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Creep and Shrinkage of High-Strength Concrete; A testreport

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Creep and shrinkage of high-strength-concrete

A test report

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Preface

This test report is a part of the research project "High-Performance Concretes in the 90's". The report concerns the experimental part of the research sub-project "Creep and Shrinkage of High-Strength Concrete".

The test program is based upon the State-of-the-Art report "State-of-the-art rapport for Højstyrkebetons svind og krybning" (in Danish). The present report contains neither analysis nor conclusions.

The experiments have been conducted at the Department of Structural Engineering, Technical University of Denmark.

The Department of Construction Management placed their laboratory at my disposal during a period of two years.
The Department of Civil Engineering Building Materials Laboratory placed some of their equipment at my disposal for the short-time loading testperiod.
I would like to express my gratitude to all involved departments for their support making this project become a reality and to the staff at the Department of Structural Engineering for their work.

I thank Matthew Bloomstine and Karin Kaderková who revised the manuscript.

A special thank is offered to partly Per Kastrup Nielsen who conducted some of the tests, and partly Michael Birk Jensen and Johannes Sand Poulsen who conducted the main part of the creep/shrinkage deformation measurements. They have conducted their job with an inspiring devotion.

March 1992 Henrik Elgaard Jensen

I. Abstract

The research project has been carried out as a Ph.D. study at the Department of Structural Engineering, Technical University of Denmark. The supervisor of the Ph.D. study has been Professor Dr. techn. Mogens Peter Nielsen.

The Ph.D. Thesis consist of 3 theses performed during the period of the Ph.D. study:

1. State-of-the-art rapport for Højstyrkebetons svind og krybning.
2. Creep and Shrinkage of High-Strength Concrete; A Test Report. + Appendices A-D.
3. Creep and Shrinkage of High-Strength Concrete; An Analysis.

1. State-of-the-art rapport for Højstyrkebetons svind og krybning.

The report deals briefly with the concepts and models which are used in relation to shrinkage and creep of concrete.
Different kinds of test-equipment are evaluated for usage in the experimental part of the project.
A review of the ingredients which are used to produce a high-strength concrete and the influence of these ingredients on shrinkage and creep of concrete, are obtained by references to tests reported in the literature.

2. Creep and Shrinkage of High-Strength Concrete; A Test Report. + Appendices A-D.

The investigation deals with some time-dependent mechanical properties of seven different concretes. The time-dependent properties are shrinkage, uniaxial-creep and aging. The compressive strength of the seven concretes vary from 10 Mpa to 100 Mpa.
The concretes are exposed to drying at a temperature of 21 °C and a relative humidity of 65 % after 28 days of water curing. The stress/strength ratio is 1/3 in the creep tests.
Three of the seven concretes are investigated further. The compressive strength of the three

concretes is 15, 80 and 100 MPa.
The stress/strength ratio is varied from 0.4 to 0.7 for the three concretes in different creep tests. The three concretes are also investigated under sealed conditions, and after a water curing period of 7 days.
The pastes of the 80 and 100 MPa concretes are investigated as well, and creep recovery of the three concretes are studied.
The period of measuring is at least 11 month for all tests.

3. Creep and Shrinkage of High-Strength Concrete; An Analysis.

This is a qualitative analysis of the test results presented in the test report. The analysis concerns a qualitative evaluation of the general mechanical properties and the time-dependent mechanical properties shrinkage, creep, weight-loss, development of strength/stiffness, age at loading, stress/strength ratio, microcracking, drying creep, static-fatigue and creep recovery. Based upon the analysis it is demonstrated that high-strength/high-performance concrete, containing microsilica fume and/or fly-ash and plasticizer, is not a new material with respect to the investigated properties.
The investigated concretes exhibit mechanical properties which comply with existing knowledge of the mechanisms of creep and shrinkage.
To avoid misinterpretations related to test conditions, the test results are evaluated quantitatively in relation to the "CEB-FIP modelcode 1990". The modelcode is used as a mathematical standard of test evaluation, as the CEB-FIP modelcode 1990 is calibrated by means of a computerized data bank to fit several shrinkage and creep laboratory tests.

Keywords: Drying creep, basic creep, shrinkage, aging, testing, high-strength concrete, high stress/strength-level, creep recovery.

I. Resumé

Forskningsprojektet er gennemført som et licentiat studium på Afdelingen for Bærende Konstruktioner, Danmarks tekniske Højskole. Licentiat studiets vejleder har været Professor Dr. Techn. Mogens Peter Nielsen.

Licentiat afhandlingen består af 3 afhandlinger udført gennem licentiat studiet:

1. State-of-the-art rapport for Højstyrkebetons svind og krybning.

2. Creep and Shrinkage of High-Strength Concrete; A Test Report. + Appendices A-D.

3. Creep and Shrinkage of High-Strength Concrete; An Analysis.

1. State-of-the-art rapport for Højstyrkebetons svind og krybning.

Rapporten omhandler kort de begreber og modeller, der benyttes i forbindelse med betons svind og krybning.
Forskellige typer forsøgsudstyr er vurderet med henblik på senere brug i den eksperimentelle del af det samlede projekt.
Der gives et overblik over de ingredienser, der benyttes ved produktion af højstyrkebeton og disse ingrediensers indflydelse på betons svind- og krybeegenskaber, ved reference til forsøg indsamlet fra litteraturen om emnet.

2. Creep and Shrinkage of High-Strength Concrete; A Test Report. + Appendices A-D.

Undersøgelsen omhandler nogle tidsafhængige mekaniske egenskaber for syv forskellige betoner.
De tidsafhængige egenskaber er svind, eenakset-krybning og ældning. Trykstyrken af de syv betoner varierer fra 10 MPa til 100 MPa.
Betonerne er udsat for udtørring ved 21 °C og ved en relativ luftfugtighed på 65 % efter 28 dg. vandlagring. Spændings/styrke forholdet er 1/3 i krybeforsøgene.

Tre af betonerne er undersøgt yderligere. Trykstyrken af de tre betoner er 15, 80 og 100 MPa. Spændings/styrke forholdet er varieret fra 0.4 til 0.7 for de tre betoner i forskellige krybeforsøg. De tre betoner er også undersøgt under forseglede forhold og efter en vandlagringsperiode på 7 dage.
80 og 100 MPa betonernes pasta er ligeledes undersøgt og tilbagekrybningen er undersøgt for de tre betoner.
Måleperioden er mindst 11 måneder for alle forsøg.

3. Creep and Shrinkage of High-Strength Concrete; An Analysis.

Dette er en kvalitativ analyse af de forsøgsresultater, der er præsenteret i forsøgsrapporten. Analysen er en kvalitativ vurdering af de generelle mekaniske egenskaber og de tidsafhængige mekaniske egenskaber som svind, krybning, vægttab, udvikling af styrke/stivhed, belastningsalder, spændings/styrke forhold, mikrorevner, udtørrings krybning, langtidsstyrke og tilbagekrybning. På baggrund af analysen er det vist, at højstyrke-/højkvalitetsbeton, der indeholder mikrosilica og/eller flyveaske og plastificerende midler, ikke er et nyt materiale med hensyn til de undersøgte egenskaber.
De undersøgte betoner udviser mekaniske egenskaber, der stemmer overens med eksisterende viden om svind- og krybemekanismerne.
For at undgå fejlfortolkninger relateret til forsøgsbetingelser, er forsøgsresultaterne vurderet kvantitativt i forhold til "CEB-FIP modelcode 1990". Modelnormen er brugt som en matematisk standard til forsøgsvurdering, da CEB-FIP modelcode er kalibreret vha. en EDB data bank mht. svind og krybning bestemt ved laboratorieforsøg.

