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System design of Dome Plug

Creep properties at high stress levels of concrete for deposition tunnel plugs

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Abstract

SKB plug reference design concept for closure of the deposition tunnels, where canisters for spent nuclear fuel are deposited, is based on a bentonite sealing layer supported by a spherical concrete dome structure arching between recesses constructed in the rock walls. This unreinforced concrete plug is built with low-pH self-compacting concrete B200, a mix specially developed to fulfill the requirements specific to the repository concept, in particular to avoid possible negative effects from leachate from the concrete on the properties of the bentonite.

The high pressure endured by the concrete plug during its service life from the ground water and the swelling of the backfill clay results in high stresses in the concrete. The aim of this investigation is therefore to determine the creep properties of the low pH concrete B200 under high sustained compressive stress levels, representative of the actual service conditions.

Creep tests are conducted on sealed concrete cylinders at three different stress levels, approximately 40%, 50% and 75% of the compressive strength. The specimens were loaded at an age of approximately three months and the tests, which are still ongoing, are planned to last three years.

In the report, the experimental method is described and test results are presented regarding both concrete material properties, such as the compressive strength and stress-strain relation, and creep properties, such as the total stress induced strain and the creep coefficient as a function of time.

These results will contribute to improve numerical modelling of the structural behaviour of the concrete plug under loading, used to analyse among others the effects of the pressure on deformations, cracking and water tightness of the concrete plug.

Sammanfattning

SKBs designkoncept för förslutning av deponeringstunnlar, där kapslarna för använt kärnbränsle deponeras, bygger på ett tätskikt av bentonit och ett mothåll i form av en sfärisk betongplugg som genom valvverkan vilar mot urtag i bergväggen. Denna oarmerade betongplugg är byggd med självkompakterande låg-pH betong B200, en betong som utvecklats för att uppfylla de speciella krav som gäller för slutförvaret. Dessa speciella krav inriktar sig särskilt på att undvika möjliga negativa effekter som lakvattnet från betongen kan ha på bentonitens funktion.

Betongpluggen utsätts under dess livslängd för högt tryck, orsakade bland annat av grundvattnet och svällningen av bentonitleran, vilket resulterar i höga tryckspänningar i betongen. Syftet med den här undersökningen är därför att bestämma krypegenskaperna hos betong B200 under höga långvariga spänningsnivåer i tryck, som är representativa för de verkliga driftförhållandena för slutförvaret.

Krypförsök genomförs på förseglade betongcylindrar vid tre olika spänningsnivåer; cirka 40 %, 50 % och 75 % av tryckhållfastheten. Proverna belastades vid en ålder på omkring tre månader och planeras pågå i tre år.

I rapporten beskrivs den experimentella metoden och resultaten från prover redovisas. Detta gäller både betongens materialegenskaper såsom kryphållfasthet och spännings-töjningssamband, samt krypegenskaper såsom den totala spänningsinducerade töjningen och krypkoefficienten för varje belastningsnivå som en funktion av tiden.

Resultaten från dessa försök kommer att bidra till att förbättra den numeriska modelleringen av det strukturella beteendet av betongpluggen under belastning, som används för att analysera bland annat effekterna av tryckbelastningen på deformationer, sprickbildning och vattentäthet av pluggen.

Contents

1 Introduction

1.1 General

SKB plug reference design concept for closure of the deposition tunnels, where canisters for spent nuclear fuel are deposited, is based on a bentonite sealing layer supported by a spherical concrete dome structure arching between recesses constructed in the rock walls. This unreinforced concrete plug is built with low-pH self-compacting concrete B200, a mix specially developed to fulfill the requirements specific to the repository concept, in particular to avoid possible negative effects from leachate on the properties of the bentonite.

The structure will endure a high pressure from swelling forces in the backfill clay, at present by introduction of a specially designed backfill transition zone assumed to be confined to approximately 2 MPa. However, due to the uncertainty a backfill swelling design pressure of 4 MPa has been adopted, which also shall be combined with the ground water pressure of about 5 MPa.

The bentonite buffer rings around the deposited canister are sensitive to erosion, which leads to that only a small leakage through the concrete plug is allowed. Even though the final value for the maximum allowed leakage is not yet established, an acceptable leakage value of 0.0025 l/min has been discussed. Awaiting the final design value to be determined the measuring range for the measuring equipment developed for the plug structure has tentatively been selected at 0.0025 – 0.05 l/min (i.e. approximately 4–70 l/day).

A feasibility study of a concrete dome made of low pH concrete has been reported in Dahlström et al. (2009). The low pH concrete B200 has been developed by CBI Swedish Cement and Concrete Research Institute, see Dahlström et al. (2009) and Vogt et al. (2009).

1.2 Objectives

The high pressure endured by the concrete plug during its service life results in high stresses in the concrete. The aim of this investigation is therefore to determine the creep properties of the low pH concrete B200 under high stress levels, representative of the actual service conditions. This will contribute to improve numerical modelling of the structural behaviour of the concrete plug under loading, used to analyse among others the effects of the pressure on deformations, cracking and water tightness of the concrete plug.

In this study, creep tests at three different stress levels are conducted, approximately 40%, 50% and 75% of the compressive strength. The creep tests are carried out on sealed concrete cylinders loaded in mechanical rigs at an age of approximately three months. The tests are still ongoing and are planned to be continued for three years.

In addition, the mechanical behavior of the concrete material in compression was evaluated. The results of these tests were used to establish stress levels in the creep tests, strength development over time, effects of different storage conditions and stress-strain relation in compression.

2 Description of creep test method

2.1 General

The creep properties of the concrete material in compression were determined by tests on concrete cylinders subjected to sustained longitudinal compressive load. The test method is based on ASTM C512-02 and ISO 1920-9:2009. The creep of the concrete is obtained by determining the total deformation of the loaded specimens and subtracting the shrinkage of the unloaded control specimens from this value. All specimens are stored in the same environmental conditions.

2.2 Test specimens and preparations

The creep test specimens and the control specimens were designed as cylinders with a height h of three times the diameter d. The specimens were cast in plastic pipes slightly longer than the final specimens. Before casting stainless steel gauge studs for strain measurements were placed in pre-drilled holes in the plastic pipes. The embedded gauge studs were placed in pair, evenly spaced at about the mid-height of the specimen, in three lines spaced uniformly around the periphery of the specimen, see Figure 2-1. The effective gauge length between the gauge points was approximately 200 mm.

In connection with the casting the ends of the pipes were sealed with plastic foil (Mataki Teno air and vapour barrier) and the openings around the gauge studs were sealed with Mataki Teno sealant to prevent moisture departure from the concrete. After approximately 24 hours the sealed specimens were moved to a climate chamber with a temperature of 20 °C relative humidity of 50%. The plastic pipes were removed and the ends of cylinders were cut and face-ground to the final length at the age of approximately 80 days. Thereafter, a steel plate (Ø100×42 mm S355) of the same diameter as the specimen was placed at each end; finally, the specimen was enclosed and sealed by an adhesive sealing strip of aluminum coated bitumen (Mataki Byggtejp).

2.3 Test equipment

The creep tests were carried out in mechanical rigs consisting of three stiff loading plates (Ø270×42 mm S355), a load maintaining disc spring system[1] and three threaded rods (M24 8.8) to take the reaction of the loaded system, see Figure 2-2. A spherical washer (Ø68×23.5 mm DIN 6319) was provided between the loading plate of the rig and the upper end plate of the specimen to ensure uniform loading of the specimens.

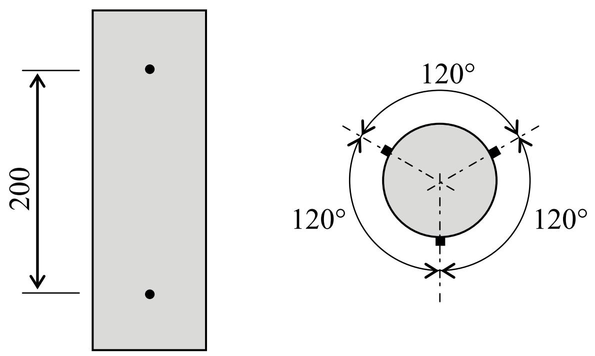

Figure 2-1. Schematic illustration of the embedded gauge studs placement.

