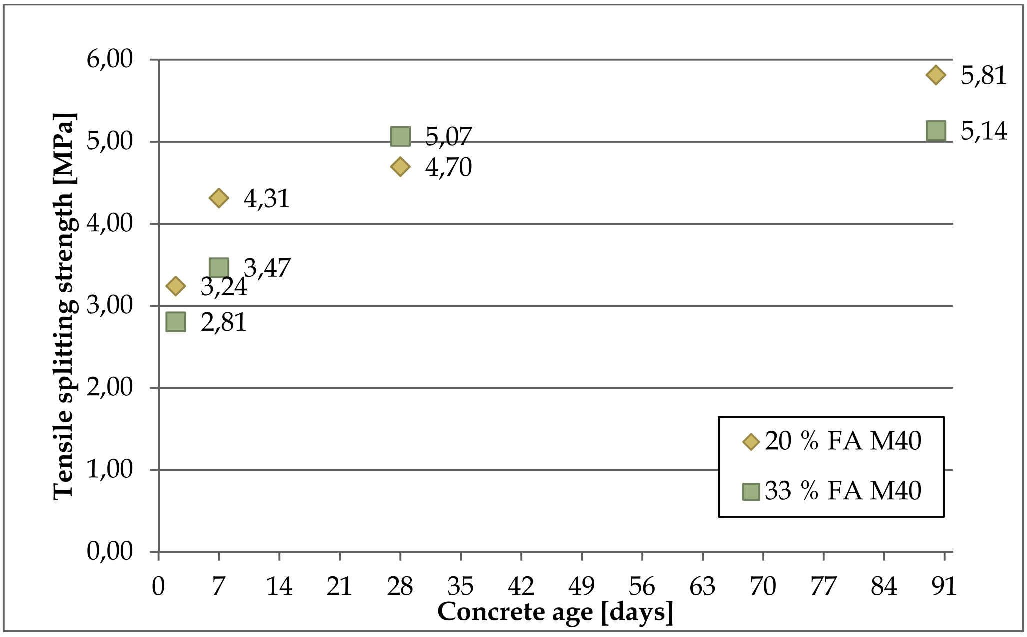

Figure 4-2: Tensile splitting strength development

Table 4-4: Results uniaxial tensile strength

Age	2 days	7 days[2]	28 days	90 days
Concrete	f_t [MPa]	f_t [MPa]	f_t [MPa]	f_t [MPa]
Aalborg 20FA M40	2.55	3.91	4.22	4.69
Aalborg 33FA M40	2.36	3.33	4.12	4.23

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[2] The testing at 7 days failed due to wrong test set-up, and new specimens had to be made from a new batch. The reported 7 days test results is therefore from another batch of mixed concrete than the others.

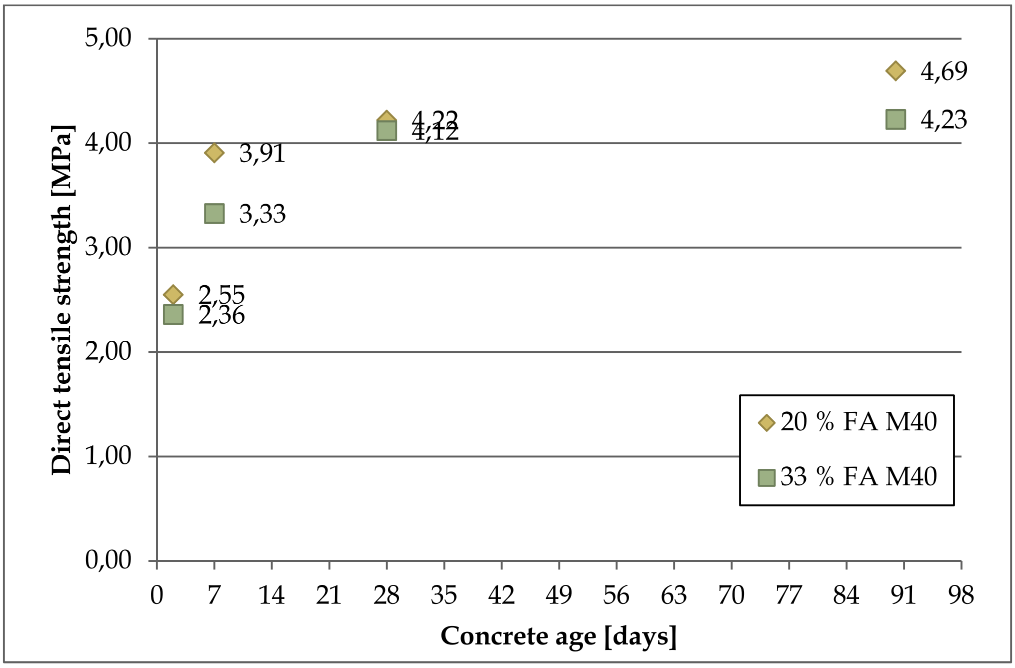

Figure 4-3: Uniaxial tensile strength development

4.2.3 Modulus of elasticity (Young's modulus)

The modulus of elasticity was measured and calculated both from a compression tests (E_c) and from the uniaxial tensile test (E_t). These results are presented in Table 4-5, Figure 4-4 and Figure 4-5. Note that the modulus of elasticity in compression was not measured at 90 days of age.