Nøgleord: Udtørringskrybning, grundkrybning, svind, ældning, forsøg, højstyrke beton, højt spændings/styrke niveau, tilbagekrybning.

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VII. Table of symbols

ϵ	Strain
ϵ_{σ}	Strain at the corresponding creep stress-level
ϵ_0	Initial strain
ϵ_{cr}	Creep strain
ϵ_{sh}	Shrinkage strain
ϵ_{total}	Total strain
$\mu\epsilon$	Micro strain
ρ	Density
σ	Stress
φ	Creep coefficient
c	Specific creep
d	Specific deformation
E	Elastic-modulus
E_{dyn}	Dynamic modulus
f_c	Compressive strength
f_{c0}	Compressive strength at the time of creep-loading
f_y	Yield stress
k_{GF}	Gauge-factor for transformation of Electrical Resistance Strain Gauge
l	Length
l_g	Gauge length
t	Time
t_0	Age at loading
U	Potential

Subscripts

I-III	Creep specimen numbers
IV-VI	Shrinkage specimen numbers
mean	Average values
measured	Measured values

Shortenings

DL	Dead-load creep rig
ERSG	Electrical Resistance Strain Gauge
MSG	Mechanical Strain Gauge
PC	Personal Computer
SL	Spring-loaded creep rig

1 INTRODUCTION

Studying concrete shrinkage and creep is one of the most complicated subjects of the concrete technology.
Shrinkage and creep of concrete are dependent on the age at loading, the humidity and temperature of the evironment, the stress/strength ratio, the cement type, the amount of aggregate, the strength, the specimen size etc. etc.
The common knowledge of the time-dependent mechanical properties is based upon experimental results of low- and normal-strength concrete (10 to 35 MPa). The strength range 10-35 MPa is a quite narrow testing range.

High-strength/high-performance concretes are used more and more in structural engineering despite of the still quite scarce knowledge of the time-dependent properties.
High-strength concrete is not just a new material of which wee need to investigate the mechanical properties for use in structural engineering, but in fact also a material which expands our test range to 10-100 MPa.

The scope of this experimental investigation is to provide the necessary experimental evidence for a better understanding of the phenomenon shrinkage and creep of concrete.

The objective is achieved by investigating seven different concretes which covers the strength range 10-100 MPa. The high-strength is achieved by the use of plasticizer, superplasticizer and microsilica.
The seven concretes are ordinary concretes for structural use. The amount of aggregate is approximately constant for all seven concretes. The pastes of two concretes are investigated and the aggregate is assumed to have time-independent properties.
The seven concretes are investigated under a set of basic test conditions which remain the same for all seven concretes during the test period. These seven tests form the basis of the investigation.

Three of the seven concretes are investigated more intensively by changing only one of the basic test conditions.
The stress/strength ratios of 0.4, 0.5, 0.6 and 0.7 are studied to find, if any, the limit of linearity between stress and creep strain.
Three tests are conducted under sealed (restrained evaporation) conditions to investigate the basic shrinkage and basic creep.
The influence of the age at loading is studied for the three concretes and creep recovery too.

A lot of the experimental investigations reported in the literature concerning high-strength concrete cover a shrinkage and creep period of only 3-4 months. In this investigation the shrinkage and the creep period is at least 11 months.

Each test serie is identified by a number. The number consists of the date and year of casting and a serial number. The serial numbers are presented in Table 1.1 in relation to the test program.

Table 1.1 Test program Number of tests are 30

Mix number →	1	2	3	4	5	6	7
Standard test conditions*	1	3	2	25	7	11	26
Sealed		4			8	12	
$\sigma/f_c = 0.4$		5			16	13	
$\sigma/f_c = 0.5$		6			17	20	
$\sigma/f_c = 0.6$		24			19	21	
$\sigma/f_c = 0.7$		9			22	33	
Recovery		29			28	27	
$t_0 = 8$ days		31			32	30	
Paste					39	38	

* The standard test conditions are :

65 % RH
21 °C
Loading after 1 day in the mould, 26 days of water curing and 2 days of preparation (air curing)
$\sigma/f_c = 1/3$

2 TEST RIGS

This section deals with the 30 testrigs used in the investigation. For this investigation two different creep-test rigs are used. 8 dead-load lever arm and 22 spring-loaded rigs are used.

2.1 General remarks

In both types of test rigs 3 cylindrical specimens size Ø 100 x 200 are examined. The 3 specimens are placed on top of each other. The top-specimen is denoted I and the bottom-specimen is denoted III. The specimen in between specimen I and III is denoted II.
At the top of specimen I and underneath specimen III dummy-specimens are placed between the specimens examined and the load plates of the test rig. The purpose of the dummy-specimens are to provide equal boundary conditions for all 3 specimens.
For high σ/f_c-levels fiber boards are used between the specimens to avoid failure.
The creep-rigs are designed to require as little maintenance as possible during the investigation.

2.2 Dead-load lever arm creep rig

The dead-load lever arm rig (DL) has a lever arm ratio of 20:1. The DL-rig has been used for previous investigations. The specimen size was Ø 100 x 200 mm. For this investigation the DL-rigs are modified. The specimen size is now Ø 100 x 720 mm.
Before loading the specimens in the DL-rig, the necessary dead-load needed to provide the force which satisfies the wanted stress/strength-level (σ/f_c) is determined by means of a load cell for each particular DL-rig.
The lever arm is hooked to a movable hydraulic crane. The hydraulic crane makes it possible to satisfy the required loading speed.
The DL-rigs have been designed for a stress-range of 0 to 10 MPa. The DL-rig is shown in Figure 2.1 and Figure 2.2.

2.3 Spring-loaded creep rig

For stress-levels exceeding 10 MPa a spring-loaded (SL) rig is designed for this investigation.

Four SL-rigs are designed for stress-levels ranging from 10 to 21 MPa, 21 to 33 MPa, 33 to 46 MPa and finally 46 to 83 MPa. The basic design for all four SL-rigs is the same. The dimensions are the only variables. The SL-rig is shown in Figure 2.3 and in Figure 2.4.
The springs are combinations of disc springs which are combined in four stacks for each SL-rig. The number of disc springs in each stack varies from 4 to 21. A combination of disc springs is shown in Figure 2.5. The combinations of disc-springs provide a deformation of approximately 10 mm at the wanted load-level.
The SL-rig is loaded in a 2000 kN hydraulic jack to satisfy the required loading speed. Each SL-rig has a dynamometer which is used to determine the load level at all times.
For maintenance of the wanted load-level a hydraulic momentum jack is used, see Figure 4.1.

3 MEASURING EQUIPMENT

This chapter deals with the primary test equipment used for the investigation. The test equipment is Electrical Resistance Strain Gauge, Mechanical Strain Gauge, Weight, Dynamometers, Strain indicator and Ultra-sonic equipment.

3.1 Electrical Resistance Strain Gauge

Measuring concrete strains during a period less than 3 hours is done by means of Electrical Resistance Strain Gauge (ERSG). ERSGs are glued to the surface of the concrete specimens. The ERSG is a chrome-nickel alloy 15 μm thread. The gauge length is 88-89 mm. The ERSG is instrumented as a 600 Ω ¼-bridge. The accuracy is ± 20 $\mu\epsilon$. The gauge range is 4000 $\mu\epsilon$. The gauge factor $k_{GF} = 2.27$. Measurements are registered either by a 4-pen plotter or a datalogger connected to a personal computer (PC).

