HETEK

Control of Early Age Cracking in Concrete
Main Report

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Abstract

This report forms a part of the Danish Road Directorate's research programme called High Performance Concrete - The Contractor's Technology (abbreviated to HETEK). The report summarizes the work carried out in the HETEK project that deals with control of early-age cracking in concrete.

The project has shown that it is possible to choose methods of execution that reduce the risk of crack formation during hardening based on stress calculations. This is in line with current practice.

As improvements to current practice the project has shown that the coefficient of thermal expansion should be specified as a function of maturity (as for the E-modulus, tensile strength, etc.). Also a stress-level has been identified - in relation to the splitting tensile strength - which experience shows will result in crack-free structures.

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0. Preface

This project on control of early-age cracking is part of the Danish Road Directorate's research programme High Performance Concrete - The Contractor's Technology (in Danish: Højkvalitetsbeton - Entreprenørens Teknologi, abbreviated to HETEK).

In this programme high performance concrete is defined as concrete with a service life of at least 100 years in an aggressive environment.

The research programme includes investigations concerning the contractor's design of high performance concrete and execution of the concrete work with reference to the required service life of 100 years.

The total HETEK research programme is divided into segments with the following topics:

- chloride penetration
- frost resistance
- control of early-age cracking
- compaction
- curing (evaporation protection)
- trial casting
- repair of defects

The Danish Road Directorate invited tenders for this research programme which is mainly financed by the Danish Ministry for Commerce and Industry - The Commission of Research and Development Contracts.

The present report refers to the part of the HETEK project that deals with control of early-age cracking.

For durability reasons reinforced concrete structural members should be well protected against penetration of water, chloride, etc. This means that cracks should be avoided or at least the crack-width limited. Cracks can form already during the hardening process. An evaluation of the risk of crack formation involves a stress analysis. In stress analysis of hardening concrete structures, the load consists of the differences in thermal strains that arise from the heat of hydration. The mechanical properties (including autogenous shrinkage) of the concrete also change during the hardening process. If a stress analysis shows high stresses relative to the tensile strength there is a high risk of crack formation.

The project was carried out by a consortium consisting of:

The Danish Concrete Institute, represented by:

Højgaard & Schultz A/S
Monberg & Thorsen A/S
RAMBØLL
COWI

and

The Danish Technological Institute, represented by the Concrete Centre

and

The Technical University of Denmark, represented by the Department of Structural Engineering and Materials.

Two external consultants, Prof. Per Freiesleben Hansen and manager Jens Frandsen, are connected with the consortium.

1. Introduction

This report summarizes the work carried out in the HETEK project that deals with the control of early-age cracking in concrete. A number of reports have been prepared in connection with the project; they are listed in Section 4. In "State of the Art" [Pedersen, 1997] the following fields of investigation are identified as important:

- Can development of mechanical properties (incl. autogenous shrinkage) be described by using the concept of maturity?
- How do high tensile stresses affect creep deformation?
- Are the material properties specified adequately, and are they "combined" correctly in the calculations?
- Can the 3-dimensional stress-state in a hardening structure be calculated, taking the interaction between structural components into account?
- How should the support conditions be modelled?
- What is the permissible tensile stress if crack formation is to be avoided?

In the project the above-mentioned fields were investigated by determinations of material properties, a full-scale test under laboratory conditions, and observations on actual structures. The results of the project are given in the following.

2. Results

2.1 Applicability of the concept of maturity

Investigations were carried out to determine whether changes in the mechanical properties (incl. autogenous shrinkage) could be accounted for by using the well-known concept of maturity, based on the Arrhenius function with the energy of activation determined on the basis of compressive strength.

2.1.1 E-modulus and strength

The development of E-modulus, compressive strength, splitting tensile strength and uniaxial tensile strength were determined at 20°C and 40°C for one type of concrete. The tests are described in the report "Creep in Concrete" [Hauggaard, 1997]. These tests indicate that the usual maturity concept can be used to describe the dependence of the rate of development of as well compressive strength as the other properties regarded on temperature.

2.1.2 Coefficient of thermal expansion

The development of the coefficient of thermal expansion was determined in the course of the full-scale test. The results are given in the report "Measured and Predicted Deformations in Hardening Concrete" [Pedersen, 1997]. These measurements do not indicate that the coefficient is dependent on temperature.

The measurings show that the thermal coefficent of expansion of the concrete tested rises suddenly at approx. 24 maturity hours from approx. $0.85 \cdot 10^{-5}\,°C^{-1}$ to $1.0 \cdot 10^{-5}\,°C^{-1}$. The coefficient subsequently rises to approx. $1.1 \cdot 10^{-5}\,°C^{-1}$ during approx. 10 maturity days. This development has essential practical importance in evaluation of the risk of through-going cracks in the cooling phase. Therefore a coefficient of thermal expansion as a function of maturity determined on the actual concrete should be used in calculations. This improves current practice where a constant value is assumed.