Table 4-5: Modulus of elasticity in compression and tensile stress

Age	2 days		7 days		28 days		90 days	
Concrete	E_c [GPa]	E_t [GPa]	E_c [GPa]	E_t[3] [GPa]	E_c [GPa]	E_t [GPa]	E_c [GPa]	E_t [GPa]
Aalborg 20FA M40	24.58	25.46	26.07	28.37	30.96	30.96	-	34.43
Aalborg 33FA M40	22.86	23.29	25.44	27.62	29.64	31.2	-	33.16

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[3] The testing at 7 days failed due to wrong test set-up, and new specimens had to be made from a new batch. The reported 7 days test results for E_t is therefore from another batch of mixed concrete than the others

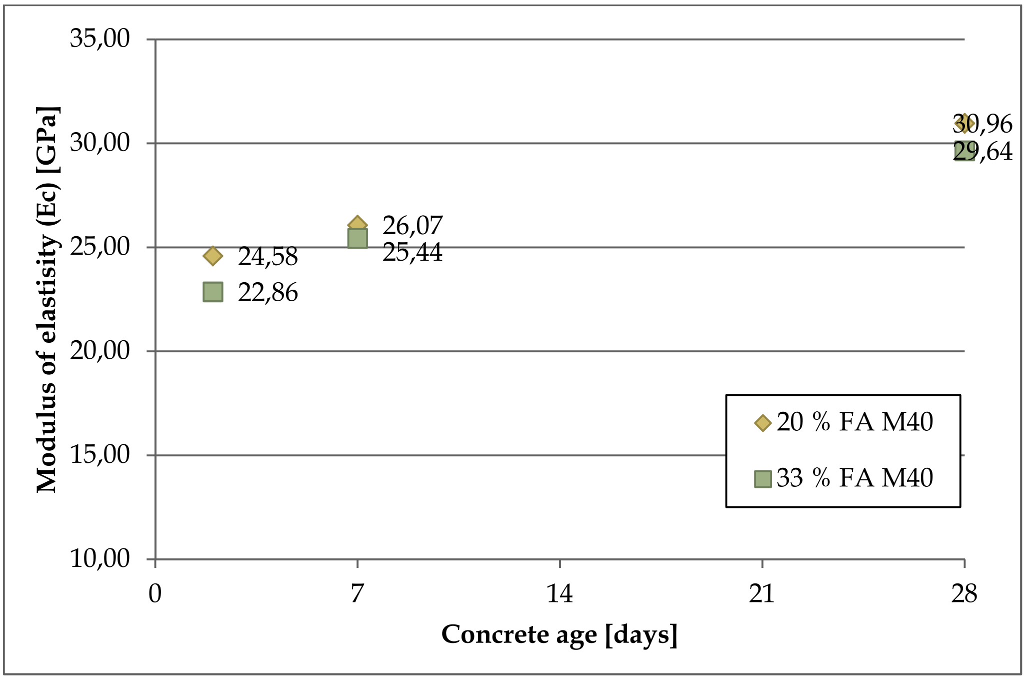

Figure 4-4: Modulus of elasticity according to NS 3676 (compressive test)

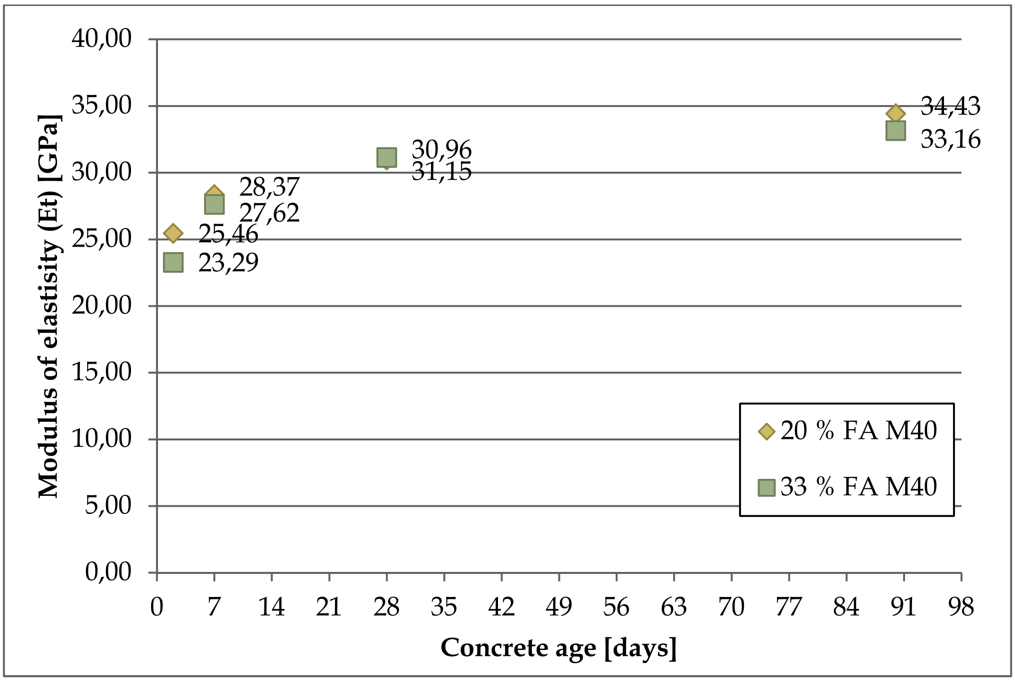

Figure 4-5: Modulus of elasticity from the uniaxial tensile strength test

4.2.4 Uniaxial tensile Strength versus splitting tensile strength

The splitting tensile tests were conducted on Ø100×200 mm cylinders while the uniaxial strength tests were conducted on 100×100×600 mm prisms. If a linear relation analysis is applied, the following relation between tensile (f_t) and splitting strengths (f_{ts}) is found, see Figure 4-6:

$$f_t = 0.77x + 0.34$$

Kanstad, Hammer et al. [1] obtained the relation $f_t = 0.79x + 0.53$

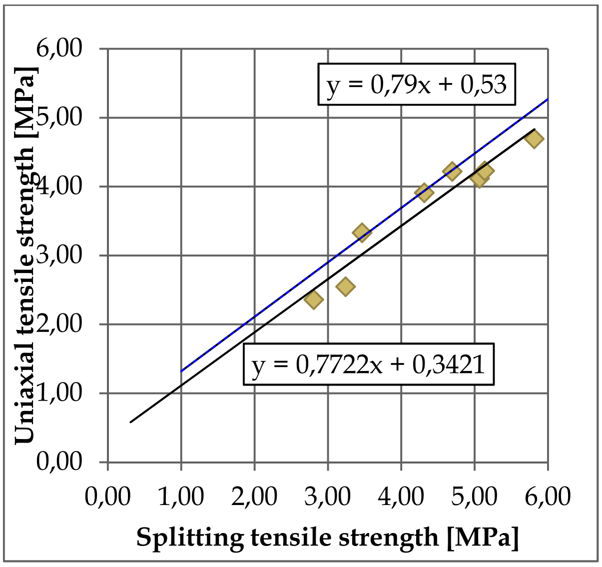

Figure 4-6: Uniaxial tensile strength versus splitting tensile strength.

