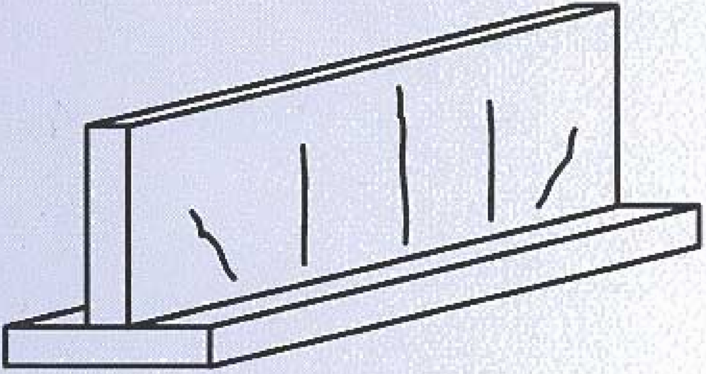
# HETEK

## Control of Early Age Cracking in Concrete
## Proposal for Supplementary Research



Report No.116
1997

Road Directorate Denmark
Ministry of Transport

# IRRD Information

| | | |
|---|---|---|
| Title in English | HETEK -Control of Early Age Cracking in Concrete - Proposal for supplementary research | |
| Title in Danish | HETEK - Styring af revner i beton i tidlig alder - Forslag til supplerende forskning | |
| Authors | Jens Ole Frederiksen, Erik Steen Pedersen, Helle Spange, Anders Nielsen, Lauge Fuglsang Nielsen, Anders Bo Haugaard, Jacob H. Hansen | |
| Subject classification | Field 32 | Concrete |
| Key words | Concrete | 4755 |
| | Cracking | 5211 |
| | Material (Constr) | 4555 |
| | Properties | 5925 |
| | Simulation | 9103 |
| | Number | 6432 |
| | Stress | 5575 |
| | Denmark | 8028 |
| 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). This report describes the "Proposal for supplementary research" on the subject: Control of Early Age Cracking | |
| UDK | 691.32<br>620.191.33 | |
| ISSN | 0909 4288 | |
| ISBN | 87 7491 830 3 | |

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# 0. Preface

This project regarding 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.

High Performance Concrete is concrete with a service life in excess of 100 years in an aggressive environment.

The research programme includes investigations regarding the conctractor's design of high performance concrete and execution of the concrete work with reference to obtain the requested service life of 100 years.

The research programme is divided into eight parts within the following subjects:

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

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

This project regarding Control of Early Age Cracking is performed by a consortium consisting of:

Danish Concrete Institute

and

DTI Building Technology represented by the Concrete Centre

and

DTU represented by Department of Structural Engineering and Materials.

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

For durability reasons 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. Formation of cracks can take place 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.

The purpose of this project is to investigate these effects and to prepare a guideline regarding Control of Early Age Cracking.

March 1996

# 1. Introduction

In recent years it has often been required that the planning of the curing process shall be based on a stress calculation. The HETEK Tasks 3 and 4 on self-desiccation and curing technology will result in guidelines for the planning of the curing process so that undesirable crack formation is prevented. In order to make the guidelines as complete as possible, it will be necessary to carry out supplementary research as described in the following.

## Material models

The stress calculations performed during recent years have been based on the assumption that the material parameters are functions of the concrete maturity, but investigations have not been made in support of this. As an example of models that might deviate considerably from the above assumption, models for shrinkage and creep can be mentioned. Phases 2 - 6 of the supplementary research therefore comprise a number of investigations on the temperature dependence of the material models.

## Support conditions

Another issue that has not been sufficiently investigated is the modelling of the support conditions to be used in a stress calculation. It must be considered whether the structure can move freely on the subsoil or whether it is fixed. It should also be considered to what degree the temperature distribution over the cross-section can result in flexural stress.