[1] Four disc springs: SF-TAF DIN 2093, D_e = 180 mm, D_i = 92 mm, t = 13 mm

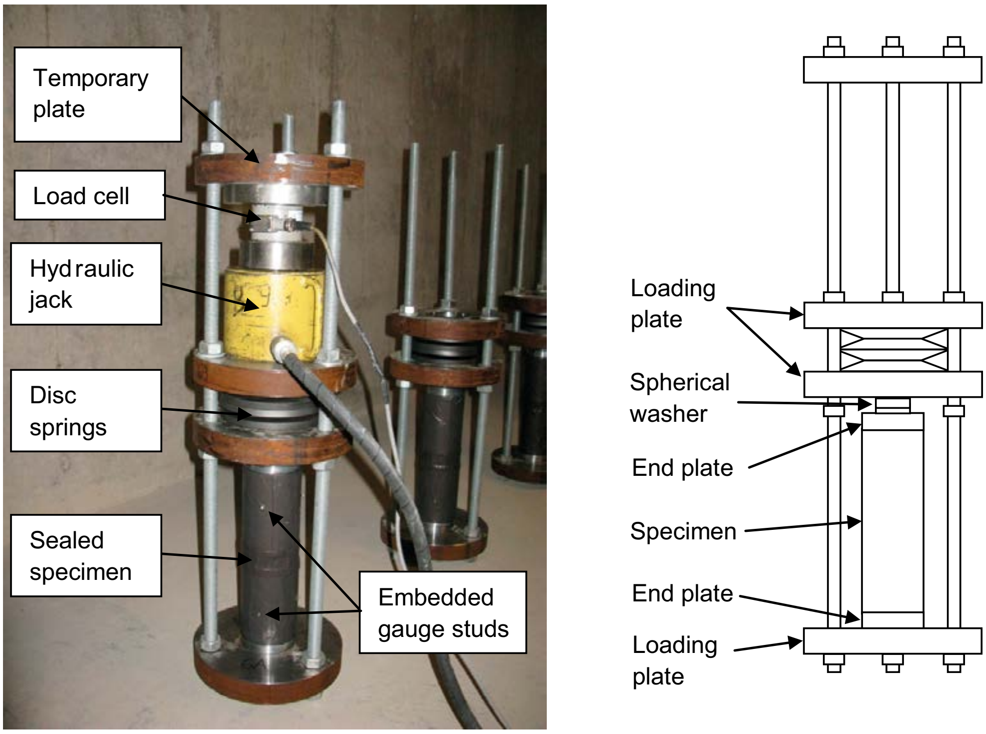

Figure 2-2. *Loading of a sealed creep test specimen in a mechanical creep rig and a schematic presentation of the rig.*

The initial compression load was applied by means of a portable hydraulic jack and a load cell that were placed between the upper plate of the rig and a temporary plate. When the correct load was achieved the nuts at the upper plate were tighten and the load cell and jack were removed. To compensate for the load relaxation caused by creep deformation during the test, the load level was checked regularly and adjusted if it varied more than ±2% from the correct value. To avoid unnecessary disturbance of the specimens by direct load measurement, the load was instead calculated based on the spring deformation and the spring stiffness. The spring deformation was taken as the change in distance between the loading plates on each side of the spring. The distance was measured between gauge points at three positions around the plates with a center hole calliper. The total spring stiffness was determined to 22.7 kN/mm in pretests.

The strains in the specimens were measured between the embedded gauge studs with a DEMEC mechanical strain gauge with a gauge length of 200 mm and a strain accuracy of approximately 4×10^{-6}. Each strain reading was taken as the mean value of three independent measurements at each measuring line.

2.4 Test procedure

The compressive strength and stress levels to be applied to the creep test specimens were determined shortly before the creep specimens were loaded. The specimens were placed and aligned in the mechanical rigs to avoid eccentric loading. Prior loading the reference values of the specimen strains and spring deformation were measured. The predetermined stress was applied and the strains and the spring deformation were measured directly after. In addition, the strain values of the control specimens were measured immediately after the loaded specimens.

The subsequent strain measurements were done after approximately 2 and 6 hours, then daily for 1 week, weekly until the end of 1 month, monthly to the end of 1 year, and thereafter once every third month. Before each measurement occasion the load level was first determined by measuring the spring deformation, and adjusted if it varied more than ±2% from the correct load value. The strains of the control specimens were measured on the same schedule as the loaded specimens.

3 Concrete material

3.1 Concrete mix

The concrete was manufactured at the laboratory of CBI Swedish Cement and Concrete Research Institute. The concrete mix composition and mixing order of the low pH SCC B200 were in accordance to the specifications reported in Vogt et al. (2009), see Table 3-1 and Table 3-2, respectively. The coarse aggregate (8–16 mm) used in this project was crushed granite from the Gothenburg area. The fine aggregate (0–8 mm) was natural sand taken from same source in the Äspö area as used in Vogt et al. (2009). The concrete was mixed in a forced action mixer for a total time of approximately 10 minutes. The tests were performed in two separate test runs; the first was cast 2011-05-25 and the second 2011-12-19. The final concrete mix in each test run can be seen in Table 3-1. The concrete had a slump flow value of approximately 680 mm and 690 mm in the first and second run, respectively. Simultaneously with the casting of the creep tests, concrete cubes and cylinders were cast for determination of the compressive characteristics.

Table 3-1. Composition of concrete mix B200 in the first and the second test run.

Constituents	Manufacturer	Quantity [kg/m^3]		
		Design mix	Final mix 1	Final mix 2
CEM I 42.5	Cementa	120	120	120
Silica fume	Elkem	80	80	80
Water		165	164	165
Limestone filler Limus 25	Nordkalk	369	368	369
Sand 0–8 mm	Fogelheim 6:2	1037	1028	1032
Gravel 8–16 mm		558	548	551
Glenium 51	BASF	6.4	6.0	6.0
Water/cement		1.375	1.367	1.367
Water/binder		0.825	0.820	0.825
Water/powder		0.290	0.289	0.290

Table 3-2. Mixing order of B200 in the laboratory test.

Sequence 5	Activity
1	Aggregates and silica fume
2	Mixing
3	Cement and limestone filler
4	Mixing
5	Water and superplasticizer
6	Final mixing

3.2 Concrete material properties

In this study, the mechanical behavior of the concrete material in compression was evaluated. The test results were used to establish stress levels in the creep tests, strength development over time, effects of different storage conditions and stress-strain relation in compression. A summary of the concrete properties for the first test run can be found in Table 3-3 and for the second test run in Table 3-4. Detailed information of the material test results can be found in Appendix A.

Table 3-3. Summary of concrete properties in the first test run.

Property	Unit	Specimen dim. [mm]	Curing condition	Age [days] 90	110 2)	450	X	X
$f_{cm,cube}$	[MPa]	150×150×150	water	76.7	75.4	85.9	xx.x	xx.x
$f_{cm,cyl}$	[MPa]	Ø150×300	water	74.6	–	–	–	–
E_0	[GPa]	Ø150×300	water	33.2	–	–	–	–
E_c	[GPa]	Ø150×300	water	33.5	–	–	–	–
f_{cm}	[MPa]	Ø100×200	water	75.3	–	–	–	–
f_{cm}	[MPa]	Ø100×200	Sealed pipe 1)	75.0	–	–	–	–
f_{cm}	[MPa]	Ø100×300	Sealed pipe 1)	70.5	–	–	–	–

1) Manufactured and stored in sealed plastic pipes in the same way as the creep test specimens.

2) Concrete age at the start of the creep tests.

Table 3-4. Summary of concrete properties in the second test run.