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

If a linear relation analysis is applied, the following relation between modulus of elasticity in tension and compression is found, see Figure 4-7:

$$E_t = 0.95x + 2.59$$

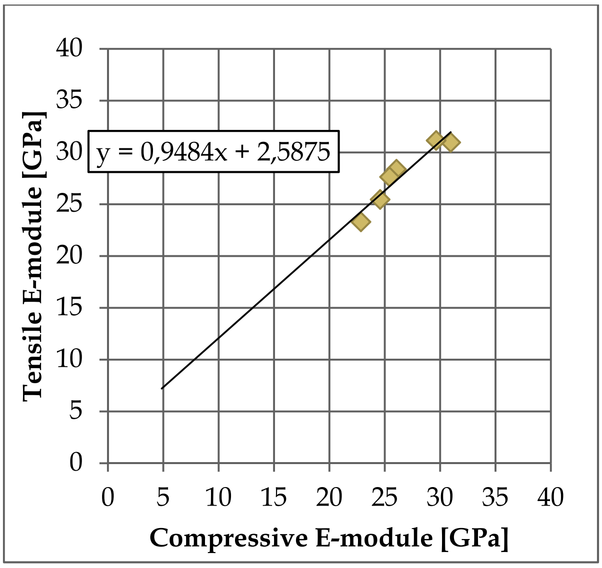

Figure 4-7: Modulus of elasticity in compression versus tension

4.3 Compressive strength for temperature sensitivity calculations

The influence of the temperature on 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 eleven 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, and in Figure 4-8 and Figure 4-9.

More specific, the results were used to calculate the activation energy model parameters A and B, see chapter 5.

Table 4-6: Compressive strength development at 5, 20 and 35 °C

Aalborg 20FA M40					
5 °C		20 °C		35 °C	
Age	MPa	Age	MPa	Age	MPa
24h	7.3	10h	3.6	5h	2.0
30h	14.1	12h	7.8	6h	6.5
42h	23.3	16h	15.2	8h	14.8
48h	24.5	24h	26.2	12h	25.9
72h	37.4	48h	41.2	24h	40.4
5d	51.3	72h	49.3	42h	50.6
8d	54.9	7d	62.1	72h	64.0
14d	66.0	14d	74.7	8d	77.0
28d	75.9	28d	86.5	28d	85.1
Aalborg 33FA M40					
5 °C		20 °C		35 °C	
Age	MPa	Age	MPa	Age	MPa
20h	1.8	10h	1.9	5h	1.7
24h	3.3	12h	4.5	6h	4.7
26h	4.2	16h	11.5	8h	11.3
31h	5.9	24h	19.2	12h	18.8
42h	12.7	48h	33.5	24h	31.1
48h	15.1	72h	40.0	42h	39.2
72h	24.1	7d	51.5	72h	51.3
6d	39.1	14d	65.7	10d	73.7
10d	49.1	28d	77.6	28d	84.9
14d	57.3				
28d	64.1				

