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The cracking risk of hardening concrete exposed to realistic curing temperature regimes and restraint conditions – Experimental investigations of important parameters

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ABSTRACT

Early age cracking in hardening concrete can be evaluated using dedicated calculation methods. Such calculations require a wide selection of input parameters, e.g. autogenous- and thermal deformation, hydration heat evolvement, tensile strength, E-modulus, creep, cross-section dimensions, structural configuration (degree of restraint) and climatic conditions. However, several factors can affect these materials properties and input parameters, and hence the cracking tendency of the concrete. Over the recent years, early age cracking has been included in several research projects at NTNU. In this regard, various laboratory test programs on early age cracking have been performed, providing a comprehensive matrix of results and a unique opportunity for parameter studies on e.g., fly ash content, SRA-addition, aggregate type, cement batch, w/c-ratio, degree of restraint and climatic conditions. The laboratory tests comprise both mechanical testing and restrained stress tests in the Temperature-Stress Testing Machine (TSTM). The present compilation showed that in addition to the obvious effects of degree of restraint and climatic conditions, also several of the other investigated parameters had a considerable influence on the cracking tendency of the given concrete, e.g., cement-by-fly ash replacement caused a clear reduction of the cracking risk, while variations between different batches of the same type of cement highly influenced the strength, the heat evolvement, the AD development, and consequently also the cracking risk of the given concrete.

1. Introduction

Early age cracking is a recurring issue when it comes to concrete structures. Cracking in the hardening phase may cause cracks that go through the whole thickness of the concrete member, and such “through-cracking” may further lead to esthetical-, durability-, functionality-, and hence economic problems. Early age cracking is known to be caused by restrained volume changes due to autogenous deformation and thermal dilation [1–3]. The thermal and mechanical behavior of a concrete structure, and hence the cracking risk, can be simulated by dedicated calculation methods. However, such simulations are totally dependent on the quality of the input data, and they require well characterized concretes and a wide selection of input parameters, e.g. autogenous deformation, thermal expansion coefficient, hydration heat evolvement, development of tensile strength and E-modulus, creep, cross-sectional dimensions, structural configuration (degree of restraint) and climatic conditions.

Variations in the above-mentioned parameters for one given concrete mix, which are very likely to occur, can affect the cracking tendency in several and crucial ways. Some of these parameters can, to a certain degree, be predicted and adjusted by special measures. For instance, autogenous deformation can be reduced by adding shrinkage reducing admixtures (SRA) [4–6]. Also, the heat evolvement and thus the thermal dilation of the concrete can be reduced by partly replacing cement by fly ash, however, it should be noticed that an increasing amount of fly ash content also may reduce the tensile strength and affect the autogenous deformation [7,8]. Other parameters may be predicted, but not always controlled, like climatic conditions and degree of restraint. For instance, casting directly onto rock will cause an inevitable high degree of restraint and an appurtenant high risk of cracking. Unpredictable parameters can also influence the early age cracking behavior, like for instance variations between different batches of

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cement and different types of aggregate. Variations in hydration heat evolvement between different cement batches will affect the temperature development and hence the thermal dilation, but it will simultaneously affect the autogenous deformation and the development of properties such as tensile strength and E-modulus [9]. Likewise, changing to a "stiffer" type of aggregate may increase the tensile strength of the concrete, it may however also increase the E-modulus, causing a higher generated stress due to the restrained volume changes. Hence, the influence of parameter variations on the cracking tendency of hardening concrete is complex and it is important to consider the totality. Although Multi-physical modelling has had good progress the last decade, see for instance Gasch et al., [10,11], most researchers and calculation experts (practitioners), due to the complexity of early age cracking, still prefer to work on the macroscopic level, i.e. utilize input material parameters that can be determined experimentally [12].

A suitable way of evaluating the general effect of a parameter variation on the cracking tendency of hardening concrete, is by performing restrained stress tests in the Temperature-Stress Testing Machine (TSTM). The TSTM at NTNU offers the possibility to apply a realistic temperature history to the specimen during testing. In addition, the user is free to apply a desired degree of restraint (the ratio between restrained and total deformation) as opposed to the original cracking frame which had a high, but unknown, degree of restraint [13]. Consequently, a restrained stress test in the TSTM directly simulates the stress development and the failure stress level for a given structural member, including all the different aspects of a parameter variation.

The current article compiles and compares several different test series performed over the recent years on a specific fly ash concrete frequently used for Norwegian infrastructural facilities. These test series include tests on mechanical property development as well as restrained stress development in the TSTM. Small adjustments have been made to the concrete between the different test series, providing a unique opportunity for a parameter study. The varying parameters have been cement-batch, aggregate type, SRA addition, cement-by-fly ash replacement, climatic conditions and degree of restraint. All presented test series were performed based on a previously established early-age cracking methodology as described in [14]. Material properties for each concrete were found by extensive laboratory testing and succeeding model fitting, and further evaluated and calibrated by restrained stress tests in the TSTM. Both previously published as well as unpublished TSTM results have been compiled and evaluated. It is essential for such test results to be published, as they form the basis for a possible future database that can be launched and used as background for development and verification of guidelines, standards and material/structural Finite Element Modelling.