In order to illustrate the problem, the middle section of an infinite long structure is considered. In this case, the self-weight will prevent the structure from bending just as the friction will have the effect that no axial movements can take place in the structure. In this case it is therefore easy to choose the support conditions.

Similarly, a structure that is short compared to the cross-section dimensions will be able to change length and to bend freely.

Most relevant structures, however, have dimensions that make it difficult to determine the support conditions. In phase 8 of the supplementary research a number of actual structures are measured in order to provide a better basis for determining the support conditions.

## "Full-scale" testing in the laboratory

The accuracy with which a stress calculation can predict the risk of cracking depends partly on the input data and thus the accuracy of the material models available, partly on the way the one-dimensional material models are converted to multi-dimensional cases.

To document the capability of the model (CIMS-2D) to predict the behaviour of actual structures, phase 7 includes "full-scale" laboratory testing of structures with well-defined supports in which deformations and temperatures can be measured accurately.

## Crack predictions

Stress calculations determine the tensile stress distribution in the structure. If the tensile stress at a point is too high compared to the tensile strength, there is a risk of crack formation. When assessing a planned curing process, the ratio of the calculated tensile stresses to an indicator of the tensile strength, e.g. the splitting tensile strength, is used. The lower the ratio, the lower the risk of crack formation. Phase 9 of the supplementary research includes an evaluation of this ratio compared to the requirements for avoidance of cracking. In this phase the results of the laboratory tests in phase 7 are used.

# 2. Phase 1 - Testing of seleted concrete

In phase 1 a complete test will be carried out on a typical concrete for use in bridge structures (in the following called VD-concrete). During this testing all necessary material parameters will be determined according to the normal testing programme used at DTI. This determination of parameters forms the basis of a stress calculation for the full-scale test. The investigation will be carried out by DTI Concrete Centre.

The tests will include determination of the heat development, coefficient of thermal expansion, E-modulus, compressive strength, splitting tensile strength, shrinkage and creep under compression.

## Test methods

### Heat development

The heat development will be determined according to the Nordtest Method NT-Build 388. A triple determination will be performed.

### Coefficient of thermal expansion

The coefficient of thermal expansion will be determined according to DTI test method TI-B 101 at ages 1, 3 and 7 days.

Simultaneously measurements will be carried out according to a new test method under development at DTI Concrete Centre. This test method determines the coefficient of thermal expansion continuously after approximately 24 maturity hours.

The measurements made using this new test method are very promising and indicate that the coefficient of thermal expansion may depend on the temperature of the concrete i.e. that a higher temperature increases the coefficient of thermal expansion. If that is the case, and if the change is significant, it will affect the results of stress calculations. An increased coefficient of thermal expansion results in higher stresses.

This possible temperature dependence will be investigated on the selected VD-concrete. The investigation will be carried out according to the method developed by the Concrete Centre. The coefficient of thermal expansion is determined within the interval of 15 - 35°C. If this preliminary test confirms a temperature dependence, the investigation should be extended to comprise the development of numerical material models including the maturity and temperature dependence. This investigation will be reported separately.

### E-modulus, compressive strength and splitting tensile strength

E-modulus, compressive strength and splitting tensile strength are measured at the ages of 1/2, 1, 2, 3, 7, 14 and 28 maturity days in order to determine the dependence of the parameters on the maturity of the concrete. The tests will be performed according to DS 423.23, 25 and 34.

### Shrinkage and creep

Shrinkage and creep under compressive load are determined according to the DTI test method TI-B 102. Measurements are made for a period of 28 days and both shrinkage and creep are measured on three test specimens. The three test specimens for the creep test are subjected to different load sequences as recommended in the annex to TI-B 102.

# 3. Introduction to phases 2 - 6

Phases 2 - 6 of the supplementary research programme will be carried out at DTU (the Technical University of Denmark). This programme will include the following investigations:

Phase 2: Shrinkage in concrete and cement paste
Phase 3: Creep in concrete
Phase 4: Development of material models
Phase 5: Documentation of models
Phase 6: Test and documentation of models for a different concrete

The investigations in phases 2 - 6 are planned to fulfil the HETEK contract and to form the basis of more intensive research work.

