EFFECT OF SILICA FUME ON EARLY AGE CRACK SENSITIVITY OF HIGH PERFORMANCE CONCRETE

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Abstract
In order to reap the benefits of impermeable high performance concrete, it is important to prevent cracks. Experience has shown that concrete mixes with low water-to-binder (w/b) ratios are particularly susceptible to early cracking if subject to conditions where deformations are restrained. The sensitivity of concrete to cracking is determined by a complex interaction between structural geometry and several materials parameters during the hardening process: Heat, E-modulus and tensile strength development, thermal dilation coefficient, autogenous shrinkage and finally the creep/relaxation properties. These materials properties are determined for concretes with different silica fume contents. The crack sensitivities of these concretes are then assessed by calculating the ratio over time between self-induced stress / and the strength under a variety of external conditions. The overall result is that effects of variation in silica fume content (0, 5 or 10%) is of minor importance compared to other factors such as cement type, w/b-ratio, structural configuration, degree of insulation, environmental conditions etc.

1. Introduction
Rating of concrete compositions in terms of sensitivity to early cracking is by no means simple. Traditionally, the shrinkage of concrete has been used directly as an indicator, but while this is insufficient under any circumstances; it is particularly so during the first few weeks of hardening. In this period the “driving forces” to stress generation (thermal dilation and autogenous shrinkage) change rapidly and interact very strongly, while the “response parameters” (E-modulus, Creep/Relaxation and strength) develop at slower rates. Thus, all the 5 properties listed above influence the crack sensitivity of a given concrete mix, and it is their interplay at a given time in a given structural situation that determines the risk of cracking. A realistic rating of cracking risk of concrete mixes used in a given structural configuration can only be achieved by constructing models for the relevant materials properties, performing tests in the STRESS-RIG (to verify the quality of the models) and finally carry out calculations based on these models for the given structural configuration and given environmental conditions. A number of such cases must
be evaluated in order to ensure that the results of a given case have general validity - and thus can be used to rate the concrete mixes in a meaningful way with respect to crack sensitivity.

In the present context, early age concrete refers to the time from setting is completed up to a few weeks later. No water loss from the concrete is assumed in the whole period, i.e. early plastic shrinkage cracking due to evaporation and drying shrinkage after setting are both conditions not considered in this paper.

This paper is a summary of a preliminary report, “Crack sensitivity of bridge concretes with variable silica fume contents”. The final report will also include a concrete with 15 % silica fume, and it will be available in mid 2000 /1/. The deformation and stress measurements reported here are fully presented in a recent dr. thesis by the second author/2/.

2. Principles and procedure

Since the actual cracking risk in practice depends on the structural configuration of the member in question and its relation to previously cast parts of the structure, the actual cracking risk has to be evaluated with a model that accounts for these external parameters. Thus the complete work procedure consists of the following steps:

1) Determination of material parameters under isothermal and semiadiabatic conditions:
   Heat development
   Mechanical properties: E-modulus and tensile strength
   Thermal dilation coefficient
   Autogenous shrinkage
   Relaxation properties deduced from uniaxial tests in the STRESS-RIG.

2) Time-step simulation of stress build up using a FE model of the structure in question with the material parameters as input.

3) Partial verification of the model by running a simulation of the uniaxial situation established in the STRESS-RIG.

Thermal dilation and autogenous shrinkage are the two stress generating deformations occurring in the concrete mass during hardening. Thermal dilation is caused by the temperature changes due to heat of hydration and environmental conditions. Autogenous shrinkage is a result of the hydration reactions in the cement which binds water - leading to so-called selfdesiccation and shrinkage, to be clearly distinguished from drying shrinkage due to water loss from the concrete. Thermal dilation and autogenous shrinkage occur simultaneously.
The amount of stress generated by thermal dilation and autogenous shrinkage in a given time interval depends on the degree of restraint of the concrete element, the E-modulus and finally the creep/relaxation properties of the concrete which will reduce a given stress increment over time. The block diagram below illustrates the interplay of the factors; each of which changes with time.

\[
\text{Thermal Dilation} + \times \text{E-modulus} \times \text{Relaxation Factor} = \text{Concrete Stress}
\]

**Fig. 1 Principle of Stress Calculation**

The stress at a given position at a given time is a consequence of the restraint conditions as well as the entire history of the concrete since setting. The assessment of crack risk at a given time/position then involves comparing the calculated stress in the actual concrete structural element to the concrete tensile strength at the time.