Simplified calculation methods for early-age and long-term cracking can be found in guidelines and prevailing regulations regarding cracking and design in the serviceability limit state (SLS) with respect to early age volume changes, for instance CIRIA C766, CEOS.fr, and the upcoming Eurocode 2 annex: *Annex D, Evaluation of early-age and long term cracking due to restraint* [15–17]. Eurocode 2 Annex D is planned implemented together with the revised Eurocode 2 which now is on public hearing, and the annex is meant to increase the awareness and knowledge of concrete in the hardening phase. Common for the above-mentioned calculation methods is that the accuracy of the outcome is very dependent on the quality and correctness of the applied material parameters. An accurate characterization of the development of relevant material properties is therefore of great importance when it comes to the design of concrete in the hardening phase.

2. Experimental equipment

Each investigated concrete was characterized by laboratory testing as described in detail in Klausen, Kanstad and Bjøntegaard [14]. Hydration heat evolvement was found by semi-adiabatic calorimeter tests, and compressive strength was found from 100x100 mm cubes. In addition, uniaxial tensile strength tests were performed to determine strength and E-modulus in tension.

The concretes were also tested in the Temperature-Stress Testing Machine (TSTM) and the Free Deformation (FD) system at NTNU. The TSTM measures the stress development in the hardening phase for a concrete specimen subjected to a pre-defined temperature history and a given degree of restraint. The TSTM is both deformation-controlled, and load-controlled: the deformation is controlled by the applied degree of restraint, while the load is kept constant between the deformation regulations. The TSTM temperature history during testing was applied in order to simulate semi-adiabatic conditions, i.e. each concrete was exposed to its own temperature history representing the temperature development for the given concrete in a section of an 800 mm thick wall cast under Norwegian summer or winter conditions. The semi-adiabatic temperature history was calculated based on the hydration heat evolvement of the given concrete and the special purpose program CrackTeSt COIN [18]. TSTM tests can also be used to determine thermal dilation, autogenous deformation, incremental E-modulus development, and the coefficient of thermal expansion CTE. The CTE is in fact a complex parameter that varies with both concrete mix constituents (particularly aggregate type) and degree of self-desiccation [19]. In the current work, the commonly used simplification of a constant CTE was adopted, and the CTE was determined as a constant value by exposing the specimen to temperature loops of 20 °C ± 3 °C after the TSTM-test was ended. The FD system consists of four rigs that are designed to measure the autogenous deformation (AD) directly from 100x100x500 mm sealed concrete specimens subjected to 20 °C isothermal curing conditions.

To make it possible to compare test results from the hydration heat- and the TSTM tests, the maturity principle was applied. The reference temperature was set to 20 °C, and the Arrhenius equation was used as temperature function [20].

The currently used experimental equipment and test set-ups are described in detail in Klausen, Kanstad and Bjøntegaard [14] and [21].

3. Concrete mix design and test program

"ANL FA" is the term used here for a concrete made with a fly ash-based cement, widely used for Norwegian infrastructures. In the current study, TSTM test results from various test series containing the concrete ANL FA have been compiled. All currently presented ANL FA mixes had a water-to-binder ratio of 0.4, and a cement paste volume of 292 l/m^3. In addition, all mixes contained about 5% of silica fume, which is within the 3% − 5% silica fume requirement requested by the Norwegian Public Roads Administration for infrastructural facilities in Norway [22]. The detailed concrete mix design for each currently presented ANL FA concrete is given in Table 2. The parameters varying between the different test series were cement batch, aggregate type, additives and variations in test conditions. Each ANL FA test series, i.e. a defined set of concrete mix and test conditions, has been denoted according to the following notation:

"Mix no" – "cement batch" – "aggregate type" – "other variation"

"*Mix no*" is a unique number in roman numeral (I-VIII) given to each of the eight currently presented test series.

"*Cement batch*" describes the cement batch used for the given concrete mix. In total, three different batches of Cem II/A were used, currently denoted B1, B2 and B3. The physical properties of each cement batch are given in Table 1. Cement batch B1 and B2 are different batches of the same cement, it can however be seen from Table 1 that the physical properties of the two batches are quite divergent. The difference in 7-day strength, which often is used as a reference for cement evaluation, was as much as 7 MPa between the two batches. The standard 7-day strength for the given cement is defined to be around 37.0 MPa. Hence, B1 was in the lower range, while B2 was in the upper. The third batch B3 differed from batches B1 and B2 as it contained limestone and somewhat less fly ash.