Property	Unit	Specimen dim. [mm]	Curing condition	Age [days] 87	470	X	X
$f_{cm,cube}$	[MPa]	150×150×150	water	67.8	86.6	xx.x	xx.x
$f_{cm,cyl}$	[MPa]	Ø150×300	water	64.0	–	–	–
f_{cm}	[MPa]	Ø90×180	sealed pipe 1)	71.3	–	–	–
f_{cm}	[MPa]	Ø90×270	sealed pipe 1)	68.7	–	–	–

1) Manufactured and stored in sealed plastic pipes in the same way as the creep test specimens.

The compressive strength (f_{cm}) tests were conducted according to SS-EN 12390-3:2009. In both the test runs the compressive strength was determined using cubes 150×150×150 mm ($f_{cm,cube}$) and cylinders Ø150×300 mm ($f_{cm,cyl}$). In the first test run small cylinders Ø100×200 mm were also tested according to the same method. The modulus of elasticity (E_0, E_c) was evaluated from compression tests on cylinders Ø150×300 mm according to SS 137232:2005. The specimens were stored in water at a temperature of approximately 20 °C up to the time of testing.

In addition concrete cylinders of two different sizes, $h = 2d$ and $h = 3d$, were manufactured and stored in sealed plastic pipes in the same way as the creep specimens, see Section 2.2. At the time of testing the plastic pipes were removed and the ends of cylinders were cut and face-ground to the final length.

The compressive strength parameters were evaluated at a concrete age of approximately 90 days. In the first test run the cube strength was also evaluated at the actual time for the start of the creep tests at an age of 110 days. Since the strength at 110 days was somewhat lower than at 90 days and within the standard deviation, it was decided to use the strength values at 90 days to determine the stress levels to be used in the creep tests. To study the concrete strength development during the time for the creep tests, the cube strength has been determined each year from the start of the first and the second creep test run, respectively.

From Table 3-3 and Table 3-4 it can be noted that there is an unexpected small difference between the cube strength and cylinder strength in both test runs. The ratio $f_{cm,cube} / f_{cm,cyl}$ is 1.03 and 1.06 for the first and second test run, respectively. However, both the cube strength and the cylinder strength were significantly lower in the second test run compared with the first test run, despite that the same concrete recipe was used. This reduction in strength was not as pronounced for the cylinders stored in the sealed plastic pipes. The reason for this discrepancy in strength values has not been found.

Comparing the results for the small cylinders (Ø100×200 mm) in the first test run, the different curing conditions for the cylinders stored in water and those stored in sealed plastic pipes do not seem to have any significant influence on the compressive strength, see Table 3-3.

The small concrete cylinders (Ø100×200 mm and Ø90×180 mm) stored in sealed plastic pipes were used to determine the compressive stress-strain relations, see Appendix A. In the second test run the stress-strain relations were also determined for the slender cylinders (Ø90×270 mm) to examine if the higher slenderness, corresponding to the creep tests specimens, affected the response. The strain was measured as the mean value of three inductive displacement transducers with a gauge length of 100 mm. The elastic modulus E_0 was calculated as the secant modulus between 0.5 MPa and $0.45f_c$. The compressive stress $\sigma_c(\varepsilon_c)$ is compared with a linear response $E_0\varepsilon_c$ using a ratio η defined as

$$\eta = \left|\frac{E_0\varepsilon_c}{\sigma_c(\varepsilon_c)}\right| - 1 \qquad (3\text{-}1)$$

In Table 3-5 the linear elastic response $E_0\varepsilon_c$ and the resulting ratio $E_0\varepsilon_c / f_c$ is given for η equal to 0.01, 0.02 and 0.05; representing a deviation from linearity by 1%, 2% and 5%, respectively. The mean values of the compressive strength f_{cm} and the elastic modulus E_{cm} are also give.

There was no major difference in the behavior between the slender (Ø90×270 mm) and shorter specimen (Ø90×180 mm). The modulus of elasticity was approximately the same and the elastic region was even a little bit larger for the slender specimens, see Table 3-5. However, as in the first test run, the slender specimens show slightly lower compressive strength.

Table 3-5. Evaluation of linearity from the stress-strain relations.

Specimen dimensions [mm]	Test run	f_{cm} [MPa]	E_{0m} [GPa]	Mean value $E_0\varepsilon_c$ [MPa]			Mean value $E_0\varepsilon_c$ / f_c [%]		
				η=0.01	η=0.02	η=0.05	η=0.01	η=0.02	η=0.05
Ø100×200	1	75.0	33.5	42.0	46.7	56.3	56	62	75
Ø90×180	2	71.3	34.0	33.0	36.5	43.3	46	51	61
Ø90×270	2	68.7	34.1	37.5	40.4	47.0	55	59	68

4 Creep test

4.1 Creep test programme

In this study, creep tests at three different stress levels were conducted, approximately 40%, 50% and 75% of the compressive strength. A summary of the test program is given in Table 4-1 and detailed information can be found in Appendix B. The creep tests were performed in two test runs; two stress levels in the first test run (TR 1a and TR 1b) and one stress level in the second test run (TR2). The stress levels to be applied $\sigma_c(t_0)$ to the creep specimens were determined from compressive tests described in Section 3.2. The stress levels are given in relation to the compressive strength on standard cylinders and the sealed slender specimens. Five creep specimens were loaded for each stress level and for each test run five control specimens were remained unloaded.

Table 4-1. Summary of creep test programme.

Test run	Specimen #	Specimen dim. [mm]	Age at time of loading, t_0 [days]	Applied stress, $\sigma_{cm}(t_0)$ [1)] [MPa]	$\sigma_{cm}(t_0)$ / $f_{cm,cyl}$ [2)] [%]	$\sigma_{cm}(t_0)$ / f_{cm} [3)] [%]	$E_{cim}(t_0)$ [GPa]
TR 1a	1–5	Ø100×300	110	30.0 (*0.2*)	40.2 (*0.3*)	42.6 (*0.3*)	32.9 (*0.5*)
TR 1b	6–10	Ø100×300	111	38.5 (*0.5*)	51.6 (*0.6*)	54.6 (*0.7*)	32.7 (*0.8*)
TR 2	11–15	Ø90×270	91	49.4 (*0.6*)	77.3 (*0.9*)	72.0 (*0.9*)	28.9 (*1.0*)

1) $\sigma_{cm}(t_0)$ is the average value of the applied stress $\sigma_c(t_0)$ of the specimens in the test group.

2) $f_{cm,cyl}$ is the average compressive strength from standard cylinders Ø150×300 mm.

3) f_{cm} is the average compressive strength from sealed cylinders Ø100×300 mm and Ø90×270 mm for first and second test run, respectively.

4.2 Creep test results

The total strain of the loaded creep specimens $\varepsilon_c(t)$ and the control specimens $\varepsilon_{c,control}(t)$ was calculated as the average value of the strain measurements at the three lines spaced uniformly around the periphery of the specimen. The total strain-time relations can be found in Appendix B. The instantaneous elastic modulus $E_{ci}(t_0)$ of the creep specimens is calculated as the applied stress divided by the average strain $\varepsilon_{ci}(t_0)$ immediately after loading as:

$$E_{ci}(t_0) = \frac{\sigma_c(t_0)}{\varepsilon_{ci}(t_0)} \tag{4-1}$$

The mean value of the instantaneous elastic modulus $E_{cim}(t_0)$ of the specimens at each stress level is given in Table 4-1. In the first test run, the elastic modulus determined from the creep tests is in the same order of magnitude as those determined by material tests presented in Table 3-3 and Table 3-5. This is expected since the applied stress levels are within the assumed elastic range, see Table 3-5. However, in the second test run the instantaneous elastic modulus from the creep test is lower than that from the material tests given in Table 3-5. Here, the applied stress level is outside the assumed elastic range and a response corresponding to the elastic modulus from the material tests cannot be expected. A secant modulus E_0^* evaluated between 0.5 MPa and $\sigma_{cm}(t_0)$ = 49.4 MPa gives a better agreement to the instantaneous elastic modulus in the creep tests, see Appendix A. In addition some creep strains may have occurred already before the measurement of strains after loading.