Presently this rigorous procedure, where no single parameter is sufficient, is considered necessary to evaluate the cracking risk in situ. With a larger amount of data available, it may be possible to eliminate some of the complex determination of material parameters by applying models based on material composition and ambient conditions.

### 3. Materials and mix composition

Three concrete compositions with 0, 5 and 10 % silica fume by weight of total binder were tested. The basis has been the Norwegian Road Directorate SV-40 quality concrete, required (with silica fume) for marine or other chloride exposed structures. A w/b-ratio of 0.40, a binder volume fraction of 28 % and only “natural” air content (2 - 3 %) were used. The sum cement + silica fume was constant at 386 kg/m³. The amount of superplasticizer was adjusted to keep a slump for each concrete in the range 16 - 18 cm. All the concretes used Norwegian Anleggssement, a low-alkali high strength cement of grade CEM 52.5 LA according to EN-197.

The three concretes tested were:

<table>
<thead>
<tr>
<th>Composition</th>
<th>Silica Fume</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>No silica fume</td>
</tr>
<tr>
<td>BASIC-5</td>
<td>5 % silica fume</td>
</tr>
<tr>
<td>BASIC-10</td>
<td>10 % silica</td>
</tr>
</tbody>
</table>

(Some results for a mix containing 15% silica fume are also shown)
4. Experiments

A large number of experiments were carried out to characterize the properties shown in Fig. 1 for each of the three concretes. The adiabatic heat development was also measured and used as a basis for calculating the temperature development in the structures.

The development of tensile strength and E-modulus over time were measured under isothermal (20 °C) and realistic (reaching 55 - 58 °C after one day and then gradually cooling to 20 °C) conditions. The sum of thermal dilation and autogenous shrinkage was measured for the realistic temperature history; while in an isothermal test of course the thermal dilation is zero, and autogenous shrinkage is measured directly. The sum of thermal dilation and autogenous shrinkage is used in the stress calculations, since a reliable model separating the two effects does not exist presently.

Creep/Relaxation properties were not measured directly. However, for the simple case of uniaxial tension in a slender concrete beam fully restrained against longitudinal movement this is the only unknown property in stress calculation. A specially designed STRESS-RIG was used for such uniaxial test, and the results have been used to check the validity of the creep/relaxation models used for the concretes.

5. Experimental Results

5.1 Heat
The measurements of heat of hydration show little effect of the silica fume. This is in line with earlier experience, and imply that the temperature development at a given position in a concrete structure largely depends on the initial concrete temperature, ambient conditions, structural geometry, degree of insulation etc., and not on silica fume dosage as long as the amount of cement + silica fume and w/b-ratio are constant.

5.2 Realistic temperatures
Fig. 2 shows the realistic temperature developments imposed by the temperature control system on the concrete during the deformation and stress experiments. The differences between the temperature curves for the different mixes qualitatively indicate the magnitude of the differences to be expected in a real structure (60 cm thick wall), but are by no means to be taken as accurate. Testing of mechanical properties under realistic temperatures followed a similar temperature history, but with a somewhat lower maximum (55 - 58 °C).

5.3 Tensile Strength and E-modulus
Best fit lines for the development of tensile strength and E-modulus for the 3 concretes are shown in Fig. 3. The time scale is expressed as maturity (i.e. equivalent time at 20 °C) in order to compare data obtained under different temperature developments. This approach also facilitates calculations. The procedure is fully explained in the report /1/. The point
where the concretes start to develop measurable strength (denoted $t_0$ in the following) was after 12, 11 and 10 maturity hours for 0, 5 and 10% silica dosage respectively; which are the starting points of the curves in Fig. 3. Note that different activation energies are used for the 3 concretes (more silica fume means increased activation energy, see full report/1/).

Fig. 3 shows that, as expected, increasing silica fume dosage leads to increased tensile strength. A large number of data points were used to determine the lines - the majority from experiments using cylinder splitting strength. The few direct uniaxial tensile tests gave even greater positive effects of silica fume for high curing temperatures, a point which is further discussed in the section on crack risk evaluation. Fig. 3 also shows a positive effect of silica fume on the E-modulus. Thus, the increased tensile strength amplified by the greater robustness to elevated temperatures with silica fume are beneficial in terms of crack risk, while the increased E-modulus is detrimental since a given restrained deformation (thermal dilation + autogenous shrinkage) will produce a higher stress.