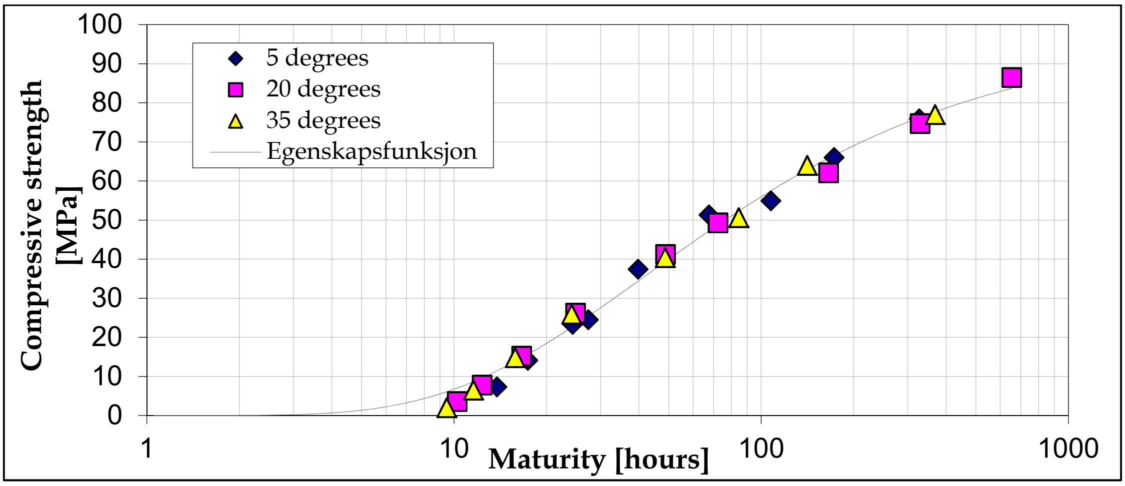

Figure 4-8: Aalborg 20FA M40

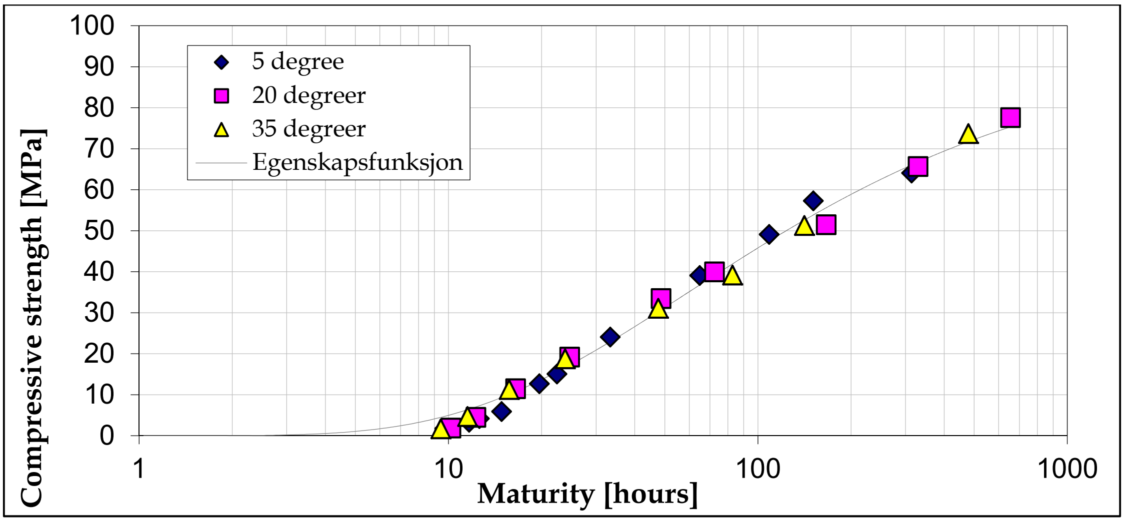

Figure 4-9: Aalborg 33FA M40

4.4 Heat development

Calculations of heat development are performed with an excel sheet developed by Sverre Smeplass according to the descriptions in SINTEF's internal procedure KS 14-05-04-138. Guiding values for choosing a suitable *dQ/dm* (heat loss through the external boundaries) for different maturity ranges and increasing amount of fly ash are given in Table 4-7. The values in the table are established by previous experience.

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

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

4.4.1 Aalborg 20FA M40

The input parameters for concrete properties, temperature transformation coefficient and heat function are given in Table 4-8. The resulting heat polygon is given in **Error! Reference source not found.**. Evolved heat and measured temperatures are shown in **Error! Reference source not found.**.

Table 4-8: Input parameters for heat calculations 20FA M40

Concrete parameters		Temp. trans. coeff.	
Temp. trans. coeff.	0.0209	dQ/dm	0.025
Density	2358	m>	300
Heat capacity (fresh)	1.03	m<	350
Heat capacity (hardened)	1.03		
Cement content	383	Heat function	
Set time	6.6	m-limit	350
A - set time	29958	Q_∞	335
B - set time	447	t	13.31
A - hydration	29958	a	0.97
B - hydration	447	R^2	0.9821
Adia. start temperature	20	SD_Q	8157

Table 4-9: Heat polygon 20FA M40

Reference heat [kJ/kg cem]	Corresp. maturity [h]
0	0.0
10	3.6
20	5.2
40	7.0
60	8.3
80	9.2
100	9.9
120	11.3
140	13.9
160	17.0
180	21.3
200	26.6
220	34.6
240	46.1
270	67.8
290	94.1
305	141.6
310	172.1
315	227.8
319	328.5

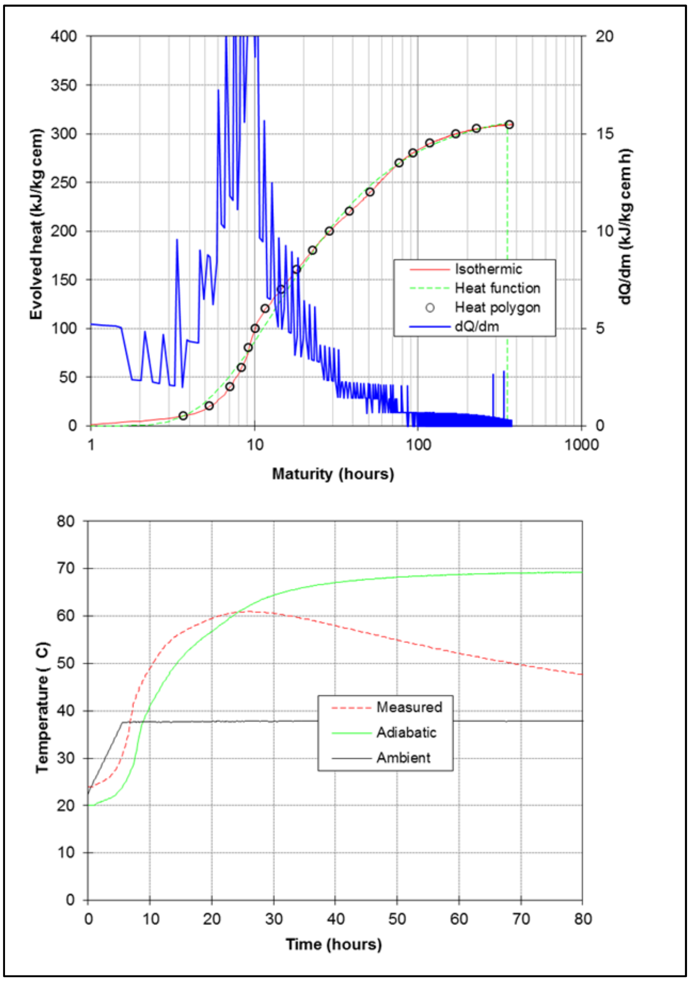

Figure 4-10: Measured temperature 20FA M40

4.4.2 Aalborg 40FA M40

The input parameters for concrete properties, temperature transformation coefficient and heat function are given in Table 4-8. The resulting heat polygon is given in **Error! Reference source not found.**. Evolved heat and measured temperatures are shown in **Error! Reference source not found.**.

Table 4-10: Input parameters for heat calculations 40FA M40

Concrete parameters		Temp. trans. coeff.	
Temp. trans. coeff.	0.0227	dQ/dm	0.075
Density	2380	m>	250
Heat capacity (fresh)	1.03	m<	300
Heat capacity (hardened)	1.03		
Cement content	375	Heat function	
Set time	7.5	m-limit	300
A - set time	30281	Q_∞	326
B - set time	530	t	17.94
A - hydration	30281	a	0.84
B - hydration	530	R^2	0.9810
Adia. start temperature	20	SD_Q	9361

Table 4-11: Heat polygon 40FA M40

Reference heat	Corresp. maturity
[kJ/kg cem]	[h]
0	-0.1
5	3.7
10	5.2
20	6.9
40	8.7
60	10.0
80	10.9
100	12.7
120	16.2
140	20.5
160	25.8
180	33.2
200	45.1
220	59.9
250	87.6
260	102.7
270	125.9
280	163.0
290	229.7
297	333.3

