

HOW TO BUILD CRACK-FREE DURABLE CONCRETE STRUCTURES - CONCRETE HARDENING TECHNOLOGY INCLUDING MODELLING OF SHRINKAGE, CREEP AND TEMPERATURE OF YOUNG CONCRETE AND ITS INFLUENCE ON DURABILITY AND LIFETIME

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Abstract: Control of thermal and shrinkage cracking in hardening concrete is of great importance to ensure desired service life and function of concrete infrastructures. Making reliable stress estimations, and thereby conclusions about cracking risks caused by temperature movements and shrinkage involves advanced modelling of material properties and structural restraint. The paper presents the main outline of a model for description of material properties needed. Special focus is given to a creep model denoted LLM (Linear Logarithmic Model), which is shown to be robust, easy to use, and capable to extrapolate short-term test into long-term effects. Applications of the presented model using the computer program ConTeSt Pro demonstrates that it can be used to decide what measures to be taken to minimize the risk of cracking during the hardening phase for concrete structures.

Keywords: Hardening concrete, Cracking risk, Creep model, Hardening control

1 INTRODUCTION

1.1 Hardening Concrete Behaviour

Infrastructures are often massive constructions, and sometimes high cement contents and low water cement ratios are used. These circumstances alone or in combination might lead to undesired cracks originated from a) slow exchange of temperature and moisture with the environment, b) high temperatures due to the exothermic chemical reaction at hydration, and c) shrinkage caused by internal change of pore humidity in the concrete.

Infrastructures are often exposed to harsh environment with an expected service life in the size of order of 100 years. Estimation of cracking risks must thus be included in the design process in order to minimize the risk of future durability problems, such as corrosion risks of the reinforcement, water tightness, chemical degradation, and damages according to frost.

The assessment of low cracking risks includes decisions regarding necessary measures on the working site, and also an evaluation of the mix composition and its heat and mechanical properties during hardening.

1.2 Objective

The main objective of this paper is to present and summarize a method giving possibilities to assessments of cracking risks in infrastructures taking into account the main factors in material behaviour, environmental conditions, spatial relations, and effects of different measures on site.

2 MATERIAL PROPERTIES

The material properties of hardening concrete may be divided into the following areas:

- Maturity function
- Heat of hydration
- Strength growth at variable temperature
- Creep function
- Free deformation at variable temperature
- Arising stress at full restraint

Tests concerning the properties listed above have been derived and evaluated at Luleå university of technology (LTU) during a long period of time (Emborg, 1989, Jonasson, 1994, Westman, 1999, Hedlund, 2000, Groth, 2000, Nilsson,

2003, Larson, 2003, Carlswärd, 2006, and Utsi, 2008). A connected description of the total evaluation procedure is found in Vogt et al (2008) and Jonasson et al (2009).

Here, the creep function for hardening concrete used at LTU in recent evaluations will be shown, as it seems to have a high potential in numerical applications, and is easy and invitable to use in extrapolation to long-term effect from short-term tests. It was first presented in Larson (2003), and it is called *Linear Logarithmic Model (LLM)* for concrete creep. The model starts with a choice of “elastic” load duration, Δt_0 , here chosen to be 0.001d (Westman, 1999). From this definition the elastic modulus for numerical calculations at the concrete age t_0 , $E(t_0)$ [Pa], is described by

$$E(t_0) = \frac{1}{J(\Delta t_0, t_0)} = \frac{1}{J(0.001d, t_0)} \quad (1)$$

where $J(0.001d, t_0)$ = total deformation 0.001d after loading [1/Pa]; t_0 = age at loading [d].

The total deformation (creep compliance), $J(\Delta t_{load}, t_0)$ [1/Pa], is expressed by

$$J(\Delta t_{load}, t_0) = \frac{1}{E(t_0)} + \Delta J(\Delta t_{load}, t_0) \quad (2)$$

where $\Delta t_{load} = t - t_0$ = load duration [d]; $\Delta J(\Delta t_{load}, t_0)$ = creep part of the total deformation [1/Pa]. The elastic modulus is expressed by

$$E(t_0) = \left[\exp \left\{ s \cdot \left(1 - \sqrt{\frac{28 - t_s}{t_0 - t_s}} \right) \right\} \right]^\eta \cdot E(28d) \quad (3)$$

where t_s = concrete age when the concrete can give rise to stresses [d]; s [-] and η [-] are fitting parameters. Eq. 3 is in CEB-FIP Model Code 90 and EC2 (Eurocode 2) applied with $t_s = 0$, $\eta = 0$, and s dependent on the cement type.