3.2 Mechanical Strain Gauge

For determination of strains during a period exceeding 3 hours a mechanical strain gauge (MSG) is used. The MSG is a direct-contact pfender-gauge. The gauge-length is 100 mm and the gauge range is ± 0.5 mm. The accuracy is 2 μm. These specifications provide a strain range of ± 5000 $\mu\epsilon$ and an accuracy of ± 20 $\mu\epsilon$. The MSG has a companion fixed gauge-length for verification of the zero-values. Each time the MSG is used the fixed gauge-length is measured to verify the MSG, and the zero-values.
At the end of the testing period the pfender-gauge has been replaced by another pfender-gauge. The discrepancy between the two instruments has been determined by a standard calibration by means of the fixed companion gauge-length.

Physically the MSG measures the distance between two individually fixed steel-balls. The steel-balls fit into two grips on the MSG. One grip is fixed and the other one is movable. The steel-balls are fixed into brass-screws by deforming the brass. These gauge-screws are glued to the concrete surface by a two component glue (X60).

In some tests the strains are larger than 5000 $\mu\epsilon$. Before the gauge-range is exceeded a measurement is conducted. After the measurement one of the original gauge-screws is replaced and another measurement is performed.

3.3 The weight

The weight is a SARTORIUS 4-SA-B6100. The Range is 0-6100 g. The accuracy is ± 0.05 g.

3.4 Dynamometers (load cells)

Each spring-loaded creep rig has a dynamometer which registers the force applied to the concrete specimens. The dynamometers are designed in the way that the stress in the dynamometers does not exceed 75 % of the yield-stress, $0.75 \cdot f_y$.
Each dynamometer is instrumented by 4 HBM LY-11-6-120 ERSGs in full-bridge. Two ERSGs register the longitudinal strain and the other two ERSGs register the transverse strain. This instrumentation makes the dynamometer independent of the temperature. Further more 8 steel-balls for 4 MSG are attached to each dynamometer at an angle of 90° to the circumference.
Each dynamometer has been calibrated in either a 600 kN hydraulic jack or a 2000 kN hydraulic jack. For calibration a 200 kN or a 900 kN calibration-loadcell is used. Before the calibration is started each dynamometer is loaded 3 times to approximately 120 % of the maximum calibration load to avoid creep of the steel.
Calibration is repeated 3 times. The coherence between force and the strain indicator outputs are registered in steps of 10 % of the maximum calibration load.

3.5 Strain indicator

For determination of the force during loading/unloading and the weekly control of the load-level a strain indicator is used. The strain indicator is a BUD. The strain indicator has a digital display and a analog DC output port. The digital display is used during loading/unloading, tightening of the nuts and weekly maintenance of the load-level. The analog DC output port is used to register the force during loading/unloading by means of a datalogger and PC. A fixed full-bridge resistance has been made to maintain a fixed zero-point value.

3.6 Ultrasonic measurement

Ultrasonic measurements on the concrete specimens are determined by means of a PUNDIT ultrasonic non-destructive digital indicating tester.
The transducers are 54 kHZ type. The accuracy is $\pm 0{,}5$ %. A reference block is used before each measurement to fix the zero-value.

4 PROCEDURE OF DETERMINATION OF MATERIALS CHARACTERISTICS

This chapter deals with the procedures wanted and used to determine the desired materials characteristics. The procedures described are the loading speed, the determination of the compressive strength, the intervals of time-dependent measurements, the intervals of determination of the strength/stiffness development, the maintenance of the wanted load-level and finally the strength/stiffness development.

4.1 Loadspeed

The loading and unloading speed is kept constant at 0,6 MPa/sec for all kinds of tests where the load is changed significantly i.e. not during the periodic maintenance of the load-level of the SL-creep rigs.
The loading speed is kept constant at 0,6 MPa/sec $\pm$ 0,05 MPa/sec for determination of concrete compressive strength at all times.
The loading speed is kept constant at 0,6 MPa/sec $\pm$ 0,2 MPa/sec for loading and unloading of the creep rigs.

To provide a loading- and unloading speed of 0,6 MPa/sec at the spring-loaded creep rigs a 2000 kN hydraulic jack is used. The top- and bottom loadplates of the jack are fixed.
The spring-loaded creep rigs are placed at the center of the bottom loadplate of the jack. The concrete specimens are in the creep rig. On the topplate of the creep rig a Ø 80 x 250 mm steel cylinder is placed. The steel cylinder is centered at the top loadplate of the jack. This way the concrete specimens are loaded by the jack through the steel cylinder and through the spring and dynamometer Figure 4.2
The creep rigs are loaded to the wanted load-level by the jack. The load-level is kept constant for approximately 5 minutes and is then decreased by 2 %. After decrease of the load-level each of the 4 tierods of the creep rigs are loaded by 1 % of the wanted load-level. The tierods are loaded by tightening the nuts by means of a hydraulic momentum jack Figure 4.3. When all 4 tierods have been loaded the load-level at the concrete specimens is increased by 2 % in relation to the wanted load-level. The load-level is then decreased by 4 % of the wanted load-level and the nuts of the tierods are tightened again. This procedure is repeated until the 2000 kN jack does not provide any load on the creep rig through the steel cylinder. The load-level is then kept constant by the tierods and the creep rig can be removed from the 2000 kN jack and transported to the climate tent. The procedure is conducted the opposite way for unloading.

This load procedure keeps the load-level constant at the wanted load-level ± 2 %.

4.2 Determination of the concrete compressive strength

The compressive strength of the concrete at the time of loading (f_{c0}) for creep test is determined by crushing a number of 5 cylindrical Ø 100 x 200 mm specimens in a 2000 kN servo hydraulic jack. The accuracy of the jack is 2 %. The bottom loadplate of the 2000 kN jack is fixed and the top loadplate is able to rotate.
Between the loadplates of the jack and the concrete specimen fiber boards are placed.
The specimens are loaded until failure by a constant loadspeed of 0,6 MPa/sec. The average concrete compressive strength at the time of loading for creep tests are listed in appendix A Table A.4.1

4.3 Strength/stiffness development

The development of mechanical properties of the concretes are determined by crushing 3 cylinders Ø 100 x 200 mm in a 2000 kN servo hydraulic jack. The specimens have been cured and exposed to the same environmental conditions as the creep- and shrinkage specimens.
The strains are measured by means of ERSGs and the measurements are registered by a 4 pen-plotter. The strength/stiffness specimens are loaded to failure by a constant loading speed of 0,6 MPa/sec. Fiber boards are used in the same way as for determination of the concrete compressive strength. Strength and strains are listed in Appendix A Table A.5.1 - A.5.39.

4.4 Intervals of time-dependent measurements

Total deformation (short-time deformation measurements). During loading/unloading the total deformations (ϵ_{total}) of the creep specimens are measured by means of ERSGs each sec. until approximately 5 minutes after reaching the wanted load-level. The amount of measurements per time unit is decreased to 2-3 measurements per minute. Later the number of measurements is decreased further to one measurement per 5 minutes.
After 1 to 3 hours the acquisition of measurements by means of ERSGs is stopped and the creep rig is transported to the climate tent.
Total- and shrinkage deformation (long-time deformation measurements). Long-time

measurements are measured by means of MSG. Long-time deformation measurements include creep- and shrinkage specimens. The weightloss of the shrinkage specimens is determined at the same time as the long-time deformations.
Long-time measurements start 2-4 hours after loading/unloading. The measurements are conducted each day for the first 7 days after loading/unloading. After 7 days the measurements are conducted once a week for the next 4 weeks. Measurements are conducted once a month during a period of at least 6 month, whereafter the measurements are conducted 1 year (8760 hours) after loading. 1 year is the wanted loading period for this investigation.