Fig. 2 Temperature histories imposed on the concrete in the deformation and stress experiments.
Fig. 3  Tensile strength (a) and E-modulus (b) vs. maturity. The startpoint of the curves is $t_0$. 
5.4 Thermal dilation and autogenous shrinkage

Free deformations (thermal dilation and autogenous shrinkage) were measured in a temperature controlled DILATION-RIG. The rig is described in /4/. Fig. 4 shows that the pure autogenous shrinkage (at 20 °C) increases somewhat with silica fume (S) dosage. Most of the increase is at very short times when the E-modulus is very low, hence it will produce little stress (measured in parallel 20 °C STRESS-RIG tests - not shown here). Fig. 5 shows thermal dilation + autogenous shrinkage as developed for a realistic temperature history (60 °C max. at about 24 hours, see Fig. 2). The early expansion during heating is similar for all concretes, but the subsequent contraction caused by both cooling (thermal dilation) and autogenous shrinkage increases with silica fume dosage. Supplementary experiments were performed in which the thermal dilation coefficient was determined /2/. Since the temperature history is known it is then possible to calculate the thermal dilation component of the total deformation in Fig. 5, and to subtract it from the total deformations to produce the estimate for autogenous shrinkage shown in Fig. 6. The results in Fig. 6 are very interesting because very early the autogenous shrinkage is very large for all silica fume mixes, but beyond about 48 hours the autogenous shrinkage is small for all mixes and reverses to become expansion during the cooling period (the physical origin of the expansion is not dealt with here, but it is probably related to so-called thermally induced swelling). Longer term data (not shown here) /2/ show that the expansion again reverses to contraction under 20 °C isothermal conditions. Hence, isothermal measurements of autogenous shrinkage give very poor indication of what may occur during realistic temperature histories - a point of great practical importance, but neglected in the literature/2/.

![Graph showing measured autogenous shrinkage at 20 °C isothermal conditions. The startpoint of the curves is t₀.](image)

Fig. 4  Measured autogenous shrinkage at 20 °C isothermal conditions.  
The startpoint of the curves is t₀.
Fig. 5  Measured total deformation during realistic temperature tests (T_{max} \cong 60 \, ^\circ\text{C}, see Fig. 2). The startpoint of the curves is \( t_0 \).

Fig. 6  Estimated autogenous shrinkage - realistic temperature tests (T_{max} \cong 60 \, ^\circ\text{C}, see Fig. 2). The startpoint of the curves is \( t_0 \).
5.5 STRESS-RIG
A principle sketch of the STRESS-RIG is shown in Fig. 7. A 100% restraint condition is provided by an electronic feedback system that gives signals to a high precision screw. The signal is generated by any length change in a 700 mm central section of the beam. The length of the 700 mm central section is kept constant via the screw that moves one of the anchoring heads of the specimen. At the other head a load cell registers the restraining force. A surrounding steel frame gives support and takes care of the counter-force. The specimen and the anchoring heads are in close contact with water tubes and well insulated externally. Temperature control is provided by circulating water in the tubes from a well controlled central bath.

STRESS-RIG results performed under realistic temperatures and uniaxial full restraint for 0, 5 and 10 % silica fume are shown in Fig. 8, as well as results with partial restraint\(^1\) for a concrete with 15 % silica fume. At full restraint, increases in silica fume dosage leads to increased self-induced stress in this early period due to high autogenous shrinkage, and all three specimens fail at a tensile stress of about 3 MPa. This corresponds well with the results in Fig. 6 which shows autogenous shrinkage increasing with silica fume dosage in the critical period beyond 24 hours when the cooling rate also is high. In a real structure, however, the degree of restraint is very much less than 100 % and, as demonstrated by the 15% silica fume concrete, the stress build-up will be much slower, particularly beyond the first 48 hours when the autogenous shrinkage contributes little or nothing to tensile stresses. In such partial restraint experiments both the stress build-up and the deformations are recorded. The resulting curves are the basis for verification of the creep/relaxation models.