The total stress-induced strain $\varepsilon_{c\sigma}(t, t_0)$ is calculated as the difference between the average strain values of the loaded specimens and the control specimens as:

$$\varepsilon_{c\sigma}(t,t_0) = \varepsilon_c(t) - \varepsilon_{c,control}(t) \tag{4-2}$$

The total stress-induced strain divided by the applied stress is given in Figure 4-1 to Figure 4-3. The creep strain $\varepsilon_{cc}(t,\ t_0)$ is calculated as the total stress-induced strain minus the strain immediately after loading as:

$$\varepsilon_{cc}(t,t_0) = \varepsilon_{c\sigma}(t,t_0) - \varepsilon_{ci}(t_0) = \varepsilon_c(t) - \varepsilon_{c,control}(t) - \varepsilon_{ci}(t_0) \tag{4-3}$$

The creep coefficient $\varphi(t,\ t_0)$ is expressed as the ratio between the creep strain and the initial strain immediately after loading:

$$\varphi(t,t_0) = \frac{\varepsilon_{cc}(t,t_0)}{\varepsilon_{ci}(t_0)} \tag{4-4}$$

The developments of the creep coefficients are presented in Figure 4-4 to Figure 4-6. Figure 4-7 presents the mean value of the creep coefficient for each stress level.

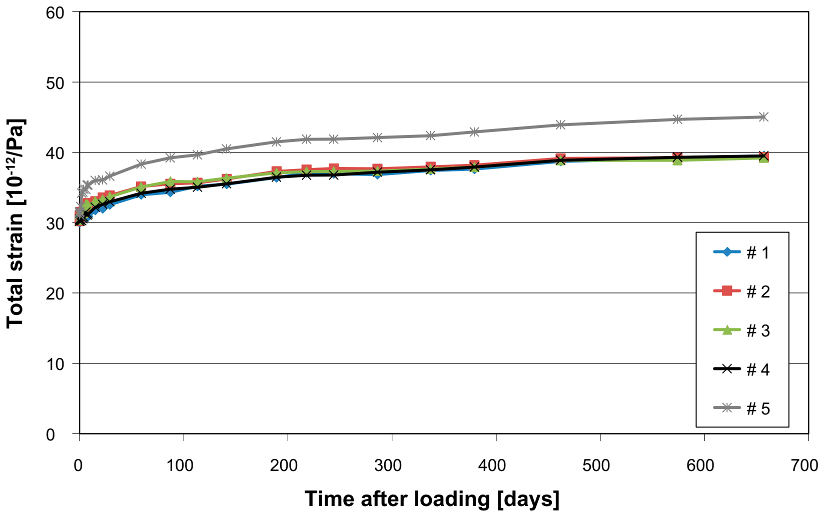

Figure 4-1. *Total stress-induced strain versus time after loading for the creep specimens in TR 1a; applied stress* $\boldsymbol{\sigma_{cm}}(t_0)$ *= 30.0 MPa.*

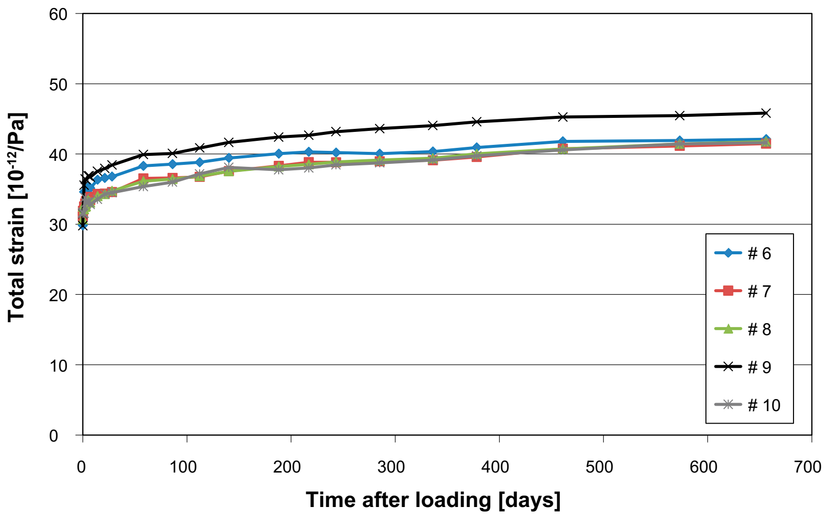

Figure 4-2. *Total stress-induced strain versus time after loading for the creep specimens in TR 1b; applied stress* $\sigma_{cm}(t_0)$ *= 38.5 MPa.*

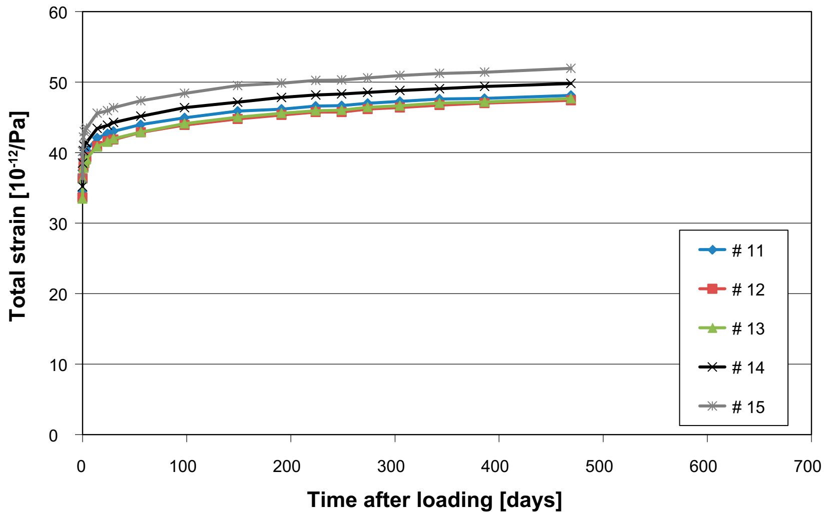

Figure 4-3. *Total stress-induced strain versus time after loading for the creep specimens in TR 2; applied stress* $\sigma_{cm}(t_0)$ *= 49.4 MPa.*

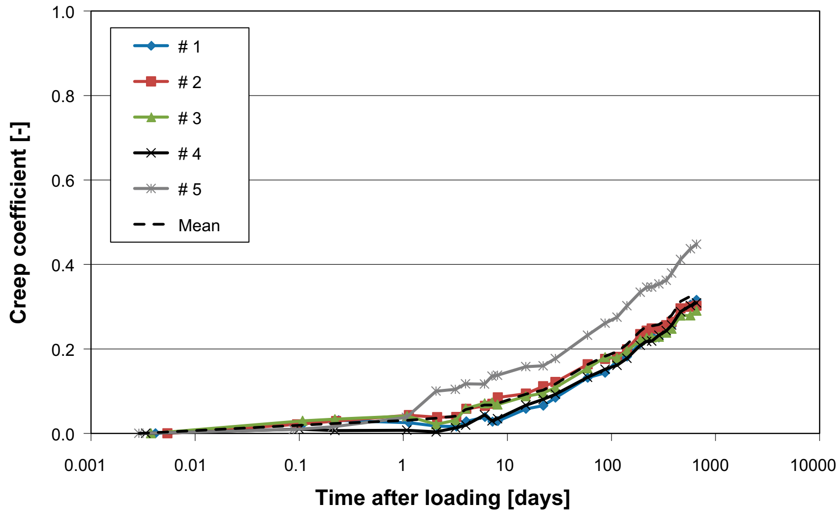

Figure 4-4. *Creep coefficient versus time after loading for the creep specimens in TR 1a; applied stress* $\sigma_{cm}(t_0)$ *= 30.0 MPa.*