With two linear lines in the logarithmic time scale, the creep part of the deformation using the *LLM* model (Larson, 2003, and Larson and Jonasson, 2003a, 2003b) is formulated by

$$\Delta J(\Delta t_{load}, t_0) = \begin{cases} a_1 \cdot \log \left(\frac{\Delta t_{load}}{\Delta t_0} \right) \\ a_1 \cdot \log \left(\frac{\Delta t_1}{\Delta t_0} \right) + a_2 \cdot \log \left(\frac{\Delta t_{load}}{\Delta t_1} \right) \end{cases} \quad (4)$$

where Δt_1 = time duration at the distinct break point in the creep behaviour [d]; a_1 and a_2 are

inclination coefficients for the linear lines in the logarithmic time scale [(Pa log-unit)⁻¹].

Finally, continuous descriptions (depending on concrete age t_0) of the inclination coefficients are formulated (for $i = 1$ and 2, respectively) by

$$a_i(t_0) = a_i^{\min} + (a_i^{\max} - a_i^{\min}) \cdot \exp \left(- \left(\frac{t_0 - t_s}{t_{ai}} \right)^{n_{ai}} \right) \quad (5)$$

Application of Eqs. 1-5 for a civil engineering concrete, from Jonasson et al (2009), is shown in Figures 1 –5.

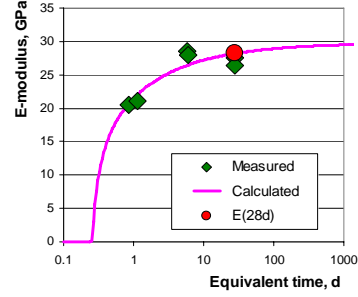


Figure 1. Elastic modulus using Eq. 3

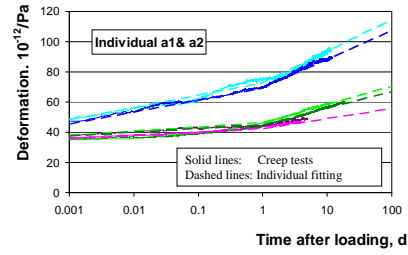


Figure 2. Fitting of creep tests using Eq. 4

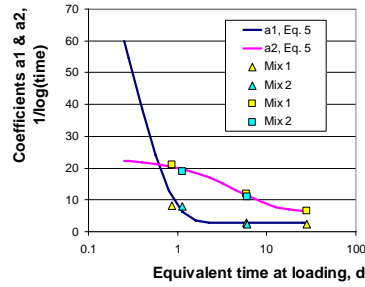


Figure 3. Continuous formulation using Eq. 5

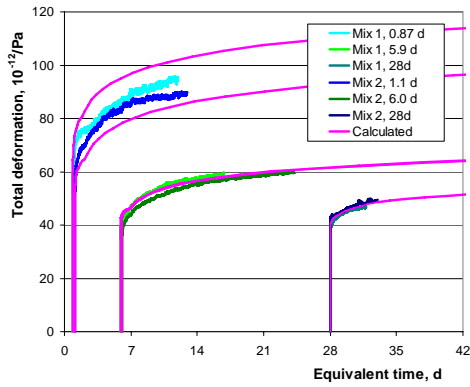


Figure 4. Creep curves in linear time scale

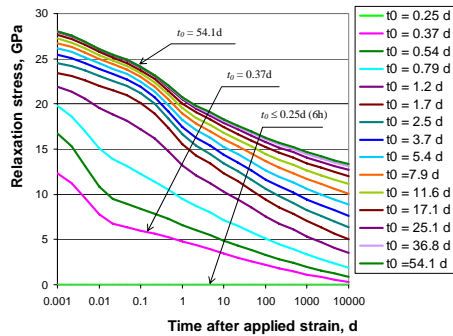


Figure 5. Calculated relaxation curves

As can be seen from Figures 1 – 4 the fitting of creep tests can be realized in a satisfactory way with the use of Eqs. 1-5.