Table 1
Cement analyses, physical and chemical properties.

Cement batch	B1	B2	B3
Fly ash *[%]*	18.7	16.6	15.7
Limestone *[%]*	–	–	3.7
Fineness, Blaine *[m^2/kg]*	370	389	421
Chemical properties [wt%]			
SO_3	2.8	2.7	3.1
SiO_2	27.0	26.7	24.8
Al_2O_3	8.7	7.9	7.2
Fe_2O_3	3.7	4.5	4.6
CaO	52.7	53.4	53.7
MgO	1.9	1.7	1.8
K_2O	0.7	0.7	0.6
Na_2O Eq.	0.9	0.9	0.8
Compressive strength [MPa]			
1-day strength	12.1	15.9	13.2
2-day strength	21.5	25.5	24.0
7-day strength	33.7	40.7	37.9
28-day strength	–	58.6	52.4

"*Aggregate type*" describes which of the two types of aggregate was used. *Aardal* aggregate by Norstone AS [23], denoted A1, is dominated by granite and gneiss, and it is used as the standard laboratory aggregate in Norway. Aardal gravel has a density of 2680 kg/m^3. The other aggregate, A2, was *Rekefjord west - Ansit* aggregate by Rekefjord Stone AS [24]. Ansit aggregate is dominated by anorthosite with a density of 2700 – 2740 kg/m^3.

"*Other variation*" describes other parameter variations. The notation "*SRA*" means the addition of 1% SRA to the concrete mix. "*FA*" indicates a cement-by-fly ash replacement 1:1 by weight while keeping the water-to-binder ratio and the cement paste volume constant, up until a total fly ash content of 45%. "*Winter*" describes that the test conditions represent Norwegian winter conditions, which has been defined to include fresh concrete temperature of 10 °C and a surrounding temperature of 5 °C. All other tests in the TSTM were performed simulating Norwegian summer conditions, i.e. with a fresh concrete temperature of 20 °C and an ambient temperature of 20 °C. The notation *"R30"* means that the TSTM test was performed with a degree of restraint of 30%, all other TSTM tests were performed with a degree of restraint of 50%.

An overview of the tests performed for each concrete mix is given in Table 3. All concretes were tested for compressive cube strength at 28 days and for restrained stress development in the TSTM. For concrete mixes I - IV, all described tests were performed, while the remaining concretes were subjected to a selection of the described tests. Tests in the TSTM system are labor-intensive but very profitable as they provide a wide set of information. For the current test program, each TSTM tests provided: measured free deformation, $AD_{realistic}$ (AD deduced for realistic temperature conditions), the starting time for stress development, coefficient of thermal expansion (CTE) and restrained stress development, from which also the creep-parameters could be deduced.

4. Results and discussion

The compressive cube strengths, tensile strengths and E-moduli in tension at 28 days, as well as the deduced CTEs, are presented in Table 4. The compressive strength values represent the average strength of 3 cubes, and the coefficient of variation (CV) for each test series is given in the table. Due to limitations regarding the number of molds, the tensile strengths and E-moduli represent the average value of only two specimens. The CVs for these properties are also reported in the table, but a statistical evaluation of only two test values should be treated with caution.

The only difference between concrete mix I and II were the cement batches. Still, the compressive cube strength at 28 days was as much as 12,7 MPa (18%) higher for concrete II when compared with concrete I. This result reflects the already stated difference in physical properties between the two cement batches, see Table 1. The considerable variation in compressive strength found for two different batches of the same cement is noteworthy. At the same time, the differences in tensile

Table 3
Test programme.

Mix no	I	II	III	IV	V	VI	VII	VIII
Name	B1-A1	B2-A1	B3-A1	B3-A2-R50	B3-A2-R30*	B2-A1-FA	B2-A1-SRA	B2-A1-winter**
Heat evolvement	x	x	x	x	–	x	–	–
Compressive strength	x	x	x	x	x	x	x	x
Tensile strength	x	x	x	x	–	x	–	–
E-modulus in tension	x	x	x	x	–	x	–	–
FD-system	x	x	x	x	–	–	x	–
TSTM-system	x	x	x	x	x	x	x	x

*) Concrete V is nominally identical to IV, only with a different degree of restraint during testing in the TSTM.
**) Concrete VIII is nominally identical to II, only with other temperature conditions during testing in the TSTM.

Table 2
Concrete mix design, fresh properties and variation parameters.