## Scope

By means of research and development activities, information is collected on the behaviour of VD-concrete and cement paste exposed to different and varying curing and restraint conditions.

By limiting most investigations to only one type of concrete the results will not be sufficient to create general models for the different material parameters. The models are created with reference to a number of material assumptions. In phase 6, tests are performed on a concrete with a different composition, and these results can be used for an assessment of the suitability of the models for other concretes. In phase 2, variations in the type of cement paste are investigated.

The investigations included in phases 2, 3, 5 and 6 are planned in such a way that the testing techniques and testing periods are harmonized with the tests performed at DTI. During the experimental work in these phases a laboratory- mixed concrete is used with a composition as stated in the mix design for VD-concrete.

# 4. Phase 2 - Autogenous shrinkage of cement paste and concrete

In this phase an investigation of the autogenous shrinkage caused by self-desiccation is carried out. Measurements are made on the VD-concrete as well as on different types of cement paste. The investigations shall explain how the shrinkage depends on the concrete composition and the concrete temperature. The present assumption is that the shrinkage is a function of the concrete maturity.

All measurements made at DTI according to TI-B 102 show significant deformations in the concrete at the start of the hardening process. With the concrete dilatometer developed at DTU the measurements are started immediately after casting and this method is therefore very appropriate for an investigation including this early-age deformation.

The cement paste corresponding to the composition of the VD-concrete is examined in a dilatometer and Rotronic hygroscope. The purpose of the investigation is to determine the autogenous deformation of this composition as well as the principal mechanisms that influence shrinkage in the cement paste.

As the first investigation in this phase, the dependence of shrinkage on temperature will be examined (can shrinkage be described as a function of the maturity?). This will be done by measurements of shrinkage on both VD-cement paste and VD-concrete at approximately 21 °C and 40 °C. Based on an analysis of the obtained results, additional investigations are planned.

Depending on the decisions based on the first part of this investigation, alternative cement paste compositions - which might present a smaller self-desiccation shrinkage - may be tested, and on the basis of the results of such investigations a concrete can be designed with a cement paste composition that minimizes the shrinkage. The shrinkage of this concrete can be measured by means of the concrete dilatometer at DTU.

The self-desiccation shrinkage may cause micro-cracking in the concrete, and thus micro-cracks may reduce the tensile strength of the concrete. Because the self-desiccation shrinkage may increase with higher curing temperature the risk of micro-cracking may increase as well. This problem will be investigated by measuring the relation between tensile strength, splitting tensile strength and compressive strength for the VD-concrete hardened at different temperatures. The compressive strength is a function of the concrete maturity. If micro-cracking caused by higher temperature reduces the ratio of tensile strength to compressive strength, this will be of great importance for the structure. Depending on the results, these tests will also be carried out on a concrete with a small self-desiccation.

The crack formation activity of the concrete may be followed by a registration of the acoustic emission.

The investigations concerning "Shrinkage in cement paste and concrete" are divided into the following three main areas:

1: Measurement of shrinkage in the VD-concrete and in a cement paste/mortar with a composition corresponding to the VD-concrete at different temperatures. Other cement pastes may be examined as well as an alternative concrete.

2: If possible the formation of local shrinkage micro-cracks will be detected by acoustic emission from the hardening concrete. With this technique it is possible to determine the development of the dynamic E-modulus in the VD-concrete at the same time.

3: Investigation of the effect of micro-cracking on the tensile strength.

The nature and extent of the work in this phase is coordinated with the investigations in phase 4 concerning development/improvement of material models.

# 5. Phase 3 - Creep in concrete

In this phase the phenomenon of creep is investigated. Measurements are made on the VD-concrete.