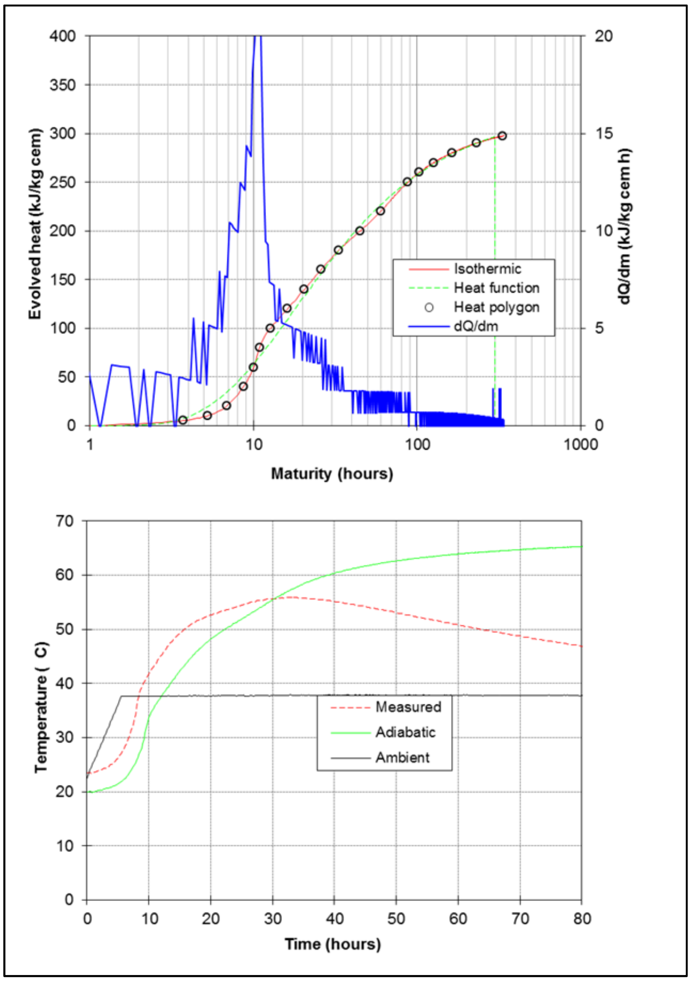

Figure 4-11: Measured temperature 40FA M40

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 heat development is described by the Freiesleben-Hansen model.

$$Q(t_e) = Q_\infty \cdot exp\left(-\left(\frac{\tau}{t_e}\right)^{\alpha}\right) \qquad \text{Equation 5.1}$$

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]:

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

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;

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

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

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

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 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 $T < 20$ °C, and $E_T = A$ for $T > 20$°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 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
Aalborg 20FA	30555	578
Aalborg 33FA	31102	465

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] and [Kjellmark et al., 2015]. As seen from Table 5-1, it was also 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] and [Kjellmark et al., 2015].

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 °C to the previously described modified CEB-FIP model code formulation, Equation 5.3, by using the method of least squares. Further, f_{c28} and *s* were found by fitting the compressive strength test results for all temperatures (5, 20 and 35 °C) to the modified CEB-FIP model code formulation, Equation 5.3, by using the method of least squares. The results are presented in Table 5-2 and in Figure 5-1 - Figure 5-3. 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 setting time for stress development, t_0, determined by the described procedure, agrees well with the compressive strength development for both concretes, Figure 5-4. However, Table 5-2 shows that t_0 stays constant with increasing FA content. Setting time for stress development determined by heat development, t_{12kJ}, shows that t_0 is increasing with increasing FA content. 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 on tests from the same batch as the tensile strength, and E-modulus tests. It is therefore decided to proceed with the current parameter determination for tensile strength and E-modulus with t_0 based on the setting time for stress development 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]
Aalborg 20FA	82.5	0.225	8.0	6.6	8.4
Aalborg 33FA	75.3	0.276	8.0	7.5	9.3

As it can be seen from Table 5-2, the model parameter s is increasing with increasing FA content. This means that an increasing FA content leads to a reduction of the rate of compressive strength development, Figure 5-3. Also in [Bjøntegaard et al., 2012] and [Kjellmark et al., 2015] the model parameter s was found to be increasing with increasing FA-content.