4.5 Intervals of determination of the strength/stiffness development

The development of strength and stiffness is determined 1 month, 2 months, 4 months and 6 months after determination of the 28 days strength.
The concretes which are loaded for creep tests after 6 days of curing follow the same time intervals after determination of the 28 days strength 3 weeks after the loading.
The investigation of strength and stiffness development is terminated when the development of the mechanical properties is assumed to have stopped. The Tables A.5.1 - A.5.39 in Appendix A show empty boxes which indicate the number of series of 3 specimens which have not been tested.

4.6 Maintenance of the wanted load-level of the spring-loaded creep rigs

The disadvantage of the spring-loaded creep rig is the decrease of the load-level caused by the creep of the concrete.
The load-level is maintained by regular control and adjustment of the load-level. The load-level is adjusted by means of a hydraulic momentum jack, see Figure 4.1.
The force subjected to the dynamometer in each creep rig is measured once a week. When the load-level has decreased 2 % in relation to the wanted load-level, the load-level is increased by 4 % to a load-level which is 2 % higher than the wanted load-level.
During the creep period the slope of the creep-time curve decreases. The consequence of this decrease is that the load-level rather seldom has to be adjusted. Because of the scarce adjustment the requirements for adjustments are decreased after a period from 2 % to 1 % of the wanted load-level.

5 TEST PROCEDURE

This chapter concerns the complete testing procedure in chronological order.

The water curing period is 26 days or 5 days. The period of preparation of the specimens are 2 days. Approximately 12 hours after the specimens have been removed from the water curing basin and they were ground at both ends by a lapidary mill. One specimen is cut into 3 parts. The mid-section is used as a lid during the storing of the shrinkage specimens which are stored on top of each other. The end-section parts are ground at both ends. The end-section parts have the dimensions Ø 100 x 60 mm. The end-section parts are used as dummies in the creep test to achieve satisfying boundary conditions.
After the grinding the specimens are sandblasted at the circular surface to make a sound base for gluing at the surface of the concrete specimens.
After sandblasting ERSGs and MSG gauge-screws are glued to the surface of the specimens. The glue is hardened for at least 12 hours.
On the day of the creep testing the concrete compressive strength is determined and the required load is determined to satisfy the wanted stress/strength ratio (σ/f_c).
Ultrasonic test is performed for the six creep- and shrinkage specimens. The weight of the six specimens is determined and the ends of the specimens are sealed by two layers of aluminum foil.
The creep specimens are placed in the creep rig. ERSGs are connected to the datalogger.
A zero-measurement of the ERSG is conducted and saved on the computer. A zero-measurement of the MSG is conducted and automatic acquisition of ERSGs measurements is started. The load is increased to the wanted load-level.
For the spring-loaded creep rigs the tightening of the nuts is performed after approximately 5 minutes. After 2-4 hours measurements of the MSG is performed and the automatic acquisition of ERSGs measurements are stopped. The spring-loaded creep rig is transported to the climate tent. Recovery tests are conducted in the opposite way as described above.
The measurements continue as described in section 4.4. The development of the mechanical properties are investigated during the load period and described in section 4.5.
Non-recovery tests are unloaded after 1 year and the weightloss of the shrinkage and creep specimens are determined.

6 MIX PROPORTIONS

Cements	Cement 1 :	PC(R); ASTM type III. Used for mix no. 1, 2, 3, 4 and 7
	Cement 2 :	PC(A/L/S); ASTM type IV-V. Used for mix no. 5
	Cement 3 :	PC(R/L/S/H); ASTM type III-IV. Used for mix no. 6
Fly-ash	Surplus product from the coal fired power-plant Amagerværket. Density assumed to be 2200 kg/m³	
Microsilica-slurry	Density 1391 kg/m³. Dry matter 51.6 %.	
Sand (0-4 mm)	Density 2567 kg/m³. Marine deposits.	
Gravel (4-8 mm)	Density 2627 kg/m³. Marine deposits.	
Granite (4-16 mm)	Density 2735 kg/m³. Crushed granite.	
Water	Ordinary tap water.	
Plasticizer	Density 1170 kg/m³. Dry matter 36.0 %. Conplast 212 is a lignosulfonat based plasticizer.	
Superplasticizer	Density 1210 kg/m³. Dry matter 34.0 %. Peramin is a melamin based superplasticizer.	

The mix proportions are presented in appendix A Table A.2.1. Declaration for the admixture is presented in appendix C. The grading of the aggregate for the 7 mixes is presented in appendix C.

The concretes are mixed in a 500 l paddle mixer in a batch of 100 l. The aggregate is dry mixed for some minutes. Cement and fly-ash are added and are dry mixed for another few minutes. Plasticizer, superplasticizer are mixed with the tap water and hereafter mixed with the microsilica-slurry. The mixed water and admixture is added to the paddle mixer. The mix-time after adding water is 3 minutes.

The slump is determined just after the mixing. 27 cylinders Ø 100 x 200 mm are casted in polystyrene mould at a vibration table. After the casting the density of the fresh concrete and the air content is determined. The air-content is determined by means of a pressure-meter. Approximately 24 hours after casting the specimens are demoulded and cured in water at 20° until preparation for testing.

7 TIME-DEPENDENT MEASUREMENTS

This chapter concerns the measurements: Weight, Dynamic E-modulus, Short-time creep, Long-time creep- and shrinkage, compressive strength and development of strength and stiffness.

The weight of the 3 creep- (I-III) and 3 shrinkage (IV-VI) specimens is determined before loading and after unloading. The weight is determined for the 3 shrinkage specimens during the test period.

For deriving the *dynamic E-modulus* and for quality check *ultrasonic tests* are conducted on the 6 specimens (I-VI). The ultrasonic transducers are held against the ends of the 6 specimens. The ends of the 6 specimens are covered with a thin layer of grease to make a sound base for the transmission.

The short-time total deformations of each creep-specimen (I-III) are determined by 4 ERSGs glued to the surface of the concrete in an angle of 90° of the circumference. The ERSGs mesure the strains in the longitudinal direction, see Figure 7.1 a).

The long-time total deformations of each creep-specimen (I-III) are determined by 4 MSGs (8 gauge-screws) glued to the surface of the concrete in an angle of 90° of the circumference. The MSGs measure the strains in the longitudinal direction. The MSGs are glued at the specimens in an angle of 45° in relation to the ERSGs, see Figure 7.1 a).

The shrinkage deformations are long-time measurements i.e. shrinkage strain is determined only by MSGs. 4 MSGs are glued to the surface of the shrinkage specimens in an angle of 90° of the circumference, see Figure 7.1 b).

The characteristic compressive strength of the concrete at the time of creep-loading is determined by crushing a number of 5 cylinders Ø 100 x 200 mm. No strains are determined on these 5 cylinders.

The development of the compressive strength is determined by crushing 3 cylinders Ø 100 x 200 mm at the wanted date.

The development of the concrete stiffness is determined by 3 ERSGs glued to the surface of the concrete specimens in an angle of 120° of the circumference, see Figure 7.1 c). The strains are registered by an analog 4-pen plotter, and determined partly at the stress-level (σ) corresponding to the stress-level of the corresponding creep-specimens, and partly at one third of the compressive strength of the specific test-cylinder.