The work will include tests on tensile and compressive creep as well as on relaxation. The tests shall be started as soon as possible after casting and continued until a maturity of at least 168 hours. It will be determined whether creep under compression and creep under tension are approximately equal.

The dependence of creep on temperature will be investigated. The present assumption is that the material properties affecting creep can be expressed as a function of the concrete maturity.

Creep under compression is measured at approximately 21 °C and 40 °C. If it turns out that the temperature dependence of the creep cannot be described by means of the traditional maturity function, the creep will also be measured at approximately 30 °C. It will also be investigated whether the creep depends on a change of temperature during the hardening period. This part of the investigation involves only creep under compression. It will also be investigated whether the E-modulus is a function of the maturity.

The tensile tests are performed at one temperature (approximately 21 °C). As a results of these tests the E-modulus under tension is determined for each change in load. It will be investigated whether the E-moduli in tension and compression can be assumed to be equal.

In a hardening concrete structure, the compressive stresses are low relative to the compressive strength, but the tensile stresses may be high relative to the tensile strength. Therefore some of the tensile creep tests must be performed with a load near the corresponding failure load in order to detect possible non- linearity of the creep under tension near failure load.

In the first investigations in phase 3, the creep under compression is measured at 21 °C and 40 °C and the creep under tension is measured at 21 °C. By doing this it can be determined at an early time in the project if it is reasonable to assume that creep is identical for compression and tension and if creep is a function of the concrete maturity. On the basis of an analysis of the achieved results it is decided which further investigations are needed.

Tests will also be carried out to show how a conversion can be made between the creep and relaxation results. This is essentially for the work in phase 4.

The viscoelastic stress-strain relation (Young's moduli and creep functions) for concrete must be known before any analysis can be made on the mechanical behaviour of concrete and concrete structures.

Examples range from the analysis of thermal stresses and temperature-induced deformations in hardening concrete to the calculation of stresses, loss of prestressing and deformations in mature concrete.

A prediction method for concrete creep must consider proportioning, quality of bond between cement paste and aggregate, and curing conditions. Elastic strain and reversible creep must be considered as well as irreversible creep and rapid consolidation deformation of materials caused by load application. Creep is essentially a logical consequence of the composite-rheological behaviour of the concrete constituents. Recognizing this feature means that consistency can be established between creep prediction and viscoelastic calculation methods.

Cement paste is the critical component in creep of concrete. There is no doubt that research on concrete creep must start with creep of plain cement paste, and then continue to concrete as a composite material. Within the period of this HETEK project such an analysis cannot be completed. However, efforts will be made to utilize the creep results obtained to deduce basic creep parameters such that creep functions can be established which meet approximately the demands on creep functions mentioned above.

An existing material model will be used for this purpose. This model has been tested by comparing its results with data from experiments with age of loading down to 7 days. There is no apparent theoretical restriction on the model with respect to lower ages at loading.

The results from the HETEK project can therefore be used to calibrate the model for use on concretes similar to those tested in the project. It is emphasized that the results obtained in this way cannot be generalized to apply to other concretes; the more complete creep analysis previously referred to is necessary to do this.

To improve consistency with creep data previously reported the duration of the test must be at least 7 days. Some tests must be carried out with constant load/deformation sequences at levels which do not exceed 30 - 40% of immediate failure load. Some measurements must continue several days after unloading. In the HETEK project the duration of the tests in phase 1 and phase 6 is 28 days including measurements several days after unloading.

# 6. Phase 4 - Establishment of model

In this phase modified models for relevant material parameters will be proposed, and based on this work possible modifications of the test programme described in phase 1 are suggested.

The objective of the work in this phase is to establish material models to be used in stress calculations. Although the models shall be as simple as possible, they must include all necessary and important parameters (e.g. temperature). The proposed material models shall be suitable for implementation in finite element programmes such as CIMS-2D.