2.1.3 Autogenous shrinkage

Autogenous shrinkage was measured on two concretes at 20°C and 40°C, as well as under a varying temperature. The tests are reported in "Shrinkage of mortar and concrete" [Jensen, 1997]. These tests do not give an unambiguous answer concerning the applicability of the maturity concept for specifying the temperature dependence of autogenous shrinkage. On the other hand, the tests do not exclude the possibility of using maturity in practice to describe the development of autogenous shrinkage.

The report "Material Modelling, Composite Approach" [Nielsen, 1997] gives a composite theoretical model for determining the shrinkage of concrete on the basis of measurements of shrinkage in mortar.

2.1.4 Creep

Tests on compressive creep were carried out at 20°C, 40°C and under a varying temperature. The tests are described in the report "Creep in Concrete" [Hauggaard, 1997]. These tests indicate that temperature changes involve an increased rate of creep deformation, as described in the report "Material Modelling, Continuum Approach" [Hauggaard, 1997]. In the test, a load corresponding to 40% of the compressive strength was applied approx. 24 hours after casting. In the same period the temperature rose by about 20°C. A relatively high rate of creep deformation was observed in connection with the load application. In the tests carried out at constant temperature, however, increased creep was also observed immediately after load application. This may be due to the stress (40% of the compressive strength) generated in the very young concrete giving rise to non-linear creep. Part of the increased creep in the test under a varying temperature may thus be due to non-linear creep. However, it is difficult to determine how great a fraction of the observed creep is caused by temperature change and how much by non-linear creep. (See also Section 2.2).

The report "Material Modelling, Composite Approach" [Nielsen, 1997] gives a composite theoretical creep model. The model is calibrated on the basis of the tests described in [Spange, 1996], and does not take non-linear creep into account.

2.2 Creep at high stresses

Tensile creep tests were carried out at load levels of 40%, 60% and 80% of the compressive strength. The tests are described in the report "Creep in Concrete" [Hauggaard, 1997], and evaluated in the report "Material Modelling, Continuum Approach" [Hauggaard, 1997]. The conclusion is that the rate of creep deformation is independent of whether a compressive stress or a tensile stress of equal magnitude is applied. The tests also show that there is agreement between the development of the E-modulus in tension and in compression, cf. "Creep in Concrete" [Hauggaard, 1997].

The test at a load corresponding to 80% of the compressive strength indicates that non-linear creep takes place. Increased creep will reduce the eigen-stress state in a hardening structure, and thus reduce the risk of cracking. In practice it will therefore be on the safe side to neglect non-linear creep at high stresses.

Both tensile and compressive creep tests indicate that at a very early age non-linear creep takes place even at a stress of 40% of the compressive strength; an increased creep rate was observed in all tests involving the application of a load at an early age. Increased creep at an early age will reduce eigen-stresses in a hardening structure and thereby reduce the risk of surface cracking in the warming phase. The reduction of compressive stresses in the warming phase can, however, increase the risk of through-going cracks in the cooling phase. It should be emphasized, however, that a load of 40% of the compressive strength is high in relation to the stress that arises in the warming phase of "real" structures. Neglecting non-linear creep at an early age will therefore make little difference in practice.

2.3 Verification of material properties

Uniaxial tests were carried out on specimens in which deformation was prevented while the temperature was varied. The change in stress was measured. Two types of concrete were tested. In the report "Material Modelling, Continuum Approach" [Hauggaard, 1997], the stresses arising in these tests were calculated on the basis of material models described in the report. In practice it was not possible to prevent deformation completely. This is taken into account in the calculations. In the calculations, the deformations due to autogenous shrinkage and temperature changes were based on measurings on a reference specimen. Therefore no models describing autogenous shrinkage and coefficient of thermal expansion enter into the calculations. The calculated stress histories differ from the measured with approx. 30%.

The calculation of the full-scale test based on measured concrete properties show that the stresses in a hardening concrete structure can be predicted satisfactory for use in practice, see Section 2.4.

2.4 Verification of the hardening stress theory

A full-scale test under laboratory conditions was carried out with a wall on a base slab, with well-defined support conditions. The test is reported in "Measured and Predicted Deformations in Hardening Concrete" [Pedersen, 1997]. The results show a constant curvature in the central zone of the structure. This indicates that it is correct to assume full interaction between structural components even at an early age.

The curvature of the structure as a function of time was calculated based on a stress calculation with the aid of the programme CIMS-2D, based on the "Compensation Plane Method" described in "State of the Art" [Pedersen, 1996]. The deviation between measured and calculated curvature is approx. $0.2 \cdot 10^{-4}$ m^{-1} corresponding to a temperature deviation in the magnitude 2-3 °C. On this basis the curvature and with it the stress is found to be determined satisfactory.

The material models used in the calculation were based on testing in accordance with practice prior to the HETEK project, as described in the report "Early Age Properties of Selected Concrete" [Spange, 1996]. However, the coefficient of thermal expansion was a function of the maturity instead of the constant value hitherto assumed. The coefficient was determined by measurements. See Section 2.1.2.

2.5 Modelling of supports

In connection with the construction of a tunnel, deformation measurements were carried out during hardening. The measurements are reported in "Modelling of Support Conditions" [Andersen, 1997].