Figure 5 illustrates long-term effects based on short-term tests. The model background is the usage of linear lines in Figure 2 together with the use of Eq. 5 as illustrated in Figure 3, which in combination is a robust and easy to understand way to inter- and extrapolate short-term creep test data.

Besides, all calculated relaxation values are above zero, see calculated stresses in Figure 5. This means that the *LLM* creep model, as described here, is inviting avoiding “reversed stresses” in calculations. It is also interesting that other research groups also have used the *LLM* model with success (Riding et al, 2008).

3 TESTS WITH WALL ON SLAB

Full scale tests at indoor conditions have been

realized at Luleå university of technology for the construction “wall on slab” for three different situations (Jonasson et al, 2009). Measurements have been performed with respect to temperatures, deformations, strains, and mapping of crack patterns. In addition, properties for the hardening concrete have been investigated to get concrete data in order to estimate temperatures and risks of cracking by calculations. The construction wall on slab represents a typical case, which can be found in many structures like walls, retaining walls, tray structures, tunnels, and bridges.

In the comparison between calculated and measured temperatures, all tests showed to be within 2°C in all monitored points, see Figure 6, which is regarded as a very good agreement.

Furthermore, one of the walls cracked due to high temperature loadings, and this could be reflected in the calculations, see Figure 7.

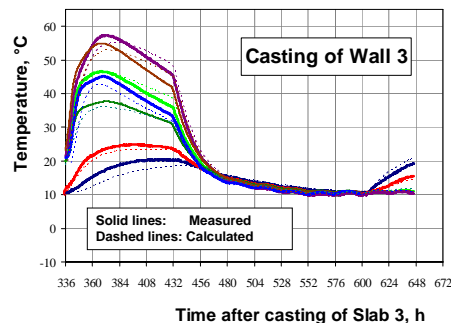


Figure 6. Measured and calculated temperatures when casting a wall on slab

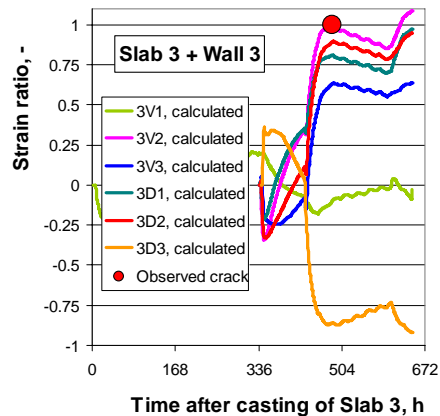


Figure 7. Calculated strain ratios in comparison with observed behavior at cracking (The red circle illustrates 1st observed crack in the wall)

The red circle in Figure 7 illustrates the time when the first crack was observed in the wall, which coincides with the calculated situation showing maximum strain ratio = 0.99. (practical crack failure criterion: calculated strain ratio ≥ 0.95). This indicates that the restraint factors in modelling reflects the real restraint condition in the wall, which gives a good base for further predictions in general.

4 ESTIMATED CRACK RISKS

4.1 Possible Measures to be Taken

Factors influencing the formation of cracks during the hardening phase of the concrete are illustrated in Figure 8.

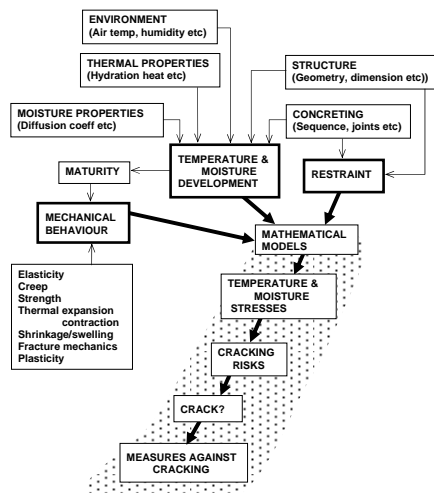


Figure 8. Factors influencing the formation of cracks in hardening concrete. Modified from Emborg and Bernander (1994)

The computer program ConTeSt Pro (1999) follows the “flow” in Figure 8, and the different measures to be taken reducing the risk of cracking may be divided into the following areas:

- Structural design
Reducing restraining
- Material choices
Type of cement
Concrete recipe
Concrete temperature at casting

- Measures on site
Cooling of newly cast structure
Heating of adjacent structure
Thermal insulation

In the sections 4.2 and 4.3 two examples, calculated by Kjell Wallin in co-operation with Jan-Erik Jonasson using ConTeSt Pro (1999), are shown for realistic constructions.