Mix no	I	II	III	IV	V	VI	VII	VIII
Name	B1-A1	B2-A1	B3-A1	B3-A2-R50	B3-A2-R30	B2-A1-FA	B2-A1-SRA	B2-A1-winter
Cement	365.3	365.3	368.4	368.4	368.4	229.8	365.2	365.3
$FA_{incl\ cem}$	68.3	60.6	57.8	57.8	57.8	38.1	60.6	60.6
FA_{added}	–	–	–	–	–	118.5	–	–
Silica fume	18.3	18.3	18.4	18.4	18.4	17.4	18.3	18.3
Free water	160.7	160.7	162.1	162.1	162.1	153.3	160.7	160.7
Sand 0–8	1216.3	1216.3	1219.6	1219.6	1219.6	1216.3	1216.3	1216.3
Gravel 8–16	614.1	614.1	615.8	615.8	615.8	614.1	614.1	614.1
SRA	–	–	–	–	–	–	3.8	–
Plasticizer	2.0	2.0	2.1	2.1	2.1	1.56	2	2.0
w/b	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Air content [%]	2	2	2	1.85	1.85	2	1.9	2
Density [kg/m3]	2390	2390	2394	2420	2420	2360	2330	2390
FA-content	19%	17%	16%	16%	16%	45%	17%	17%
Cement batch	B1	B2	B3	B3	B3	B2	B2	B2
Aggregate type	A1	A1	A1	A2	A2	A1	A1	A1
Other variation	–	–	–	–	R = 30%	FA	1% SRA	Winter

$$* \ w/b = \frac{\text{water}}{\text{cement} + k_{FA} \bullet FA + k_S \bullet \text{Silica}}, \text{ where } k_{FA} = 1.0 \text{ and } k_S = 2.0.$$

Table 4
Compressive cube strength, tensile strength, E-modulus and CTE, 28-day values and standard deviation.

Mix no		I	II	III	IV	V	VI	VII	VIII
Name		B1-A1	B2-A1	B3-A1	B3-A2-R50	B3-A2-R30	B2-A1-FA	B2-A1-SRA	B2-A1-winter
Properties									
f_{c28}*	[MPa]	71.3	84.0	80.3	80.9	80.4	45.3	75.2	82.0
f_{t28}	[MPa]	3.6	3.8	3.7	3.8	-	3.0	-	-
E_{t28}	[GPa]	30.9	30.8	30.9	35.1	-	24.9	-	-
Coefficient of Variation (CV)									
CV f_{c28}*	[%]	1.3	1.4	0.7	0.9	0.9	2.1	3.3	-
CV f_{t28}	[%]	-	4.2	4.9	5.8	-	5.3	-	-
CV E_{t28}	[%]	3.0	2.7	0.8	4.0	-	1.0	-	-
Coefficient of Thermal Expansion (CTE)									
CTE	$[10^{-6}\,°C^{-1}]$	9.1	9.1	-	9.4	9.4	9.4	9.1	9.1

*) Cube strength.

strength and E-modulus between mix I and II were insignificant. Concrete mix III was made with a third batch of cement: batch B3. For Concrete III, the tensile strength and the E-modulus at 28 days were approximately the same as for Concrete II, and the compressive strength was only 3.7 MPa (4%) lower than for Concrete II. Consequently, cement batch B2 and B3 were evaluated to provide quite similar strength properties.

Concrete IV was made with the aggregate “Ansit”, currently denoted A2. This aggregate is commonly known to be a stiffer type of aggregate, and the tests did show an increase in E-modulus of as much as 4.4 GPa (14%) when replacing aggregate type A1 (“Aardal”) with A2. The tensile strength and compressive strengths were not affected by the change of aggregate, Table 4.

Concrete mix VI, i.e. ANL FA with cement-by-fly ash replacement, differed from the other concretes with respect to material properties. A lower cement content led to an expected decrease in both compressive- and tensile strength, as well as E-modulus at 28 days. Such a cement-by-fly ash replacement is however known to cause a slower strength development, and the ultimate strength developed over a long time will bridge some of the strength gap on longer terms [7,9,25]. The current concretes were however not tested beyond 28 days.

The addition of 1% SRA for concrete mix VII gave a small reduction in compressive strength. However, this test series had a slightly higher coefficient of variation, and it should be noticed that the compressive strength reduction was smaller than the difference found between different cement batches, i.e. concrete mixes I and II. Concrete VII was not subjected to direct tensile strength tests, however, the TSTM tests showed that concrete VII with 1% SRA did not develop failure in tension at a lower stress level than concrete II without SRA, Fig. 3, indicating that the tensile strengths for the concrete with and without SRA were quite similar.

Summarized, the cement batch highly influenced the compressive strength at 28 days. The addition of 1% SRA gave a small reduction in compressive strength, while cement-by-fly ash replacement reduced the compressive strength considerably. The change of aggregate type did not influence the compressive strength at all in our case. Cement-by-fly ash replacement caused an expected decrease in tensile strength, while all the other mixes showed a very similar tensile strength at 28 days. In fact, the variations in tensile strength between the concrete mixes were smaller than the internal scatter within each test series. The E-modulus at 28 days was reduced by replacing cement with fly ash, while it was considerably increased by changing to a stiffer type of aggregate.