8 ENVIRONMENTAL CONDITIONS

This chapter concerns the environmental conditions under which the tests have been conducted.

The tests are performed under constant environmental conditions in a climate tent. The climate tent covers an area of 72 m^2 and surrounds a volume of 180 m^3.
The temperature is 21 °C ± 1 °C. During the summertime cooling is necessary, and in the wintertime heating is necessary. Both cooling and heating is controlled by thermostats.
The relative humidity (RH) is 65 % RH ± 5 % RH. The relative humidity is kept constant by adding steam into the tent. The steam is controlled by a hygrostat.
The temperature and the relative humidity are registered constantly by a thermo-hygrograph.
The air is circulated in the tent by the fan in the cooling equipment.

The sealing of the sealed specimens consists of 3 layers of aluminum foil and 3 layers of polystyrene foil. The quality of the sealing is checked by the weightloss.

9 DEFINITION OF TERMS

This chapter concerns the terms used and the definition of the way the test results have been derived in the appendices.

MSG strains (ϵ) are defined as the measured deformation (d) relative to the gauge-length before deformation by loading (l_g)

$$\varepsilon = \frac{d}{l_g} \qquad \{9.1\}$$

ERSG strains (ϵ) are determined by {9.2}

$$\varepsilon = 4 \cdot \frac{U_{measured}}{U \cdot k_{GF}} \qquad \{9.2\}$$

$U_{measured}$	is the registered potential
U	is the potential supplied to the gauges
k_{GF}	is the gauge-factor, k_{GF} = 2,27

The initial strain (ϵ_0) is defined as the registered strain of the creep-specimens measured by ERSGs at the very minute the wanted load-level is reached.
The E-modulus is defined as the secant E-modulus at the stress/strength-ratio of 1/3

$$E = \frac{\sigma}{\varepsilon} = \frac{f_c}{3 \cdot \varepsilon} \qquad \{9.3\}$$

The dynamic E-modulus is defined by {9.4}

$$E_{dyn} = \varrho \cdot \frac{l^2}{t^2} \qquad \{9.4\}$$

where l is the height of the concrete specimens and t is the registered transmission time. ρ is the density of the concrete.

The total strain (ϵ_{total}) is determined by {9.1} or {9.2}. The total strain is the strain observed at the creep-specimens (I-III) after loading.
The shrinkage strain (ϵ_{sh}) is the strain observed at the unloaded companion specimens (IV-VI) corresponding to the creep-specimens. ϵ_{sh} is defined as in {9.1}.
The creep-strain (ϵ_{cr}) is defined in {9.5}
The creep-strain is not measured directly but only derived on basis of 3 measurements. In

$$\varepsilon_{cr,mean} = \varepsilon_{total,mean} - \varepsilon_0 - \varepsilon_{sh,mean} \qquad \{9.5\}$$

{9.5} ϵ_0 is a constant i.e. ageing is not accounted for. The subscript *mean* in {9.5} refers to the average values determined on 3 specimens.
The stiffness development strain (ϵ_σ) is determined as the strain of the specific concrete specimen at the stress-level corresponding to the stress-level of the corresponding creep-specimens.

The creep coefficient (φ) is defined in {9.6}

$$\varphi = \frac{\varepsilon_{cr,mean}}{\varepsilon_{0,mean}} = \frac{\varepsilon_{cr,I} + \varepsilon_{cr,II} + \varepsilon_{cr,III}}{\varepsilon_{0,I} + \varepsilon_{0,II} + \varepsilon_{0,III}} \qquad \{9.6\}$$

The specific creep (c) is defined by {9.7}

$$c = \frac{\varepsilon_{cr,mean}}{\sigma} \qquad \{9.7\}$$

where σ is the stress applied to the creep-specimens.

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11 FIGURES

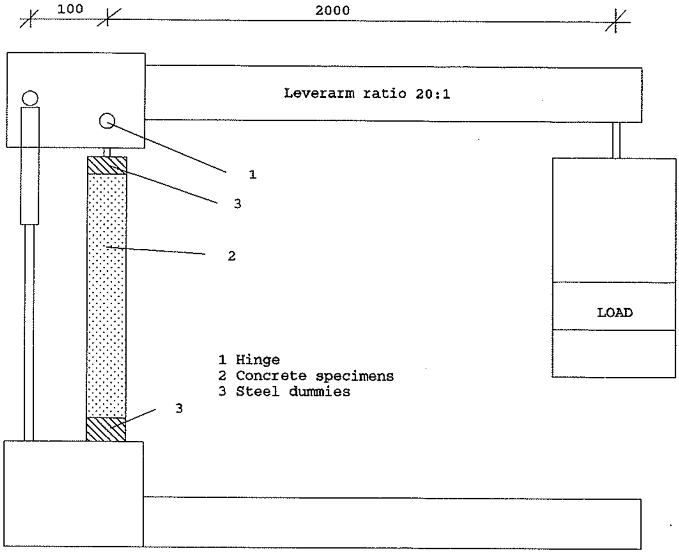

Figure 2.1 Dead-load lever arm creep rig (schematic)