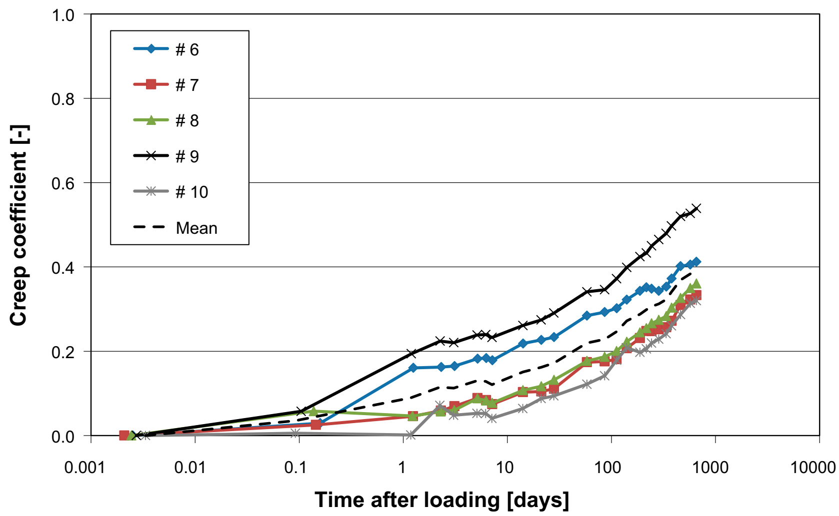

Figure 4-5. *Creep coefficient versus time after loading for the creep specimens in TR 1b; applied stress* $\sigma_{cm}(t_0)$ *= 38.5 MPa.*

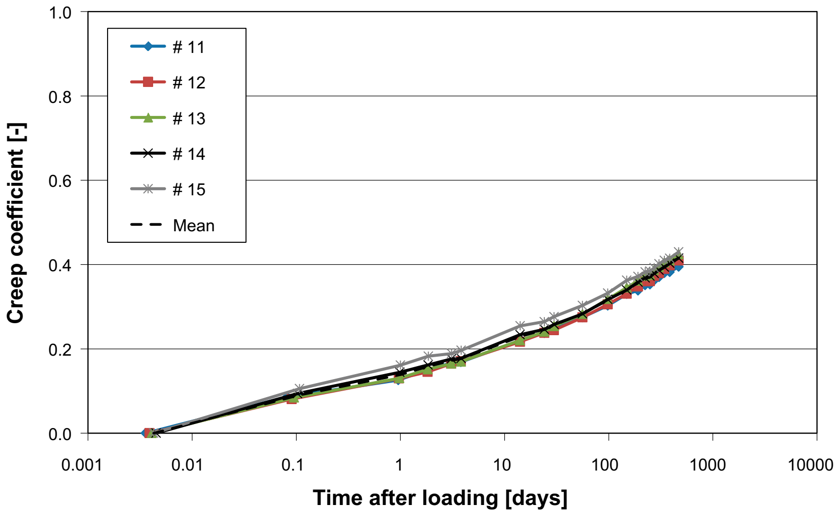

Figure 4-6. *Creep coefficient versus time after loading for the creep specimens in TR 2 applied stress $\sigma_{cm}(t_0)$ = 49.4 MPa.*

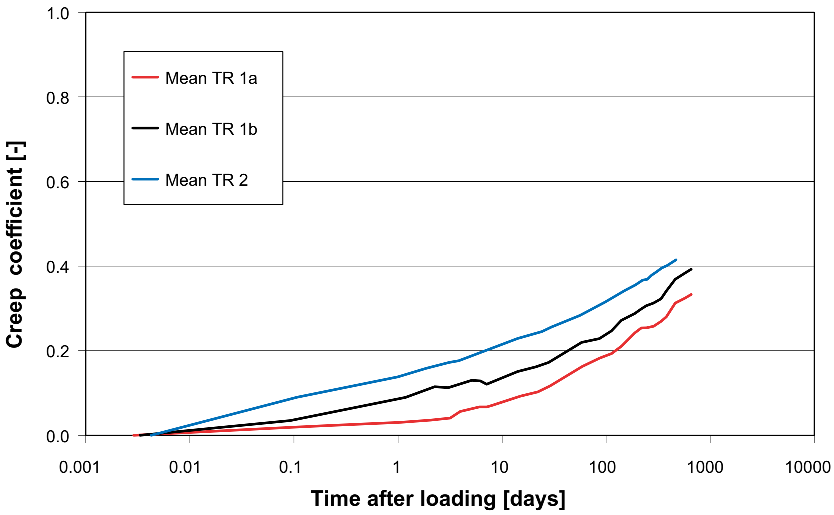

Figure 4-7. *Mean value of the creep coefficient versus time for TR 1a ($\boldsymbol{\sigma_{cm}}(t_0)$ = 30.0 MPa), TR 1b ($\sigma_{cm}(t_0)$ = 38.5 MPa) and TR2 ($\sigma_{cm}(t_0)$ = 49.4 MPa).*

5 Concluding remarks

The creep tests are still ongoing and are planned to last three years. The conclusions will be added after the tests are completed.

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Appendix A

Summary of concrete material test results

This appendix summarises the results of the concrete material tests presented in Section 3. The evaluated concrete material properties are presented in Table A-1 to Table A-6 for the first test run and in Table A-7 to A-10 for the second test run. The stress-strain relations from the compression tests are shown in Figure A-1 to Figure A-3.

First test run

Table A-1. Compressive strength – 150 mm cube. Measured density ρ (kg/m^3) is given in brackets.

Specimen #	$f_{c,cube}$ [MPa]				
	90 days	110 days	450 days	xxx days	xxx days
1	75.5 (2380)	75.8 (2380)	82.8 (2360)		
2	76.4 (2370)	75.7 (2370)	86.6 (2360)		
3	75.7 (2350)	73.4 (2360)	88.1 (2360)		
4	76.8 (2350)	76.4 (2360)	86.4 (2380)		
5	78.9 (2350)	75.6 (2360)	85.7 (2330)		
Mean	**76.7**	**75.4**	**85.9**		
Std. dev.	**1.4**	**1.1**	**2.0**		

Table A-2. Compressive strength at 90 days – Ø150x300 mm cylinder.

Specimen #	Density, ρ [kg/m^3]	$f_{c,cyl}$ [MPa]
1	2350	75.1
2	2350	74.9
3	2360	74.7
4	2360	74.6
5	2350	73.7
Mean	**2368**	**74.6**
Std. dev.	**13.0**	**0.5**

Table A-3. Elastic modulus at 90 days – Ø150x300 mm cylinder.

Specimen #	Density, ρ [kg/m^3]	E_0 [GPa]	E_c [GPa]	f_c [MPa]
1	2390	34.0	34.5	73.6
2	2360	33.0	33.5	74.7
3	2360	32.5	33.0	75.3
4	2370	33.0	33.0	74.5
5	2360	33.5	33.5	76.5
Mean	**2354**	**33.2**	**33.5**	**75.3**
Std. dev.	**5.5**	**0.6**	**0.6**	**0.9**

Table A-4. Compressive strength at 90 days – Ø100x200 mm cylinder.

Specimen #	Density, ρ [kg/m^3]	f_c [MPa]
1	2320	75.5
2	2330	75.3
3	2330	75.1
4	2320	75.3
5	2330	75.5
Mean	**2326**	**75.3**
Std. dev.	**5.5**	**0.2**

Table A-5. Compressive strength at 90 days – Ø100x300 mm cylinder cast in plastic pipe.

Specimen #	Density, ρ [kg/m^3]	f_c [MPa]
1	2370	67.8
2	2350	71.4
3	2360	72.2
Mean	**2360**	**70.5**
Std. dev.	**10.0**	**2.3**

Table A-6. Compressive strength at 90 days – Ø100x200 mm cylinder cast in plastic pipe.