The coefficients of thermal expansion (CTE) deduced from the TSTM tests were found to be in the range $9.1 - 9.4 \cdot 10^{-6}\,°C^{-1}$, Table 4. This is somewhat lower than the commonly used standard value of $10 \cdot 10^{-6}\,°C^{-1}$ as given in for instance Eurocode 2 [26]. For each concrete mix, the CTE was determined after the TSTM-test was ended, and hence not at the same age. This is however not expected to cause a large variation in the deduced CTEs, as the variation in CTE over time is highest over the initial 48 h for sealed concrete [8,27].

Obtained heat evolvement for the concrete mixes are presented in Fig. 1 (left). Cement batch B1 and B2 were different batches of the same cement, but they provided quite different heat evolvements for their appurtenant concrete mixes I and II, respectively. B2, the cement batch with the highest compressive strength, also gave the highest heat evolvement, while B1, the cement batch with the lowest compressive strength provided a much slower and lower heat evolvement. This illustrates a typical and contradicting scenario, the request for a high early compressive strength is achieved at the sacrifice of a low heat evolvement. The aggregate type had a neglectable influence on the heat evolvement, while the cement by fly ash replacement caused a clear reduction in the heat evolvement during curing.

The calculated temperature histories are shown in Fig. 1 (right). Each history represents the given concrete cast in a predefined section of an 800 mm thick wall cast under Norwegian summer or winter conditions, see [14]. Summer conditions included a fresh concrete temperature of 20 °C, an ambient temperature of 20 °C, and formwork removal after 3 days. Winter conditions, on the other hand, comprised a fresh concrete temperature of 10 °C, an ambient temperature of 5 °C, and no formwork removal. As for the heat evolvement, the cement batch was found to have a major influence on the temperature history. The difference in maximum temperature during curing between the concrete made with B1 and B2, respectively, was as much as 7.6 °C, which constitutes approx. 20% of the total temperature increase. The aggregate type showed no influence on the temperature history, while the cement-by-fly ash replacement caused a clear reduction in the temperature development during curing. Naturally, winter temperature conditions had a major influence on the temperature development during curing: The maximum temperature was reduced by 15.8 °C (27%), from 59,1 °C to 43.3 °C, however – the ambient temperature was also lower, i.e. the succeeding cooling branch from maximum temperature (43.3 °C) to ambient temperature (5 °C) was still as high as for summer conditions.

Fig. 2 presents AD measured under 20 °C isothermal conditions (left), and AD deduced from tests using realistic temperature conditions (right). The time scale for both figures was set to maturity time for comparison reasons. For the latter condition, AD was deduced by subtracting thermal dilation from the total measured deformation. Thermal dilation is given by the coefficient of thermal expansion (CTE) and the measured temperature history. The CTE was determined as a constant value by exposing the specimen to temperature loops of 20 °C ± 3 °C after testing, Table 4. This is an approximation as the CTE is known to vary over time, hence using a constant CTE will introduce a possible small inaccuracy to the deduced AD. Previous research has evaluated this inaccuracy to be rather small, and also to have only a limited influence on the stress development, as the possible inaccuracy of the AD occurs in the early phase where the E-modulus is still rather low [14]. The approximation of a constant CTE has no effect on the restrained stress development in the TSTM, which is generated by the total free deformation (TD + AD).