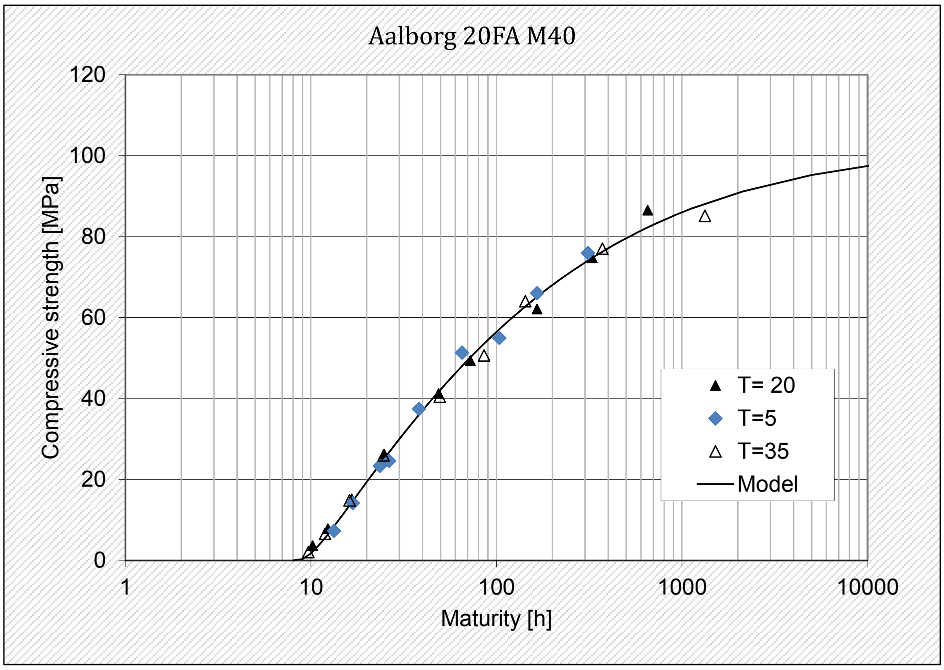

Figure 5-1: Strength versus maturity (logarithmic scale) Aalborg 20FA

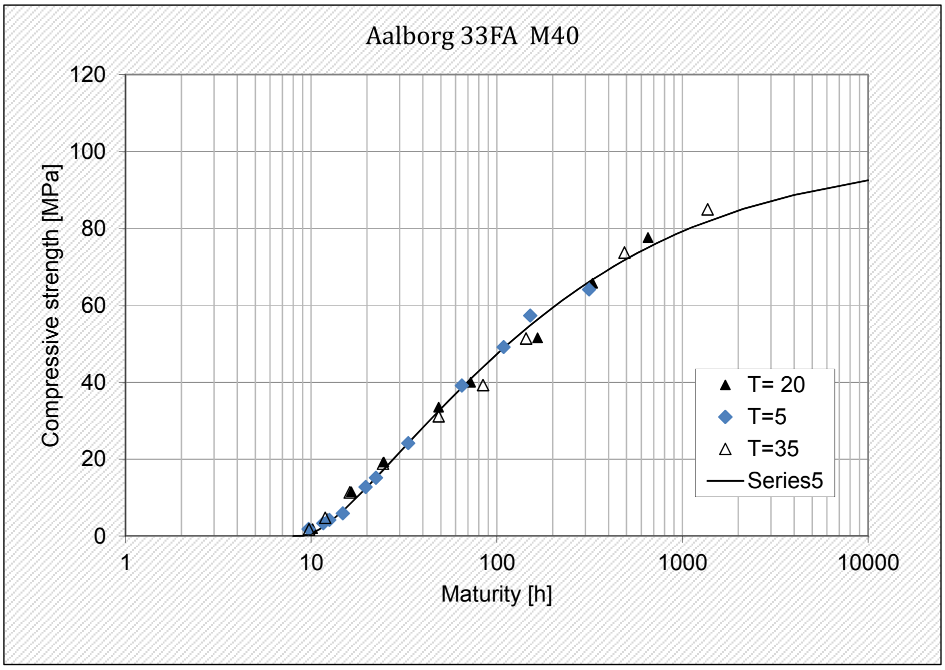

Figure 5-2: Strength versus maturity (logarithmic scale) Aalborg 33FA

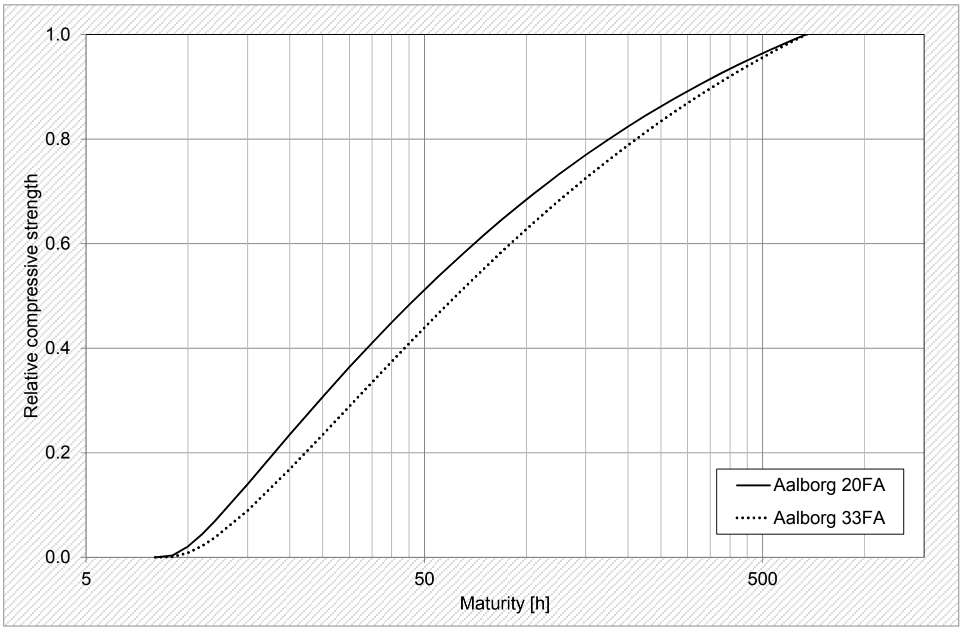

Figure 5-3: Relative compressive strength development

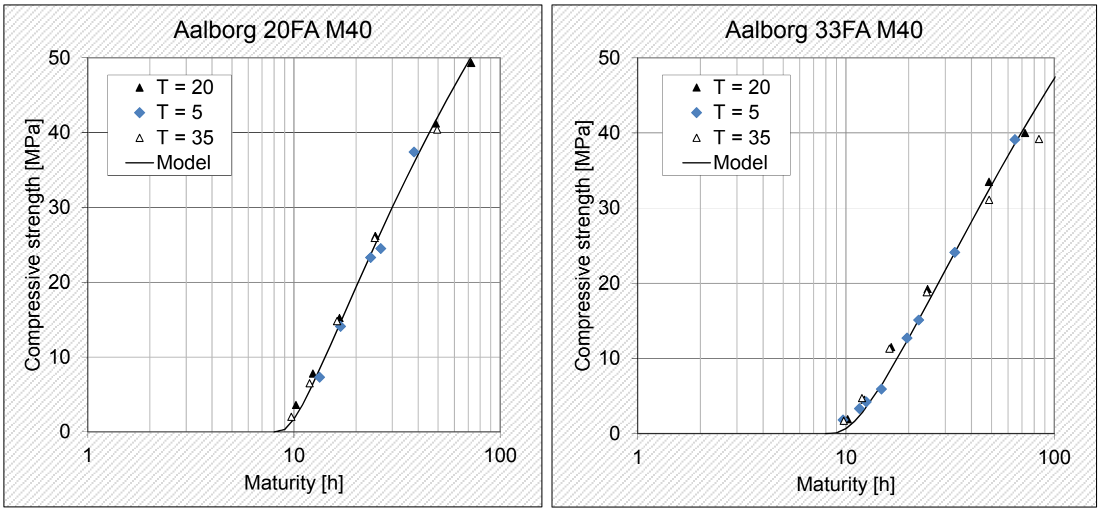

Figure 5-4: Setting time t_0 versus compressive strength development

5.3.3 Tensile strength

The concretes were tested at 2, 7, 14 and 28 days. All tensile splitting test results were adjusted to uniaxial test results by the linear relation found in section 4.2.4. The setting time for stress development t_0 was determined according to section 5.3.2, while the tensile strength at 28 days f_{t28} and the fitting parameter n_t were found by fitting the tensile strength test results to the previously described modified CEB-FIP model code formulation, Equation 5.4, by using the method of least squares.