Specimen #	f_c	E_0	$E_0\varepsilon_c$ [MPa]			$E_0\varepsilon_c$ / f_c [–]		
	[MPa]	[GPa]	η=0.01	η=0.02	η=0.05	η=0.01	η=0.02	η=0.05
1	74.6	33.7	35	43	54	0.47	0.58	0.73
2	75.3	33.1	45	49	58	0.60	0.65	0.77
3	75.7	34.1	41	46	56	0.54	0.61	0.74
4	74.4	32.4	56	58	63	0.75	0.77	0.84
5	74.8	34.1	33	38	52	0.45	0.51	0.68
Mean	**75.0**	**33.5**	**42.0**	**46.7**	**56.3**	**0.56**	**0.62**	**0.75**
Std. dev.	**0.5**	**0.76**	**8.9**	**7.3**	**4.4**	**0.12**	**0.10**	**0.06**

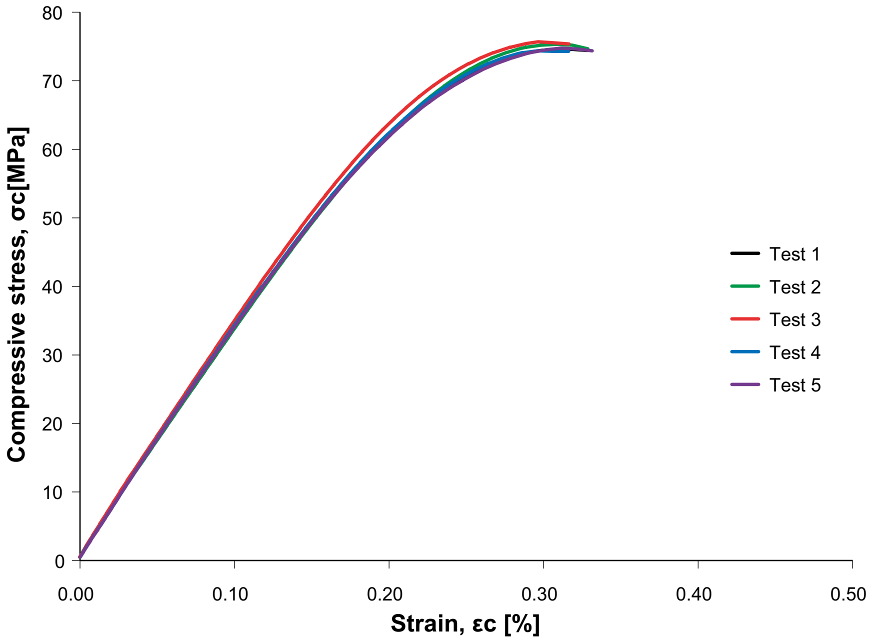

__Figure A-1.__ Stress-strain curves from compression tests on cylinders Ø100×200 cast in plastic pipe.

Second test run

Table A-7. Compressive strength – 150 mm cube. Measured density ρ (kg/m^3) is given in brackets.

Specimen #	$f_{c,cube}$ [MPa] 87 days	470 days	xxx days	xxx days	xxx days
1	65.5 (2370)	89.7 (2380)			
2	69.7 (2370)	85.5 (2370)			
3	68.2 (2370)	84.6 (2380)			
Mean	**67.8**	**86.6**			
Std. dev.	**2.1**	**2.7**			

Table A-8. Compressive strength at 87 days – Ø150x300 mm cylinder.

Specimen #	Density, ρ [kg/m^3]	$f_{c,cyl}$ [MPa]
1	2370	63.8
2	2340	64.3
3	2360	63.9
4	2340	64.1
5	2340	64.0
Mean	**2350**	**64.0**
Std. dev.	**14.1**	**0.2**

Table A-9. Compressive strength at 86 days – Ø90x180 mm cylinder cast in plastic pipe.

Specimen #	f_c [MPa]	E_0 [GPa]	E_0^* [GPa]	$E_0\varepsilon_c$ [MPa] η=0.01	η=0.02	η=0.05	$E_0\varepsilon_c$ / f_c [–] η=0.01	η=0.02	η=0.05
1	71.8	34.5	31.2	30	35	39	0.41	0.48	0.55
2	71.4	32.1	30.9	37	41	50	0.52	0.57	0.70
3	70.5	33.4	31.6	31	35	45	0.44	0.50	0.64
4	70.7	35.5	33.2	35	37	44	0.49	0.52	0.62
5	72.3	34.5	31.0	33	35	38	0.46	0.48	0.52
Mean	**71.3**	**34.0**	**31.6**	**33.0**	**36.5**	**43.3**	**0.46**	**0.51**	**0.61**
Std. dev.	**0.8**	**1.3**	**0.9**	**2.9**	**2.7**	**4.8**	**0.04**	**0.04**	**0.07**

E_0^* is evaluated from as the secant modulus between 0.5 MPa and $\sigma_{cm}(t_0)$ = 49.4 MPa, where $\sigma_{cm}(t_0)$ is the applied stress level of the creep tests in the in second test run.

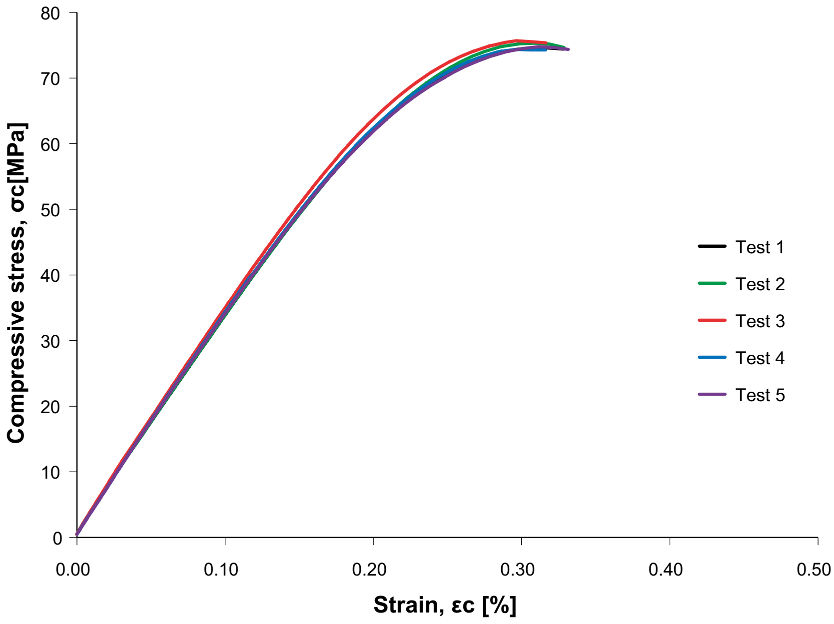

Figure A-2. Stress-strain curves from compression tests on cylinders Ø90×180 cast in plastic pipe.

Table A-10. Compressive strength at 86 days – Ø90x270 mm cylinder cast in plastic pipe.

Specimen #	f_c [MPa]	E_0 [GPa]	E_0^* [GPa]	$E_0\varepsilon_c$ [MPa] η=0.01	η=0.02	η=0.05	$E_0\varepsilon_c$ / f_c [–] η=0.01	η=0.02	η=0.05
1	68.2	32.6	31.1	35	40	48	0.51	0.58	0.70
2	67.7	35.5	32.7	33	34	41	0.48	0.50	0.60
3	70.1	34.3	33.5	45	48	53	0.64	0.68	0.75
Mean	**68.7**	**34.1**	**32.4**	**37.5**	**40.4**	**47.0**	**0.55**	**0.59**	**0.68**
Std. dev.	**1.3**	**1.5**	**1.3**	**6.6**	**6.8**	**6.1**	**0.09**	**0.09**	**0.08**

E_0^* is evaluated from as the secant modulus between 0.5 MPa and $\sigma_{cm}(t_0)$ **=** 49.4 MPa, where $\sigma_{cm}(t_0)$ is the applied stress level of the creep tests in the in second test run.