In this phase both composite theoretical and numerical material models are investigated. In a composite theoretical material model the interaction between the different materials of the concrete is taken into account. In a numerical material model the concrete is considered to be a homogeneous material. In both cases the material models are described on the basis of physical conditions in the concrete.

The establishment of the material models are based on results from the HETEK phases 1, 2, 3 and 5 and from existing measurements made on very young concretes. Also information from the literature reported in a RILEM database is used. This database contains test results from the last 50 years. The measurements in the database primarily concern hardened concrete and therefore the creep and relaxation measurements from the present project play an important part in the development of the model.

## Composite theoretical material model

The composite theoretical material model that comprises both shrinkage and creep is developed as a total model with the application of mathematical expressions. The composition of the concrete as well as the curing conditions are taken into account. It is intended that the results from the composite theoretical work should give inspiration for the development of the numerical model.

## Numerical maerial model

The objective of the numerical material model is to include creep, shrinkage and temperature influences in stress calculations. This model is incremental in order to facilitate the inclusion of the model into a numerical finite element calculation.

The number of parameters describing the material models is limited as far as possible in order to avoid several sets of parameters fitting the same data. This is achieved by using parameters that can be related to the measured parameters, e.g. the modulus of elasticity.

The influence of temperature on young concrete is governed by several activation energies. This is illustrated by the creep/relaxation phenomenon at early ages. The creep properties are changing due to the continued hydration and the influence of temperature on the rate of change is given by the activation energy for the hydration process. The rate of creep/relaxation is governed by a local diffusion process, and the influence of temperature is characterized by another activation energy. In the case of autogenous shrinkage a similar characterization with different activation energies is possible.

Different activation energies at an early age are not considered in the present numerical models.

# 7. Phase 5 - Documentation of models /Test frame

In this phase, strains and stresses are measured in a concrete cylinder placed in a test frame and subjected to both creep/autogenous shrinkage, load caused by a temperature variation during the hardening period and an external load. The results are compared with results from calculations based on the established material models.

As part of the work in this phase, a one-dimensional test frame is developed which shall make it possible to simulate any one-dimensional stress-strain process. It must be possible to apply compressive as well as tensile loads to the test specimen, just as it must be possible to maintain a fixed deformation (relaxation test). The temperature in the test specimen must be controlled in order to simulate relevant curing temperatures.

The work on the development of the test frame is coordinated with the work in phase 3 - "Creep of concrete" and phase 4 - "Establishment of model".

Tests are performed to document whether the numerical models lead to reasonable calculated results compared to the measured results.

The experience gained from the work in phases 3, 4 and 5 can be used to prepare a sketch proposal for the design of a two-dimensional test frame.

# 8. Phase 6 - Documentation of the model for alternative concrete

When a satisfactory correlation between calculated results and test results from phase 5 has been obtained the prepared test programme and the calculation models are tested on an alternative concrete with a significantly different mix design.

All necessary material parameters are determined by DTI corresponding to the suggested test programme from phase 4. A test similar to those in phase 5 is carried out at BKM. If a satisfactory agreement is obtained, the material models and the test programme are considered to be sufficiently well-defined for concretes similar to the tested concretes.

# 9. Phase 7 - "Full Scale" laboratory tests

When a concrete wall is cast on a hardened concrete foundation there is a risk of crack formation if the curing process has not been planned and controlled correctly. Such planning may be based on finite-element calculations of the distribution of temperature and stress in the structure.

The material parameters of strength, E-modulus, coefficient of thermal expansion, shrinkage and creep used for this calculation are based on results from one-dimensional tests. These parameters are used for the finite-element calculation of multi-dimensional structures. The Poisson ratio partly takes into account the difference between one-dimensional and multi-dimensional structures.

By means of full-scale tests under laboratory conditions at the Concrete Centre it is determined how accurately calculations can predict the actual behaviour of the structure.