4.2 Dam Structure in Vietnam

For the Ban La Dam in Vietnam some introductory calculations have been performed, and a calculated temperature field 10 years after casting is shown in Figure 9.

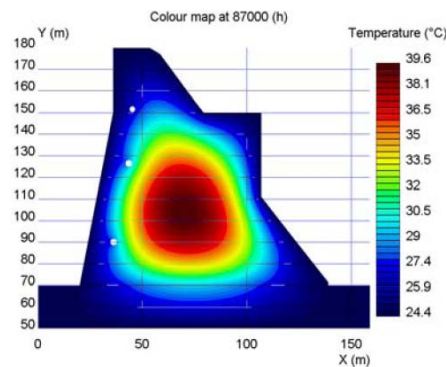


Figure 9. Calculated temperatures after 10 yrs

For the calculation of cracking risks, a lot of cases were analysed with different lengths of the monoliths and different assumptions of structural restraint, and one example of calculated strain ratios is shown in figure 10 for the situation 10 years after casting. The main idea in these calculations is the choice of a concrete with low binder content to avoid cooling pipes.

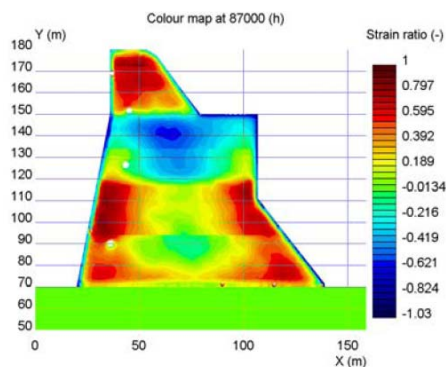


Figure 10. Example of calculated strain ratios

5 CONCLUSIONS

The derived model for properties for hardening concrete is capable to simulate a realistic behaviour concerning both the temperature field and arising stresses including creep effects in concrete specimens. This gives a base for assessments of cracking risks for different constructions.

Calculations of real concrete structures show that the computer model can be used to decide what measures to be taken to minimize the risk of cracking during the hardening phase.

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4.3 Bridge between Norway and Sweden

Different parts of the Svinesund concrete arched bridge between Norway and Sweden were planned to be cooled or heated in order to fulfil the demands of “crack-free” constructions.

In Figure 11 the temperature field in one of the footings to the concrete arch is shown at a time 60h after casting. The cooling pipes near the rock surface ($y = 6-7\text{m}$, not seen in Figure 11) are closed 2d after casting, and the more spaced pipes in the upper part of the footing are in progress longer to counteract the cooling temperature gradients inside the concrete body.

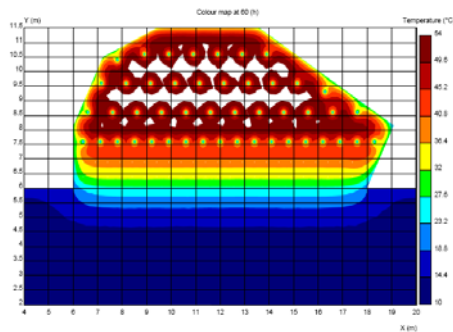


Figure 11. Calculated temperatures (60h). White areas mean temperatures above 54 °C.

The maximum strain ratios in the analysed footing arised 800h (33d) after casting, see Figure 12. To the left and to the right in the figure the stress concentrations at the support to the rock during the cooling phase are shown, and the maximum strain ratio is within the stipulated demand.

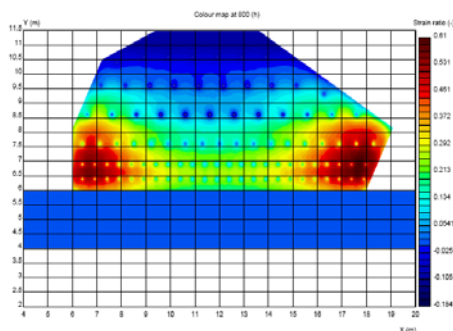


Figure 12. Strain ratios 33 days after casting.

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