There was a major difference between AD measured for isothermal

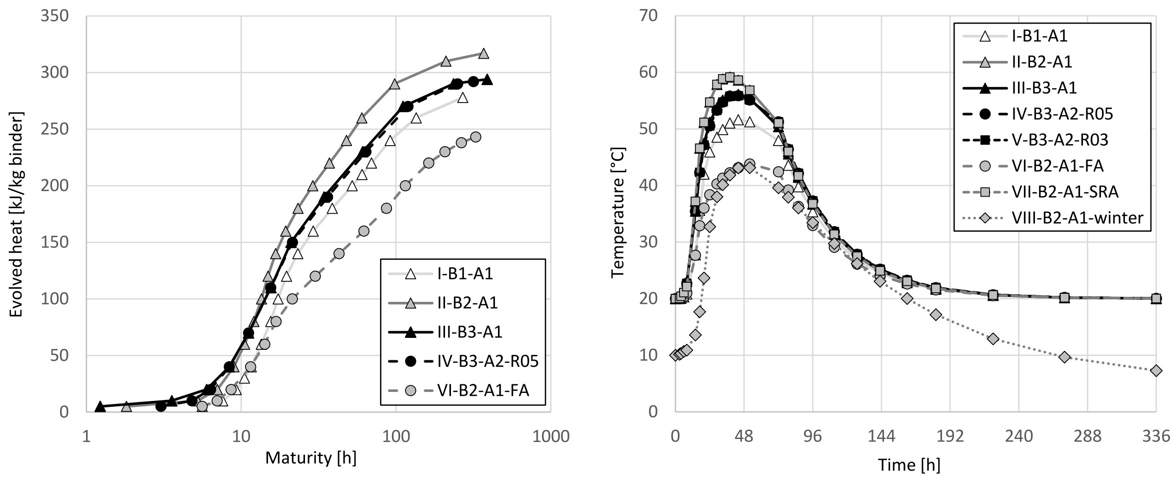

Fig. 1. Heat evolvement (left), predicted concrete temperature history for a given structural member (right).

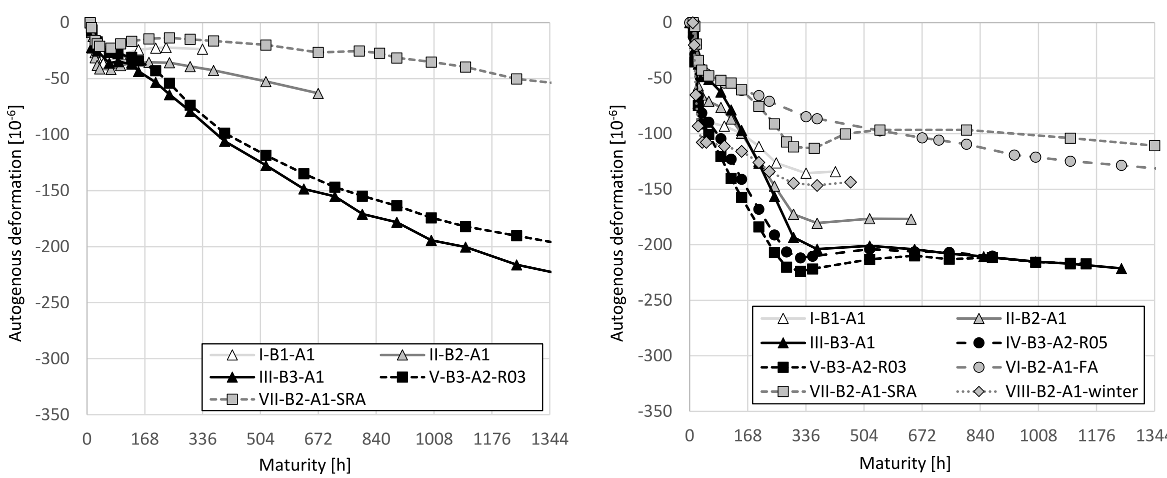

Fig. 2. $AD_{isothermal}$ (left) and $AD_{realistic}$ (right).

curing conditions ($AD_{isothermal}$) and AD deduced from realistic temperature curing conditions ($AD_{realistic}$). This difference was seen for all mixes, and it could not be explained by the uncertainty of the CTE alone. When exposed to 20 °C isothermal conditions, none of the mixes showed an AD above 50 microstrain during the first week of measurements. However, when exposed to realistic temperature conditions, all the mixes had an AD higher than 50 microstrain at 1 week of maturity. After 2 weeks of maturity, $AD_{isothermal}$ was 112 microstrain (83%) lower than $AD_{realistic}$ for Concrete mix I, and 138 microstrain (76%) lower than $AD_{realistic}$ for Concrete mix II. Beyond 2 weeks, all tests were subjected to 20 °C isothermal conditions. Still, the graphs show a considerable difference between the rate of $AD_{isothermal}$ and $AD_{realistic}$, indicating that a realistic temperature history during curing affects the fundamental behaviour of AD. Hence, measuring AD under real-life temperature conditions is vital in order to achieve as accurate and realistic AD results as possible. The guidelines CIRIA C766 and CEOS.fr, as well as the upcoming Eurocode 2 Annex D [15,16,26], do not include such a temperature effect on the modelled AD development.

For 20 °C isothermal conditions, Fig. 2 (left), Concrete mix III (cement batch B3) showed a much higher $AD_{isothermal}$ development than Concrete mixes I and II (cement batches B1 and B2, respectively). Concrete mixes III and V were made with the same cement batch B3, but with different types of aggregate. The change of aggregate type only had a minor impact on the $AD_{isothermal}$ development. The main mechanisms behind AD takes place in the cement paste [7,28,29,30], however, a stiffer aggregate is expected to reduce the AD due to an increased internal restraint. The addition of 1% SRA showed a reduction in AD of approx. 50%, see Concrete mix II vs mix VII.