The results are presented in Table 5-3, as well as in Figure 5-5 - Figure 5-6.

Table 5-3: Model parameters for the tensile strength

Concrete	f_{t28} [Mpa]	n_t
Aalborg 20FA	4.31	0.675
Aalborg 33FA	4.00	0.613

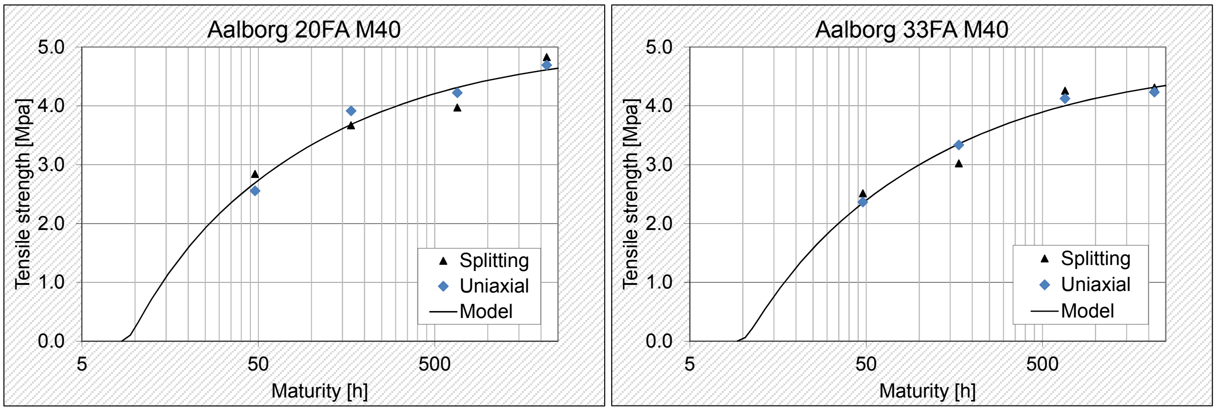

Figure 5-5: Tensile strength development. All tensile splitting test results are adjusted to uniaxial test results by the linear relation found in section 4.2.4.

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]. Figure 5-6 presents the relative tensile strength development for the given concretes.

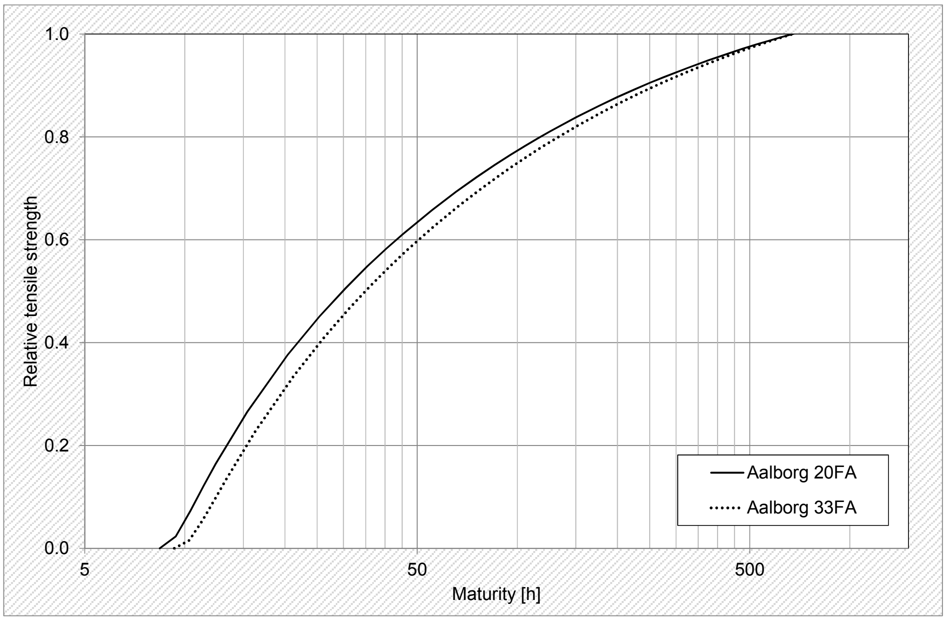

Figure 5-6: Relative tensile strength development

5.3.4 Modulus of elasticity

The concretes were tested at 2, 7, 14 and 28 days. The model parameters describing the development of the elastic modulus were determined in the following way; for both concretes, the setting time for stress development t_0 was set according to Section 5.3.2, while the E-modulus at 28 days E_{28} and the fitting parameter n_E was found by fitting the test results to the previously described modified CEB-FIP model code formulation, Equation 5.5, by using the method of least squares. The compressive and tensile E-moduli are applied as if there is no significant difference between the results obtained in tension or compression, as found in [Kanstad et al., 2003].

The results are presented in Table 5-4, as well as in Figure 5-7 - Figure 5-8.

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

Concrete	E_{28} [Gpa]	n_E
Aalborg 20FA	31.69	0.396
Aalborg 33FA	31.76	0.403

As can be seen from Table 5-4, the E-modulus at 28 days E_{28} is almost identical for the two given concretes. The achieved values for n_E are for both concretes close to the default value n_E = 0.37 established by [Kanstad et al., 2003]. Figure 5-8 presents the relative development of the E-modulus for the given concretes.