A calculation that simulates the hardening process undergone by the structure was carried out. When it is assumed in the model that longitudinal movement of the tunnel is not restrained by the underlying support, good agreement with the measured values is obtained. For very long foundations, and for other types of support such as rock and limestone, an axial constraint from the underlying support should be built in.

With regard to the influence of dead load on the interaction with the underlying support, the conclusion is that two cases should be considered:

- curvature is permitted
- curvature is prevented

For short structures, the case in which curvature is prevented can be omitted. As a rule of thumb, structures with a length/height ratio of less than 3 can be considered as short in this connection. For structures on rock or limestone, a segment of the underlying support should be included in the calculations.

2.6 Permissible tensile stresses

In the report "Stress Calculations and Crack Observations" [Pedersen, 1997], temperature and crack observations on a number of structures are presented. Stress calculations were carried out in which the observed temperature history is used as a "loading". The calculations were carried out on the basis of material properties determined during the construction of the various structures. The investigation includes hardening processes that resulted in cracking as well as those that did not. This makes it possible to determine the stress at which cracks begin to form. The calculated stresses are compared with the splitting tensile strength according to DS 423.34. The investigations show that for a tensile stress of above 80% of the splitting tensile strength, a few cracks form; the number of the cracks increase with increasing stress. At stresses below 80% of the splitting tensile strength, no cracks were observed.

3. Conclusion

The result of the project "HETEK - Control of early-age cracking in concrete" is that it is possible to choose methods of execution that reduce the risk of crack formation during hardening based on stress calculations. This is in line with current practice. It can be concluded that:

- it is possible to separate the behaviour of concrete into distinct properties measured in the laboratory and subsequently "put them together" in a given hardening process occuring in real structures

- the assumptions of the "Compensation Plane Method" are valid for actual structures.

The project has resulted in the following improvements to current practice:

- the coefficient of thermal expansion should be specified as a function of maturity (as for the E-modulus, tensile strength, etc.)

- a stress-level has been identified - in relation to the splitting tensile strength - which experience shows will result in crack-free structures.

Guidelines for control of the hardening process were prepared as part of the project [Pedersen, 1997]. The above-mentioned results are included in the guidelines.

4. Reports

The following reports were prepared as part of the project:

Andersen M. E. et al.: "HETEK - Control of Early Age Cracking - Phase 8: Modelling of Support Conditions", Danish Road Directorate, Report no. 98, 1997.

Frederiksen, J. O. et al.: "HETEK - Control of Early Age Cracking in Concrete - Proposal for supplementary research", Danish Road Directorate, Report no. 116, 1996.

Hauggaard, A. B. et al.: "HETEK - Control of Early Age Cracking in Concrete - Phase 3: Creep in Concrete", Danish Road Directorate, Report no. 111, 1997.

Hauggaard, A. B. et al.: "HETEK - Control of Early Age Cracking in Concrete - Phase 4 and 5: Material Modelling, Continuum Approach", Danish Road Directorate, Report no. 113, 1997.

Jensen, O. M.: "HETEK - Control of Early Age Cracking in Concrete - Phase 2: Shrinkage of mortar and concrete", Danish Road Directorate, Report no. 110, 1997.

Nielsen, L. F.: "HETEK - Control of Early Age Cracking in Concrete - Phase 4B: Material Modelling, Composite Approach", Danish Road Directorate, Report no. 112, 1997.

Pedersen, E. J. et al.: "HETEK - Control of Early Age Cracking - Phase 9: Stress Calculations and Crack Observations", Danish Road Directorate, Report no. 119, 1997.

Pedersen, E.S. et al.: "HETEK - Control of Early Age Cracking in Concrete - State of the Art", Danish Road Directorate, Report no. 52, 1996.

Pedersen, E.S and Spange, H.: "HETEK - Control of Early Age Cracking in Concrete - Phase 7: Measured and Predicted Deformations in Hardening Concrete", Danish Road Directorate, Report no. 106, 1997.

Pedersen, E.S and Spange, H.: "HETEK - Styring af revner i ung beton - Anvisning", Vejdirektoratet, Rapport nr. 119, 1997.

Pedersen, E.S et al.: "HETEK - Control of Early Age Cracking in Concrete - Guidelines", Danish Road Directorate, Report no. 120, 1997.

Riis, K. et al.: "HETEK - Control of Early Age Cracking in Concrete - Phase 6: Early Age Properties of Alternative Concrete", Danish Road Directorate, Report no. 114, 1997.

Spange, H. and Pedersen, E.S: "HETEK - Control of Early Age Cracking in Concrete - Phase 1: Early Age Properties of Selected Concrete", Danish Road Directorate, Report no. 59, 1996.

Spange, H. and Pedersen, E.S: "HETEK - Styring af revner i ung beton - Hovedrapport", Vejdirektoratet, Rapport nr. 117, 1997.

Pedersen, E.S et al.: "HETEK - Control of Early Age Cracking in Concrete - Main Report", Danish Road Directorate, Report no. 118, 1997.