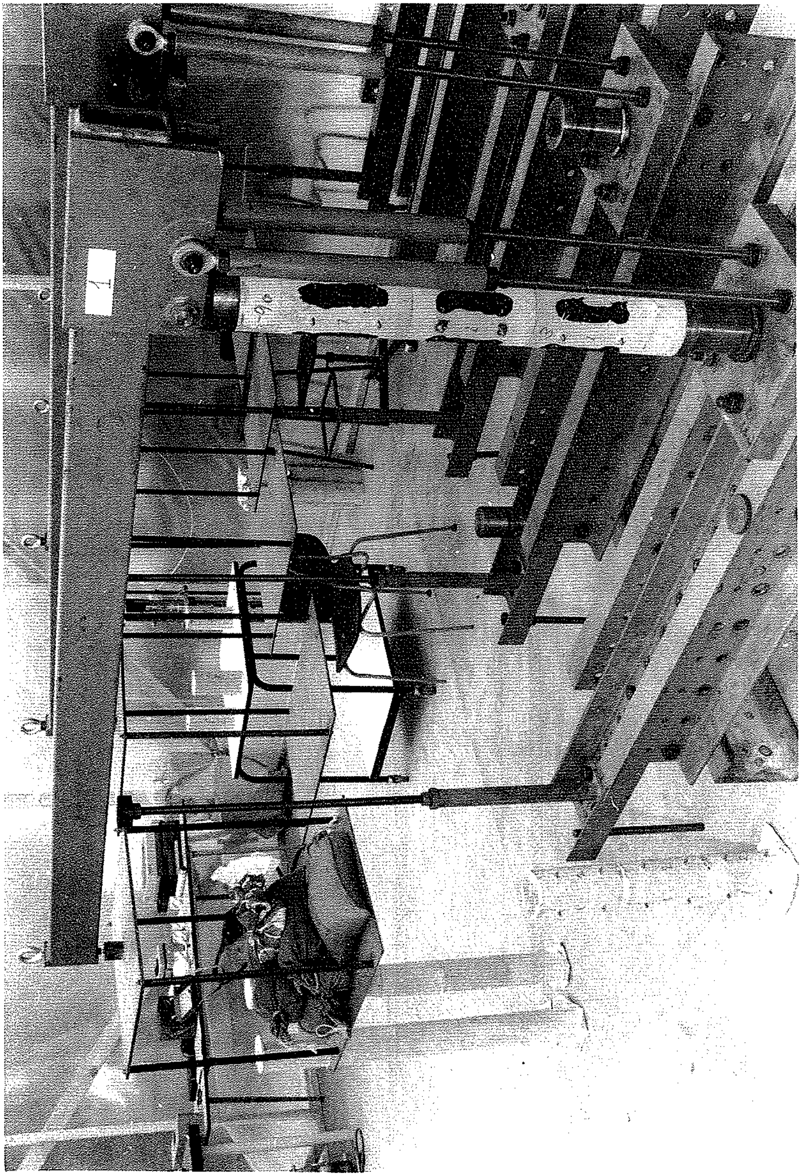

Figure 2.2 Dead-load lever arm creep rig

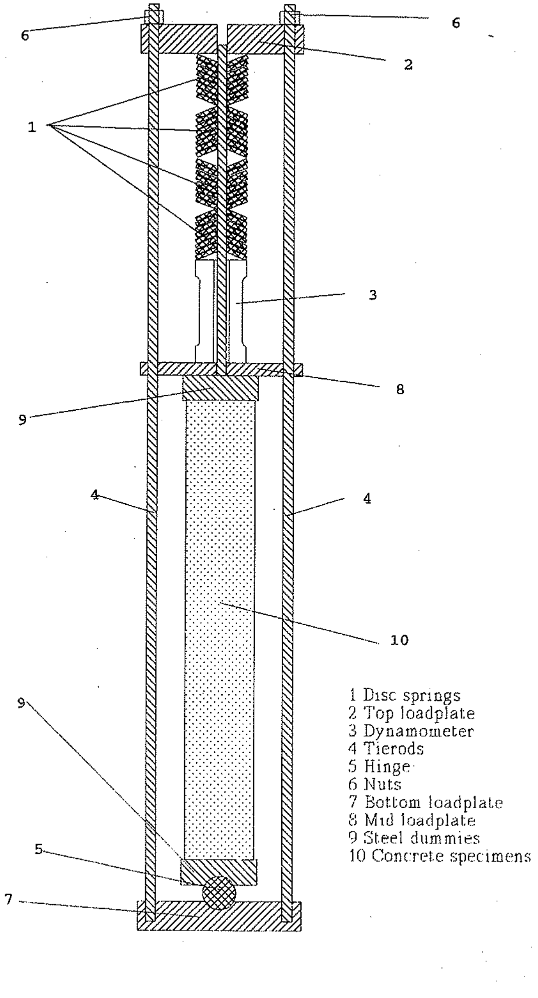

Figure 2.3 Disc spring-loaded creep rig. (Schematic)

Figure 2.4 Spring-loaded creep rigs

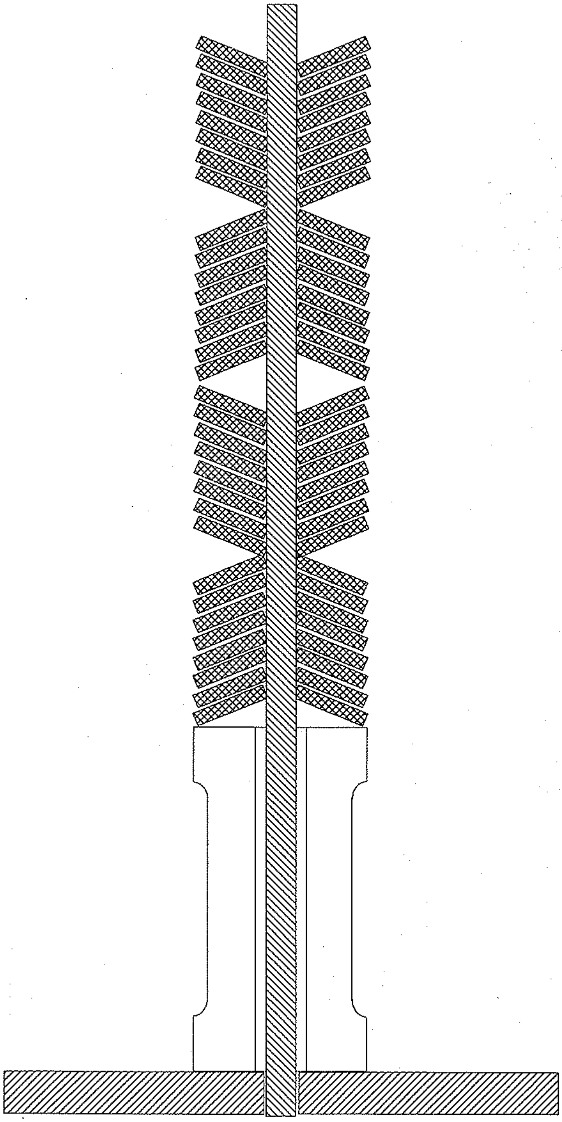

Figure 2.5 Disc-spring and dynamometer (schematic)

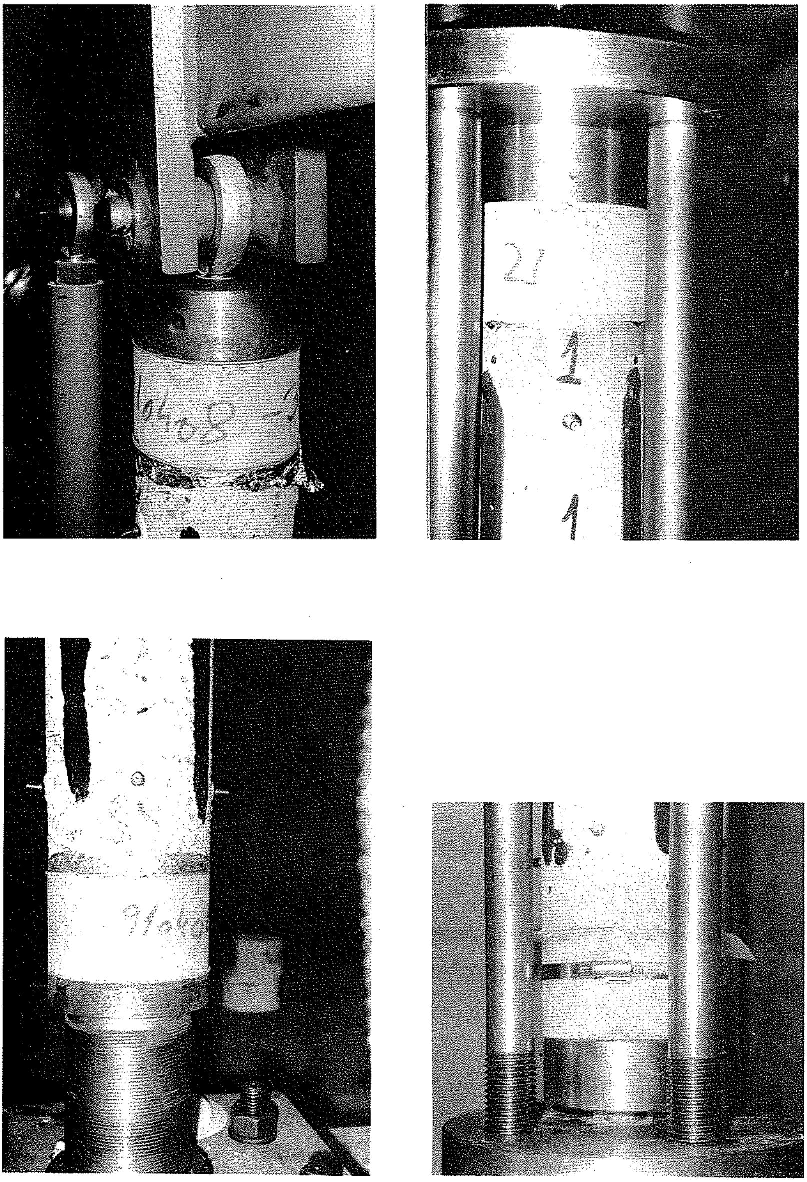

Figure 2.6 Boundary conditions for the two test rigs.