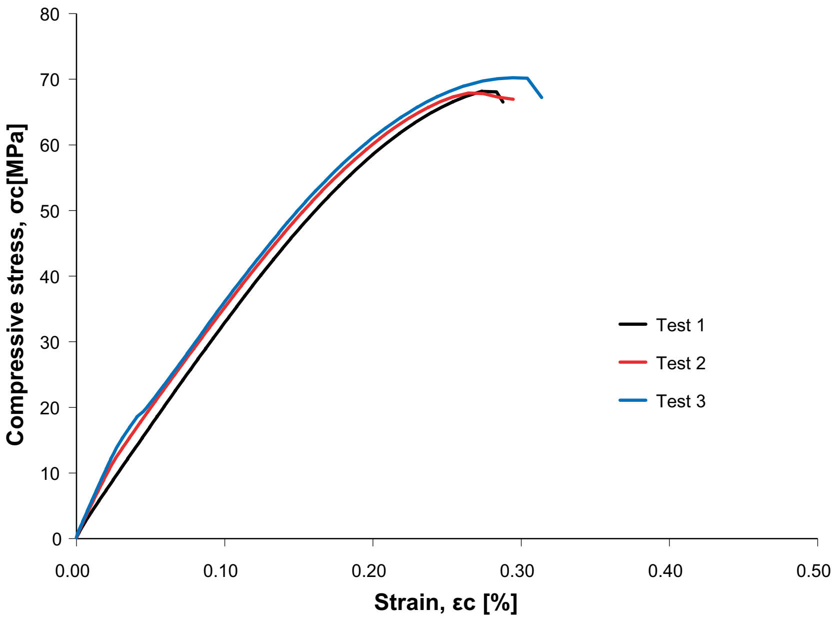

Figure A-3. Stress-strain curves from compression tests on cylinders Ø90×270 cast in plastic pipe.

Appendix B

Summary of creep test results

This appendix summarises the creep tests presented in Section 4, see Table B-1 to B-3. The total strain-time relations from the creep specimens and the control specimens are shown in Figure B-1 to B-16.

Table B-1. Summary of creep tests at approximately 40% of compressive strength in first test run (TR 1a). Cylinders Ø100×300. Concrete age at loading t_0 = 110 days.

Specimen #	Applied stress, $\sigma_c(t_0)$ [MPa]	$\sigma_c(t_0)$ / $f_{cm,cyl}$ [–]	$\sigma_c(t_0)$ / f_{cm} [%]	$E_{ci}(t_0)$ [GPa]
1	30.3	40.6	43.0	33.3
2	30.0	40.2	42.6	33.1
3	29.8	39.9	42.3	32.9
4	30.0	40.2	42.6	33.1
5	29.8	39.9	42.3	32.2
Mean	**30.0**	**40.2**	**42.6**	**32.9**
Std. dev.	**0.2**	**0.3**	**0.3**	**0.5**

Table B-2. Summary of creep tests at approximately 50% of compressive strength in first test run (TR 1b). Cylinders Ø100×300. Concrete age at loading t_0 =111 days.

Specimen #	Applied stress, $\sigma_c(t_0)$ [MPa]	$\sigma_c(t_0)$ / $f_{cm,cyl}$ [–]	$\sigma_c(t_0)$ / f_{cm} [%]	$E_{ci}(t_0)$ [GPa]
6	39.1	52.4	55.5	33.5
7	38.3	51.3	54.3	32.1
8	38.2	51.2	54.2	32.6
9	38.0	50.9	53.9	33.6
10	38.9	52.1	55.2	31.7
Mean	**38.5**	**51.6**	**54.6**	**32.7**
Std. dev.	**0.5**	**0.6**	**0.7**	**0.8**

Table B-3. Summary of creep tests at approximately 75% of compressive strength in second test run (TR 2). Cylinders Ø90×270. Concrete age at loading t_0 = 91 days.

Specimen #	Applied stress, $\sigma_c(t_0)$ [MPa]	$\sigma_c(t_0)$ / $f_{cm,cyl}$ [–]	$\sigma_c(t_0)$ / f_{cm} [%]	$E_{ci}(t_0)$ [GPa]
11	49.2	76.9	71.6	29.0
12	49.4	77.2	71.9	29.7
13	49.5	77.3	72.1	29.9
14	50.3	78.6	73.2	28.4
15	48.8	76.3	71.0	27.5
Mean	**49.4**	**77.3**	**72.0**	**28.9**
Std. dev.	**0.6**	**0.9**	**0.9**	**1.0**

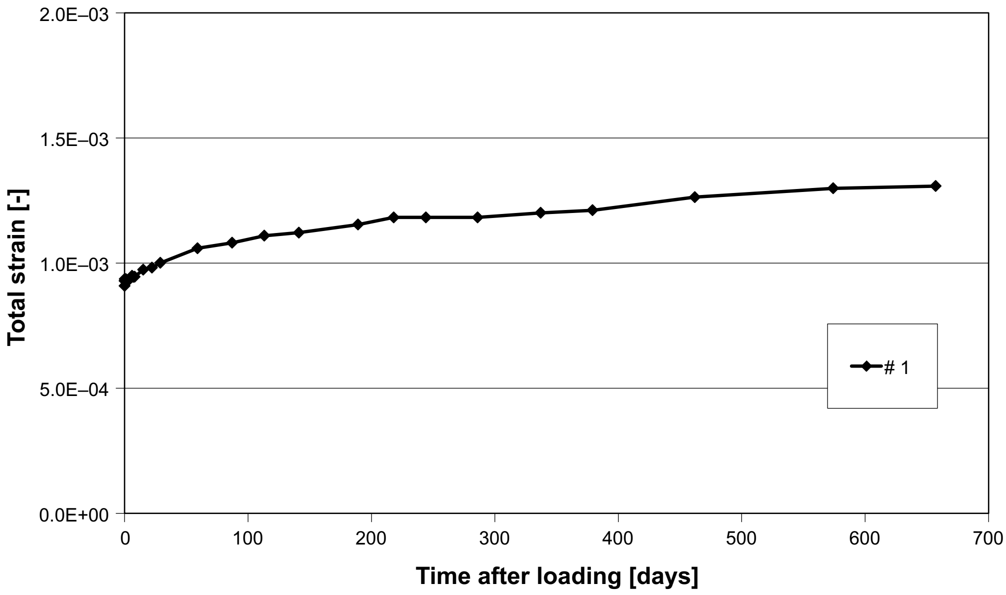

Figure B-1. Total strain versus time after loading for creep specimen # 1.

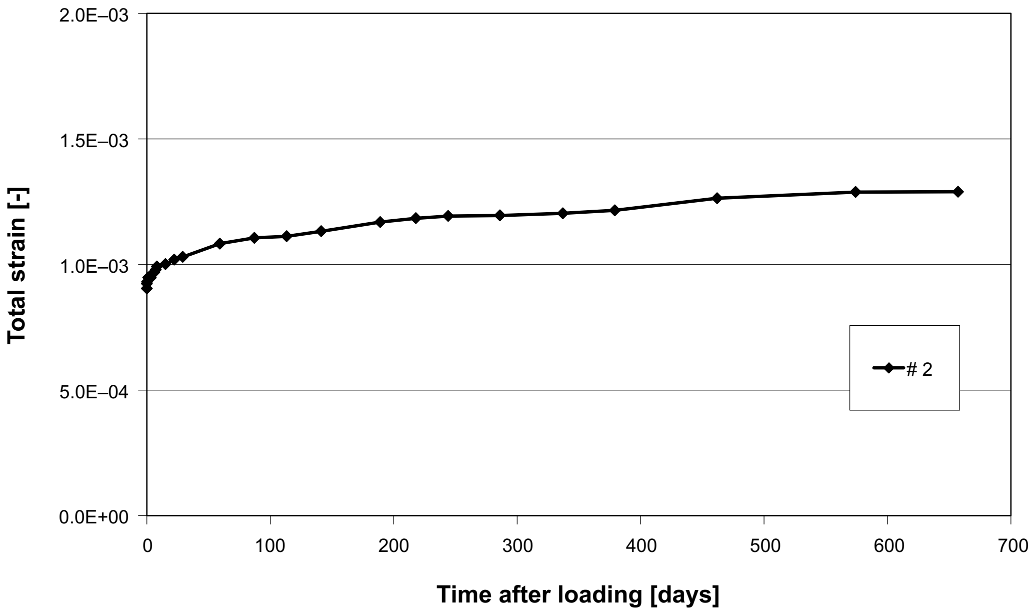

Figure B-2. Total strain versus time after loading for creep specimen # 2.