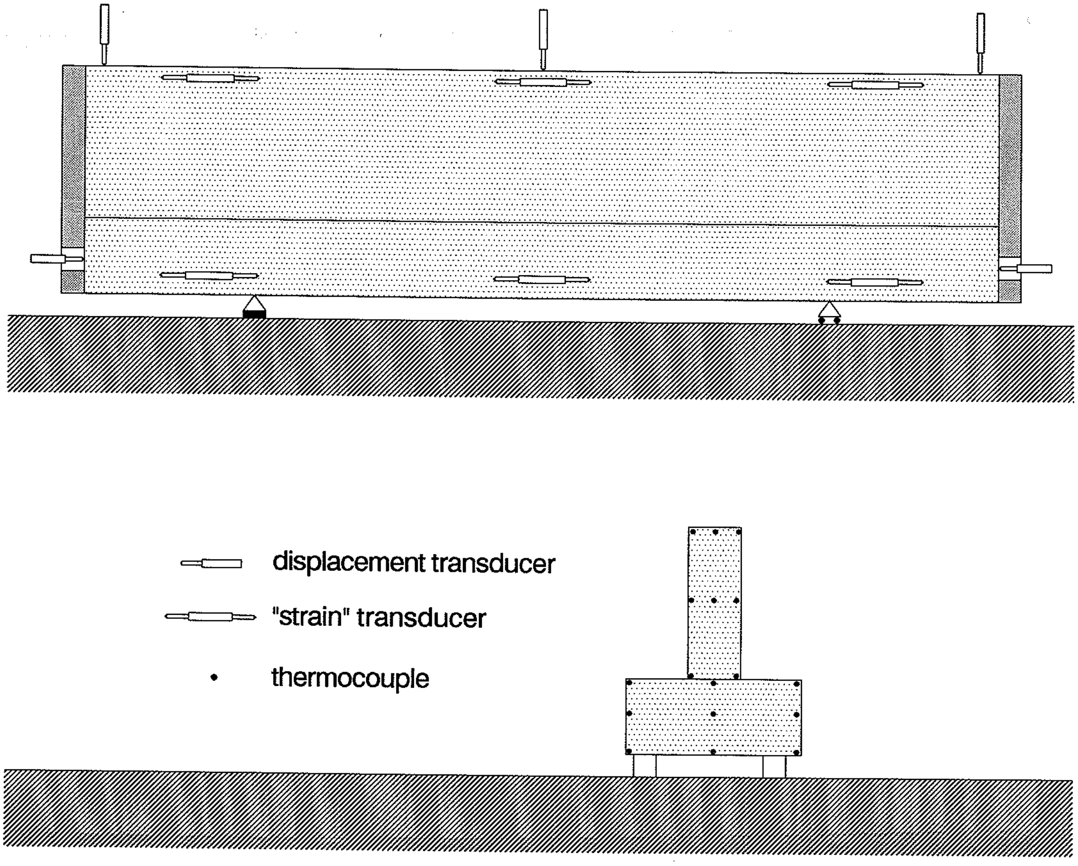
This is carried out in the test set-up sketched in Figure 1. An approximately 8 x 1 x 0.5 m foundation is cast on the floor. The support is arranged in such a way that the foundation can be supported along two lines after hardening. In this way the support conditions are well-defined.

When the foundation has achieved sufficient strength, the two line supports are established and the wall is cast on top of the foundation. The end surfaces of the structure are insulated in order to achieve approximately equal temperature distributions throughout the length. After the casting of the wall, temperatures in the foundation and the wall are measured as well as a number of deformations and strains. The results can be compared with the corresponding calculated strains and deformations.

During the detailed planning of the individual tests it will be decided when crack formation is intended during the period of hardening. Crack formation can be used to determine the ratio between the calculated tensile stress and the tensile strength at the time of cracking. The formation of cracks can be used in the investigations in phase 9 concerning prediction of crack formation/crack widths.