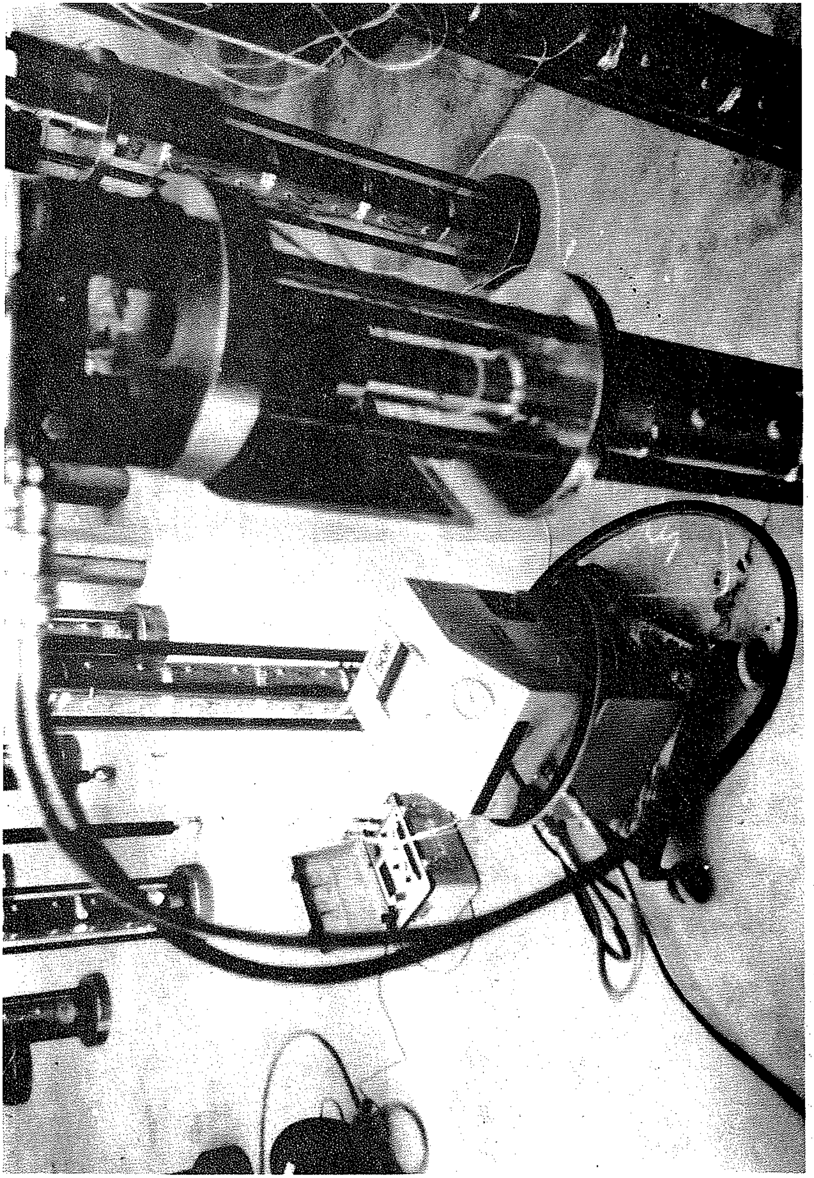

Figure 4.1 Hydraulic momentum jack for maintenance of the prescribed loadlevel.

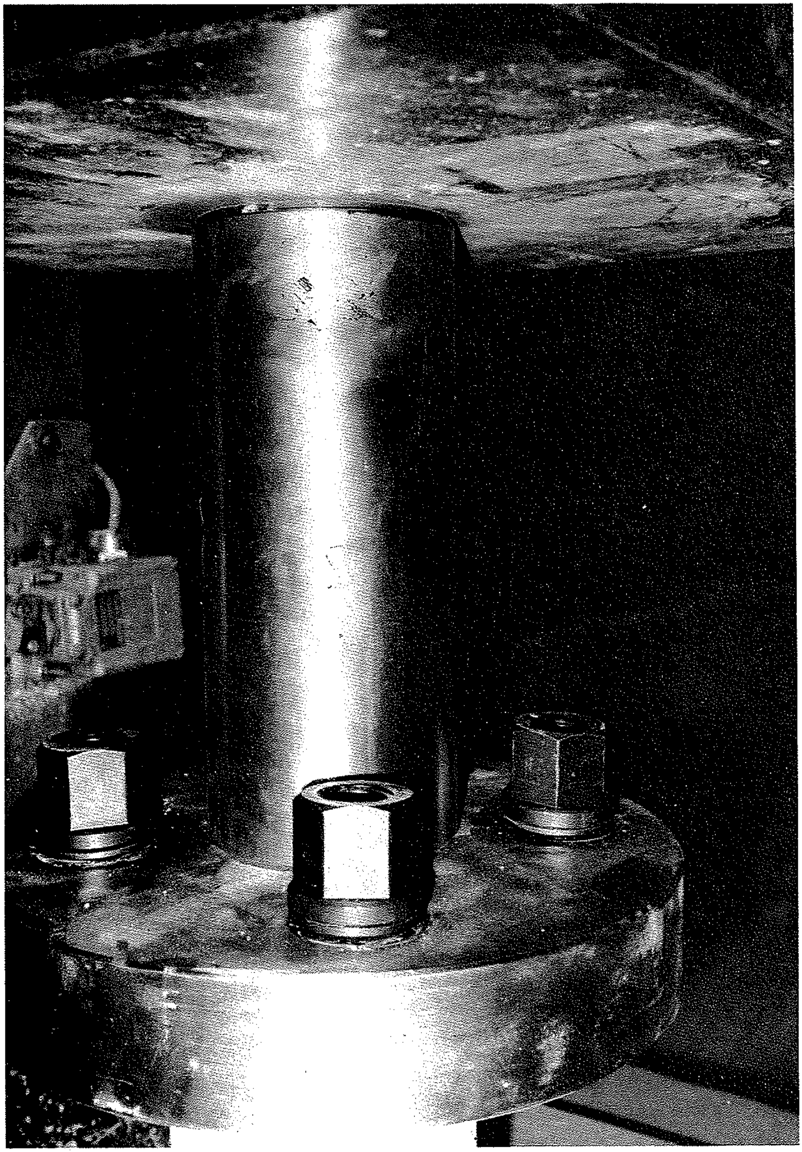

Figure 4.2 Steel cylinder for loading spring-loaded creep rigs in the 2000 kN hydraulic jack.