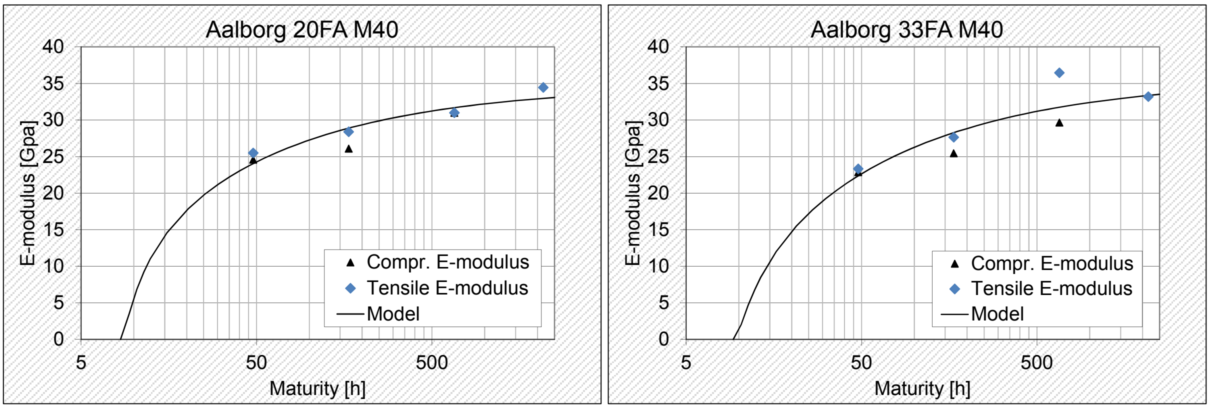

Figure 5-7: E-modulus development.

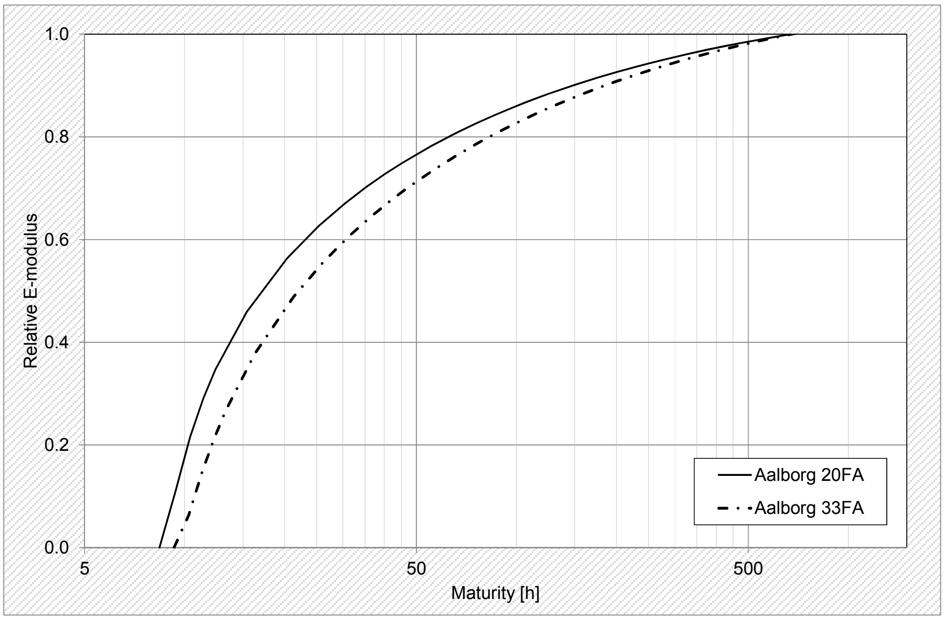

Figure 5-8: Relative E-modulus development, logarithmic scale

5.4 Model parameters for use in CrackTeSt COIN

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 section 5.3:

Model parameters for the activation energy;

Concrete	A	B
Aalborg 20FA	30555	578
Aalborg 33FA	31102	465

Model parameters for the compressive strength;

Concrete	f_{c28}	s	t_0
	[Mpa]	-	[hours]
Aalborg 20FA	82.5	0.225	8.4
Aalborg 33FA	75.3	0.276	9.3

Model parameters for the tensile strength;

Concrete	f_{t28}	n_t
	[Mpa]	
Aalborg 20FA	4.31	0.675
Aalborg 33FA	4.00	0.613

Model parameters for the E-modulus;

Concrete	E_{28}	n_E
	[Gpa]	
Aalborg 20FA	31.69	0.396
Aalborg 33FA	31.76	0.403

6 Discussion and Conclusions

A test series of two different concretes with Aalborg cement has been carried out within COIN's Focus Area 3.1 *Crack Free concrete structures*. 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 from 2 days to 91 days of age for these concretes.

A similar experimental series with Norcem cements and the same w/c-ratio was also performed earlier in the COIN FA 3.1 project, and we see the same tendencies in the present results as we saw then [Kjellmark et al., 2015].

In general, it is shown that all the investigated properties; the final heat generated, the compressive strength, the tensile strength and the E-modulus decreases when the replacement of cement clinker by fly ash is increased from 20 % to 33 %. For instance, it is shown that 33% FA content leads to a 15 % compressive strength reduction at 28 days. 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 similar differences between the two test methods as determined previously. In the Norcem experiments, the differences in the two test methods were found to be larger.

The E-modulus determined from the uniaxial tensile strength test is slightly larger than the values determined from the standard compressive test. The same difference was shown in the Norcem series.

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 tables below compare the model parameters found for Aalborg cements and Norcem cements with an equal replacement of cement clinker by fly ash.

Model parameters for the activation energy;

Concrete	***A***	***B***
Aalborg 20FA	30555	578
Norcem ANL FA	31487	197
Aalborg 33FA	31102	465
Norcem ANL FA + 16FA	37023	0

Model parameters for the tensile strength;

Concrete	f_{t28} *[Mpa]*	n_t
Aalborg 20FA	4.31	0.675
Norcem ANL FA	3.29	0.509
Aalborg 33FA	4.00	0.613
Norcem ANL FA + 16FA	3.05	0.486

Model parameters for the compressive strength;

Concrete	f_{c28}	s	t_0
	[Mpa]	-	*[hours]*
Aalborg 20FA	82.5	0.225	8.4
Norcem ANL FA	77.8	0.257	10.6
Aalborg 33FA	75.3	0.276	9.3
Norcem ANL FA + 16FA	67.9	0.356	12.0

Model parameters for the E-modulus;

Concrete	E_{28} *[Gpa]*	n_E
Aalborg 20FA	31.69	0.396
Norcem ANL FA	30.55	0.294
Aalborg 33FA	31.76	0.403
Norcem ANL FA + 16FA	27.80	0.252

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.

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.

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