A typical crack in such a structure is generated at the bottom of the cast-on wall. It is likely that cracking can be detected by measurement of the strains and deformations, but it should also be attempted to detect cracking by measuring acoustic emission.

*Figure 1: Test set-up for full-scale test*



In the test set-up an external force can be applied to produce cracking if the planned cracking fails to occur. Even if the cracking is caused by an external force the ratio between the calculated tensile stress and the tensile strength at the time of cracking can still be determined.

If the measured strains and deformations in this test correspond to the calculated values, the test will document that the calculation programme reflects the behaviour of the actual structure when the support conditions are well-defined.

# 10. Phase 8 - Interaction with subsoil

In a finite-element calculation, the support conditions shall be defined, but this cannot be done unambiguously. The explanation is the following: If a foundation is cast on a base the foundation will try to expand axially because of the development of hydration heat. If there is no friction with the subsoil, such expansion can take place freely without generation of stresses. If the friction is infinitely high, the foundation cannot expand and compressive stresses will be generated in the foundation during heating and tensile stresses during cooling. The magnitude of the actual friction against the base is of course unknown.

Similarly, the structure will try to bend if there is a temperature difference between top and bottom. For a structure that is long compared to the cross- sectional dimensions, this is possible only near the ends of the structure.

In collaboration with the contractors of FV, typical structures are selected. These structures shall be representative for the type of structures where stress calculations are relevant. By means of measurements of temperatures, strains and deformations on site it will be analysed how the structure moves on the subsoil. Measurements are made on the different types of structure, both at the ends and at the middle of the structure. By a comparison of deformations and strains at the ends and at the middle of the structure, an indication of the restraining effect of the subsoil is obtained.

If possible, a structure that consists of a long foundation on which a wall will be cast later is selected for the first measurement. Measurements are started immediately after casting. The principle of the measurement is almost the same as shown in Figure 1 for the laboratory tests. Strains are measured at both ends and at the middle of the structure. This principles for strain measurement were developed and tested in 1995 and therefore the system is ready for use in this project. Also displacements are measured at both ends.

The results of the measurements form the basis of an assessment of the restraining effect given by the subsoil. The measurements of displacements at the ends of the base show the length change to which the structure is subjected. This change of length is compared to the change that corresponds to the temperature dependent change of length that would take place if it could take place freely (average change of temperature x length x coefficient of thermal expansion). If the changes in length are approximately equal, it means that the restraining effect of the base does not influence the stresses. The strain measurements at the middle and at the ends will reveal the same thing provided the measured strain at the middle is approximately equal to those at the ends.

Based on an analysis of the results, a number of additional structures to be investigated are selected. It is expected that a total of 3 structures shall be investigated.

Finally, guidelines are prepared with recommendations for the modelling of the support conditions in stress calculations for different types of structure.

# 11. Phase 9 - Prediction of crack formations/crack widths

The objective of the investigations in this phase is to prepare guidelines for both the allowable tensile strength utilization if the requirement is a structure without cracks and how the cracks widths in hardening concrete structures can be calculated.

By means of stress calculations the risk of crack formation is assessed. If the requirement is a structure without cracks, it shall be documented that the calculated tensile stress at any point is lower than the corresponding tensile strength.

In case the structure is not required to be crack-free it must be documented that the cracks will not be too wide. There exist crack formulas which predict the crack width as a function of reinforcement stress, reinforcement dimension and amount, cover, etc.

Experience shows that the calculated crack widths in hardened concrete structures exposed to a static load are subject to a wide margin of error. It is to be expected that the crack widths in hardening structures exposed to thermal stresses are subject to an even greater margin of error.

In this phase of the project a number of present and previous projects in which the contractors and consultants of FV have been involved are analysed. The results from the stress calculations are compared to the observations of crack formation and crack widths. Reliable data on the concrete properties, including shrinkage and creep, are needed for the structures selected. Furthermore, the crack observations from the full-scale testing in phase 7 will be included.