AD was found to be higher for concretes based on cement batch B3 also for realistic temperature curing conditions, Fig. 2 (right). The difference was however not as big as for isothermal conditions. The major part of the $AD_{realistic}$ occurred over the first two weeks, i.e. while the concrete specimen was subjected to a realistic temperature history. A strong correlation was found between the temperature increase during curing and the $AD_{realistic}$ development over the first two weeks. The higher the temperature increase, the higher the $AD_{realistic}$ at two weeks of maturity. Hence, AD is in fact dependent on both the mix design as well as the structural configuration, as they both affect the temperature development during curing. Beyond two weeks of maturity, the $AD_{realistic}$ development rate was much lower, and even some expansion was observed for some of the concrete mixes.

For realistic temperature curing conditions, the addition of 1% SRA caused a 40–50% reduction in $AD_{realistic}$, i.e. almost the same percentage as for isothermal conditions. However, due to the high net value of $AD_{realistic}$, the actual SRA-induced reduction was higher for concrete subjected to realistic temperature conditions when compared to 20 °C isothermal conditions, i.e. the higher the AD, the more shrinkage for the SRA to reduce [5].

Addition of FA shows a reduction in AD. For $AD_{realistic}$, this may be related to the FA-induced reduction in temperature increase during curing as well as the FA addition itself [8].

So far, the effect of a parameter variation has been considered for each property individually. To evaluate the net effect on early age cracking, restrained stress tests were performed in the TSTM system, see Fig. 3. All tests were performed with a degree of restraint of 50%, with exception from concrete V which was tested with a degree of restraint of 30%. Concretes I and II were nominally identical concretes made with different batches of cement, B1 and B2, respectively. Concrete I showed a considerably lower and slower tensile stress development than Concrete II. The main reason for this was the variation in cement heat evolvement and hence temperature development between the two concretes: Concrete II obtained a maximum temperature during curing that was 7.5 °C higher than that of Concrete I. Followingly, the total temperature decrease beyond the maximum temperature was higher for concrete II, causing a higher contraction and thus also a higher tensile stress development in the concrete. Concrete III had a somewhat lower maximum temperature during curing than Concrete II, but simultaneously also the initial AD rate was lower. These two factors equalized each other, causing the two concretes to show approx. the same stress development over the first four days. Concrete I developed failure in tension at 3.3 MPa after 143 h of testing, Concrete II at 3.0 MPa after 96 h, while Concrete II developed failure in tension at 3.6 MPa after 110 h.

Concrete IV was made with a different aggregate than Concrete III. The aggregate *Ansit* was stiffer, causing an increased E-modulus, and followingly also a steeper stress development curve. However, when considering the cracking tendency of a concrete, the stress development must be seen in relation with the tensile strength. The tensile strength was however not found to be affected by the aggregate, and it was concluded that changing to a stiffer aggregate would slightly increase the cracking tendency of the concrete for the current case.

Concrete IV was tested in the TSTM with a degree of restraint of 50%. A nominally identical test was run with Concrete V, the only difference was a reduction in degree of restraint to 30%. As expected, a lower degree of restraint caused a lower stress development rate, both in compression and in tension. Both tests eventually developed failure in tension, Concrete IV at 3.2 MPa after 90 h and Concrete V at 3.3 MPa after 140 h. However, the stress development rate is clearly lower for the lower degree of restraint, and for another structural case or concrete, such a reduction in the degree of restraint could turn out decisive with respect to whether cracking will occur or not.

Concrete VI was made with the same cement batch as Concrete II, but the cement was partly replaced with fly-ash 1:1 by weight up until a total fly ash content of 45%. This rather high cement by fly-ash replacement caused a considerable reduction in the stress development, however, the fly ash increase did also cause a reduction in the corresponding tensile strength, Table 4. However, during the TSTM tests, Concrete II developed failure in tension at 3 MPa after 96 h, while Concrete VI run for 49 days without developing failure, indicating a very beneficial effect of cement-by-fly ash replacement when it comes to early age cracking.

Concrete VII represents Concrete II with a SRA-addition of 1%. The addition of SRA caused a 50% reduction in AD, but the net effect on the stress development was not as clear. A small reduction in the tensile stress development between 30 and 80 h could be seen, but the net effect on the stress development was marginal. It has however been seen that the effect of SRA differs strongly between different concrete mixes, e.g. the test series from which the current result was found, also showed that the addition of SRA had a clear beneficial effect on the cracking tendency for a slag concrete [5].

Concrete VIII represents Concrete II when cast during climatic winter conditions. The initial fresh concrete temperature was lower (10 °C versus 20 °C), causing a reduction of the maximum temperature during curing. The succeeding temperature decrease was still rather high for winter conditions, as the ambient temperature was as low as 5 °C. The development rate of the E-modulus and the tensile strength was reduced due to the generally lower temperature level, however, the net effect of the current ambient winter conditions was a reduction of the cracking risk for the given structural case.