\(^1\) Partial restraint means that the active deformation control of the STRESS-RIG is turned off, and restraint against deformations is provided by the steel frame of the rig.
Screw Feedback system \( \Delta L = 0 \)

Fig. 7 Principle sketch of the STRESS-RIG

Fig. 8 Stress development - realistic temperature tests \( T_{\text{max}} \approx 60 \, ^\circ\text{C}, \text{see Fig. 2} \)
5.6 Creep / Relaxation

There is no simple way to illustrate the creep/relaxation behaviour of the concrete. For purposes of calculation the parameters in the mathematical materials models are adjusted to obtain best fit to the STRESS-RIG results. An attempt to illustrate the importance of the creep/relaxation properties of a concrete mix is given in Fig. 9. The measured self-induced stresses measured under full restraint are shown for the BASIC-5 concrete with two temperature histories: Isothermal 20 °C and realistic with maximum temperature of 40 °C. The two curves named “Fictive elastic stress” are calculated incrementally as the product of the free deformation measured in the DILATION-RIG and the appropriate E-modulus from Fig. 3. Thus, the arrows marked “Relaxation” show the differences, i.e. the reductions in the elastically induced stresses caused by the viscoelastic nature of concrete. The effect is large and important, as an example at 7 days the reduction in stress is about 40% for both the realistic and the isothermal case. No major effect of temperature on relaxation is consequently apparent in the range 20 - 40 °C. For maximum temperatures above 40 °C, however, this is presently a somewhat open question that needs to be considered very carefully, see /1/.

![Fig. 9 Measured self-induced stresses under full restraint in the STRESS-RIG, compared to a fictive elastic stress calculated incrementally as free deformations (thermal dilation + autogenous shrinkage) x E-modulus. Two temperature conditions: Isothermal 20 °C and realistic with maximum temperature of 40 °C.](image-url)
6. Crack risk calculations and conclusions

A culvert wall cast on an existing hardened base was used as a model, Fig. 10 (Maridalen culvert in Oslo, see full report /3/). The formwork of the wall was removed after 4 days. In the simulation, two values for maximum temperature inside the wall were considered: LOW at 30 - 33 °C and HIGH at 47 - 51°C. Two types of cracking were considered:

Surface cracks caused by surface cooling and a hotter center with critical time with respect to cracking at 4.5 days
Through cracks caused by external restraint, i.e. the stiff hardened base plate under the wall (critical crack time 10 days). Examples of through cracks are shown in Fig. 10.

Details of the simulations are given in /1/. The crack risk results are presented in Fig. 11 as ratios between calculated stresses, caused by thermal dilation and autogenous shrinkage, and the tensile strengths (taken from Fig. 3).

The crack risk with LOW temperature maximum in the wall is always less than with HIGH, as must be expected. The difference between HIGH1 (using strength data from both uniaxial tensile tests and splitting tests) and HIGH2 (using strength data from uniaxial tests only) is smaller for the concretes with silica fume than for the reference. This illustrates that the negative effect of high curing temperature on the tensile strength is large for the reference concrete, but smaller for silica fume concrete /1/.
The overall result in Fig. 11 is that the total average crack risk for all the cases is slightly smaller for the silica fume concretes than for the reference. However, considering the uncertainties involved in the assessments and procedures, the better conclusion is that the three concretes have similar robustness with respect to cracking. The consequence is that cracking risk for these three concretes are primarily determined by factors such as structural geometry and restraint, environmental factors (particularly temperature, formwork removal time etc.), and only marginally influenced by variations in the composition (i.e. the silica fume content) as long as the w/b-ratio and the amounts of cementitious materials are kept constant.

A vital lesson to be learnt from this comprehensive analysis is that no single concrete property (such as autogenous shrinkage) should be used to assess cracking risk; in practice it is the interaction between several properties over time that decides the cracking risk.
Fig. 11 Crack Risk as a function of silica fume dosage. Risk for surface cracks after 4.5 days in (a), and risk for through cracks after 10 days (b). Low is for maximum wall temperature 30 - 33 °C; HIGH for 49 - 51 °C. HIGH 1 uses all strength data including splitting strength, HIGH 2 uses only uniaxial tensile strength data.
7. Acknowledgement

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8. References


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