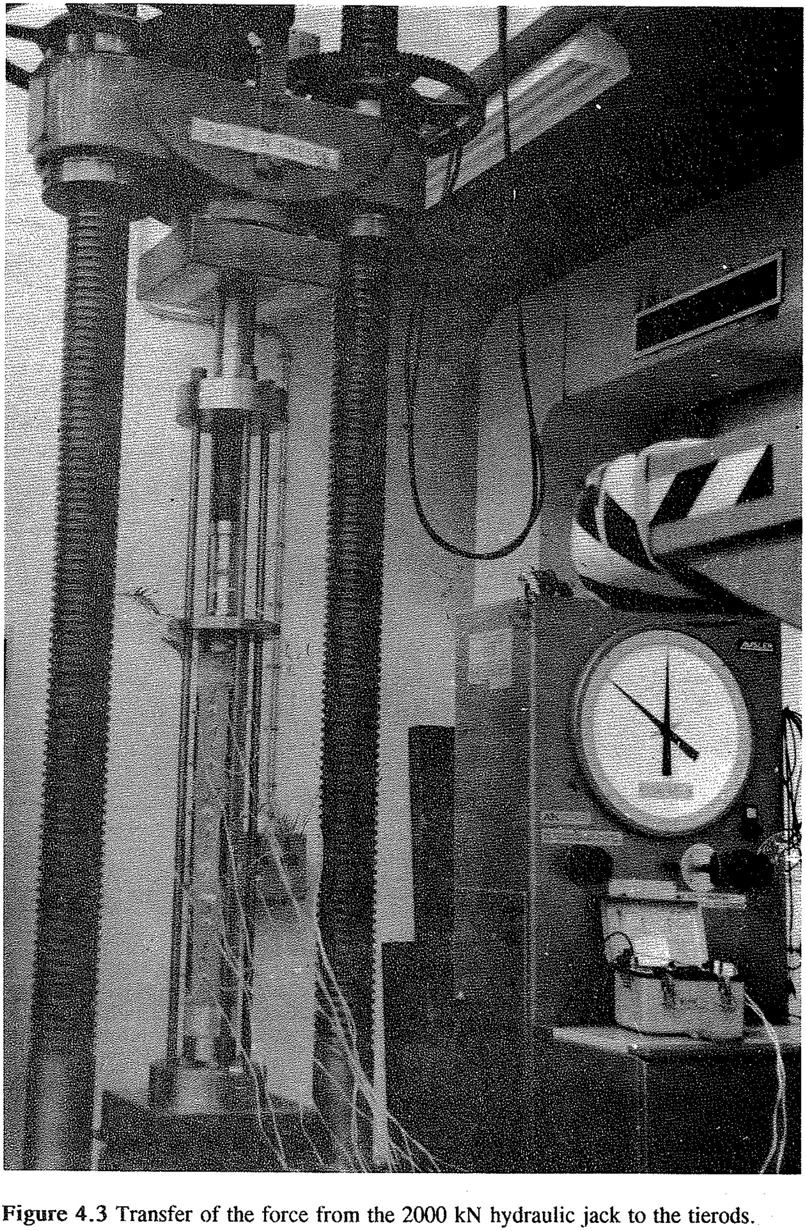

Figure 4.3 Transfer of the force from the 2000 kN hydraulic jack to the tierods.

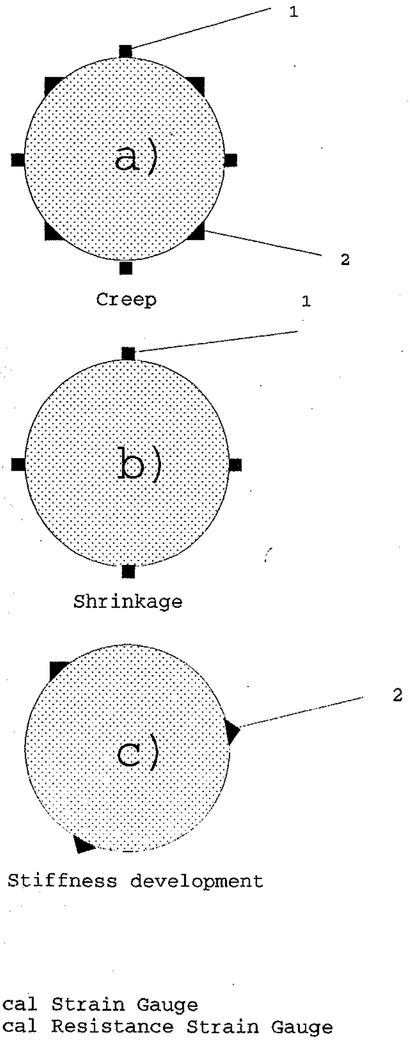

Figure 7.1 Positions of gauge-points

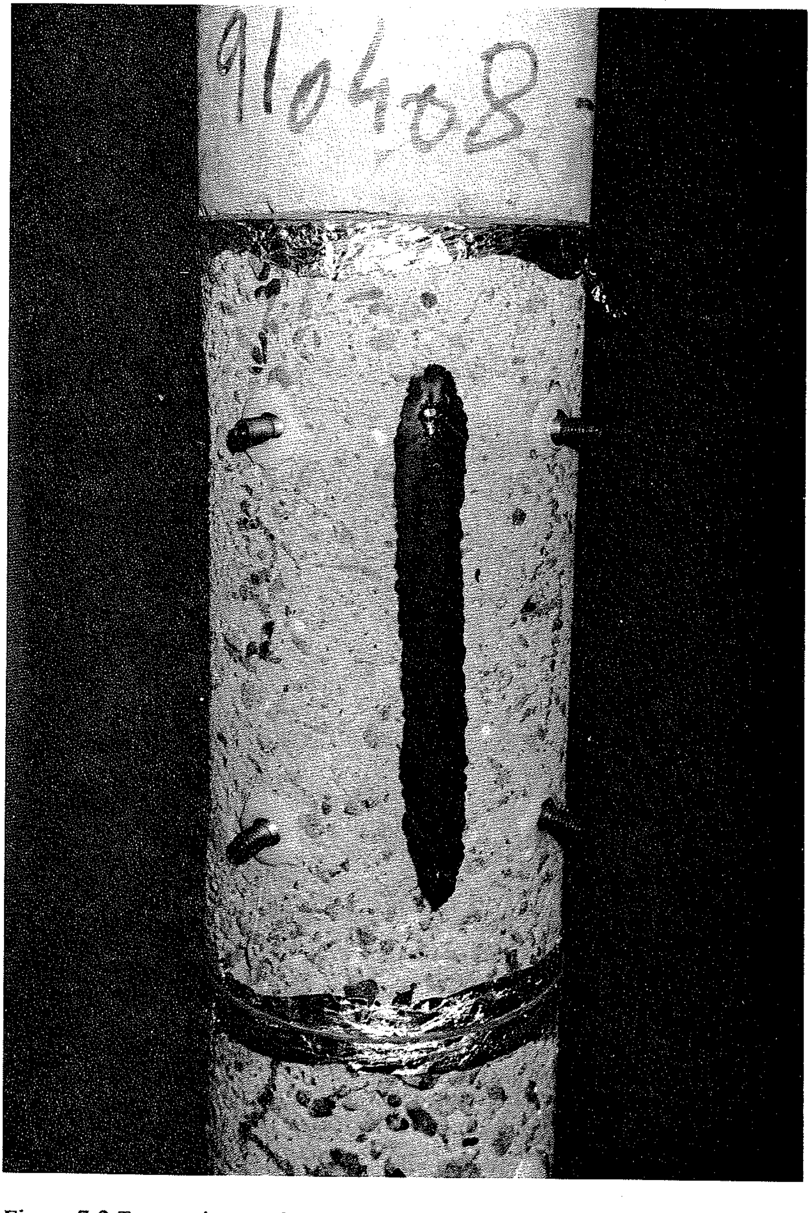

Figure 7.2 Test specimen and gauges.

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