Several of the investigated parameter variations had a considerable impact on the early age cracking tendency of the given concrete structure. Some of these parameters can, to a certain degree, be predicted and controlled: Both addition of SRA and especially cement-by-fly ash replacement were found to reduce the cracking risk of the given structure. However, more uncontrollable parameters, like climatic conditions and degree of restraint, was also seen to affect the cracking risk. In addition, more unpredictable parameters, like variations between different batches of cement and different types of aggregate, was also seen to influence the early age cracking behavior. The cement composition for the new batch is provided when the cement batch is changed, however, the current work has focused on macroscopic properties that can be measured. Hence, the influence of parameter variations on the cracking tendency of hardening concrete is complex, and each concrete mix and structural part is unique and should be calculated separately. Although Multi-physical modelling has had good progress the last decade, there is still a need for several of the required input parameters to be determined experimentally.

It should be emphasized that the current results are valid for the given structural case only. Some of the parameters show only marginal effect on the net stress development and consequently the cracking risk, however, for other structural parts with other degrees of restraint and temperature histories the effect has been seen to have a greater impact. The general validity of the current results is therefore mere to be considered as an overall guideline.

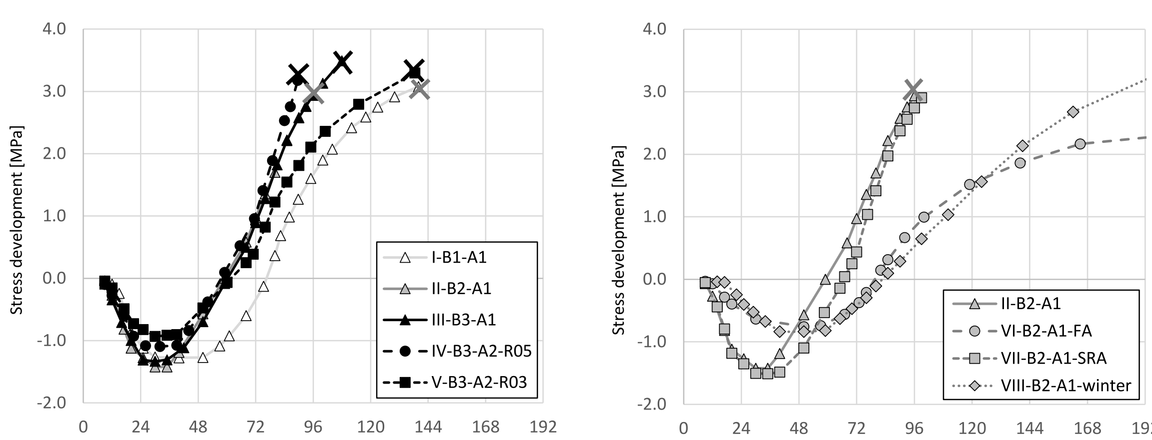

Fig. 3. Stress development for mixes I-V (left), mixes II and VI-VIII (right). A cross indicates failure in tension, while no cross indicates unloading of the specimen.

5. Conclusions

A large number of test results describing the early age properties of various concrete mixes exposed to realistic temperature histories and restraint have been compiled. The results may be included in future data bases for early age concrete, and may also be used by other researches as basis for further theoretical studies of various levels, i.e. multiscale modeling, non-linear finite element analysis and simplified methods. This holds for both estimations of the cracking risk, and as input to crack width calculations. Based on the evaluation of the obtained test results, the following conclusions were drawn:

- The effect of the degree of restraint and the climatic conditions are beyond compare the most important parameters to be considered for an accurate prediction of the cracking risk at early ages.
- Changing a parameter can cause changes to several of the material properties affecting early age cracking: strength, stiffness, heat evolvement and AD. It is vital to describe and consider the net effect, i.e. the total impact of a parameter change on the stress development.
- Cements that provide a high early compressive strength are often preferred due to the work schedule. However, a high early strength comes hand in hand with a high heat evolvement, which is unfortunate when it comes to early age cracking. The strive for a high early compressive strength should therefore be handled with care.
- Variations between different batches of the same type of cement may have considerable influence on the strength, heat evolvement, AD development, and consequently the early age stress development of a concrete.
- The AD of a concrete is highly influenced by the curing temperature. In order to obtain a reliable estimate for the given concrete, the AD development should be determined experimentally and under relevant curing temperatures.
- Cement-by-fly ash replacement 1:1 by weight up until a total fly ash content of 45% was seen to provide an unambiguous reduction of the cracking risk for the given structural case.

CRediT authorship contribution statement

Anja Estensen Klausen: Conceptualization, Investigation, Validation, Visualization, Writing – original draft, Funding acquisition. **Terje Kanstad:** Conceptualization, Writing – review & editing, Funding acquisition. **Øyvind Bjøntegaard:** Conceptualization, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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