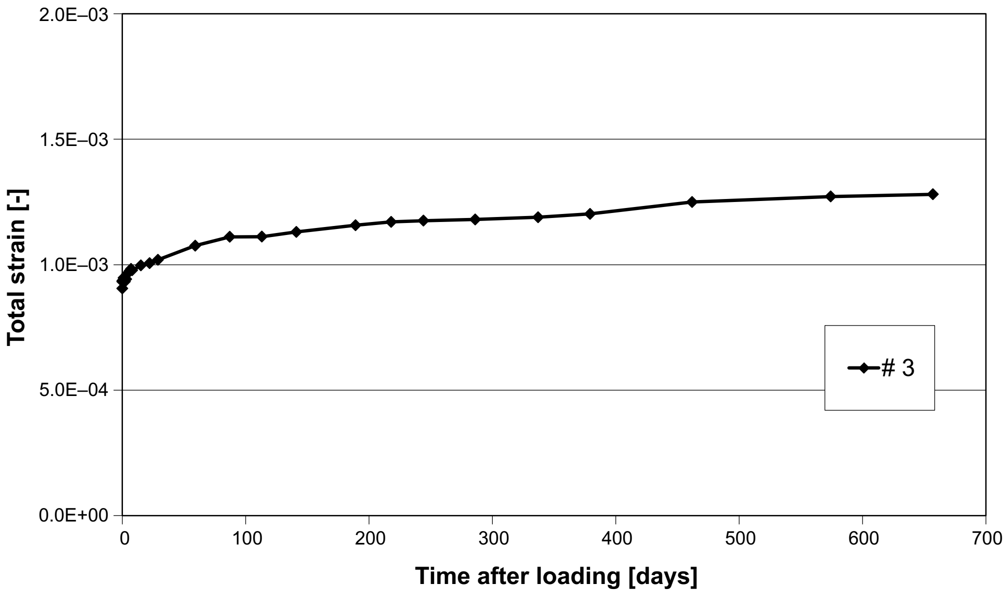

Figure B-3. *Total strain versus time after loading for creep specimen # 3.*

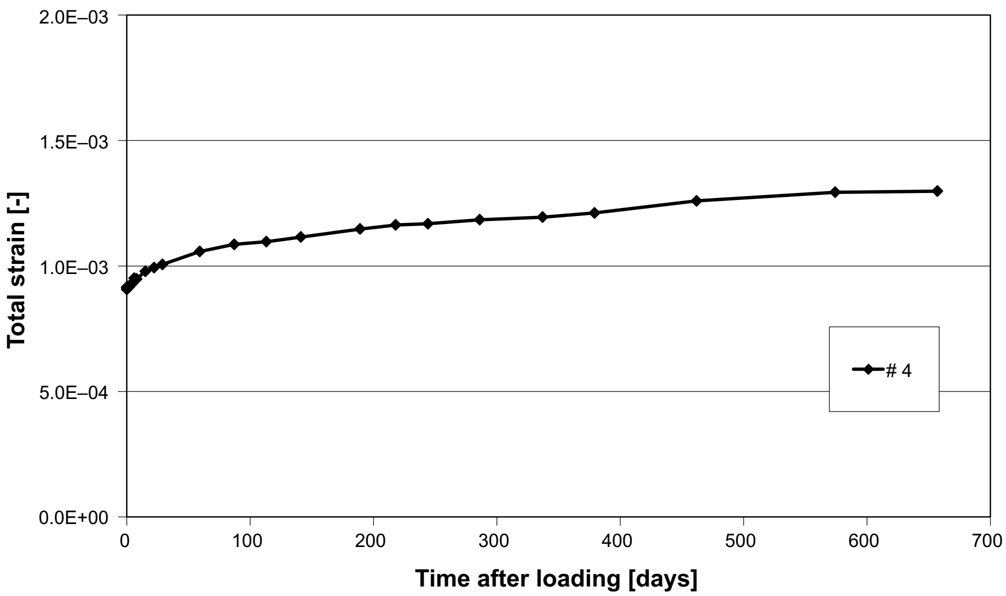

Figure B-4. *Total strain versus time after loading for creep specimen # 4.*

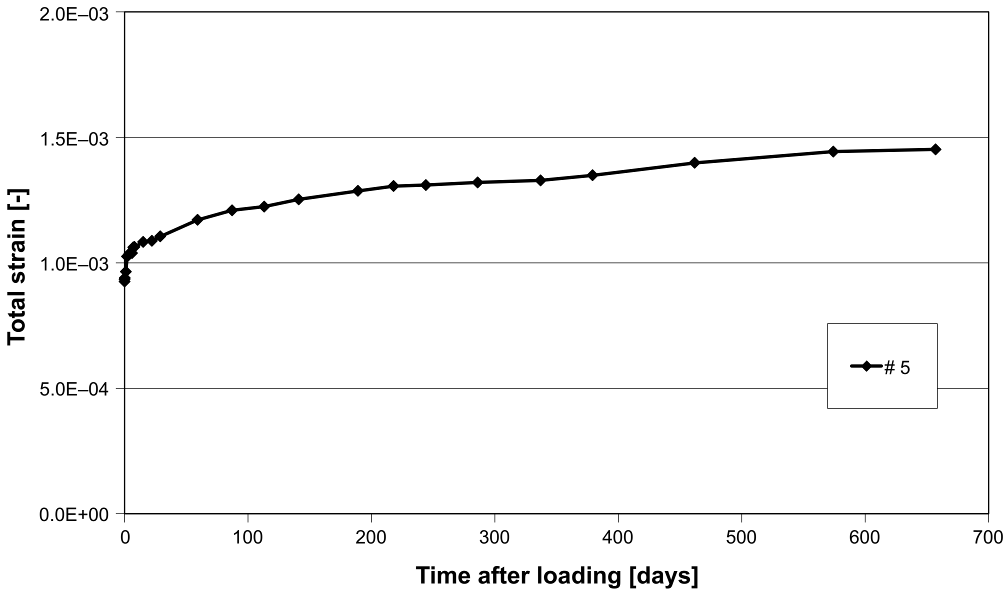

Figure B-5. *Total strain versus time after loading for creep specimen # 5.*

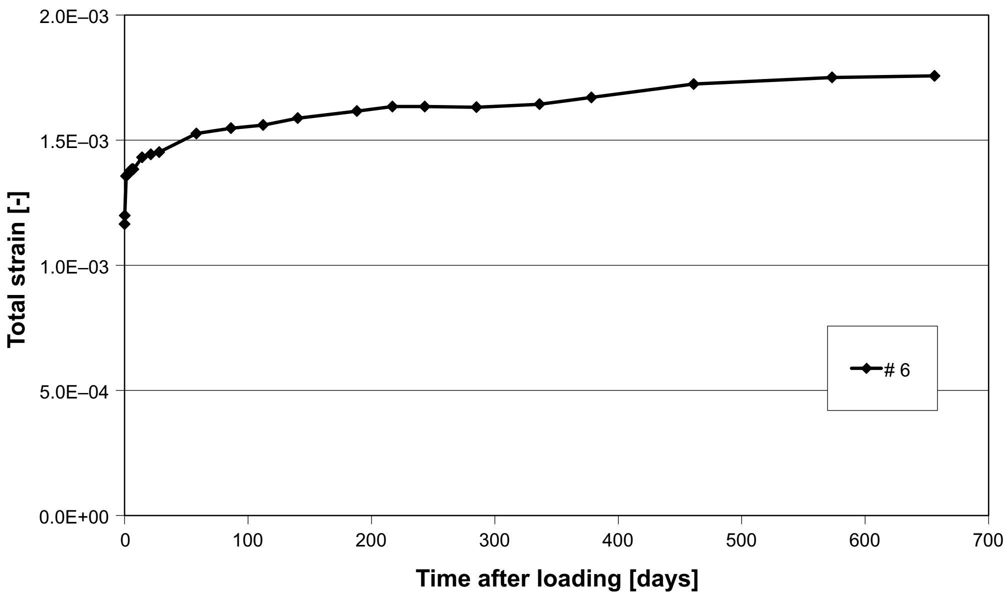

Figure B-6. *Total strain versus time after loading for creep specimen # 6.*

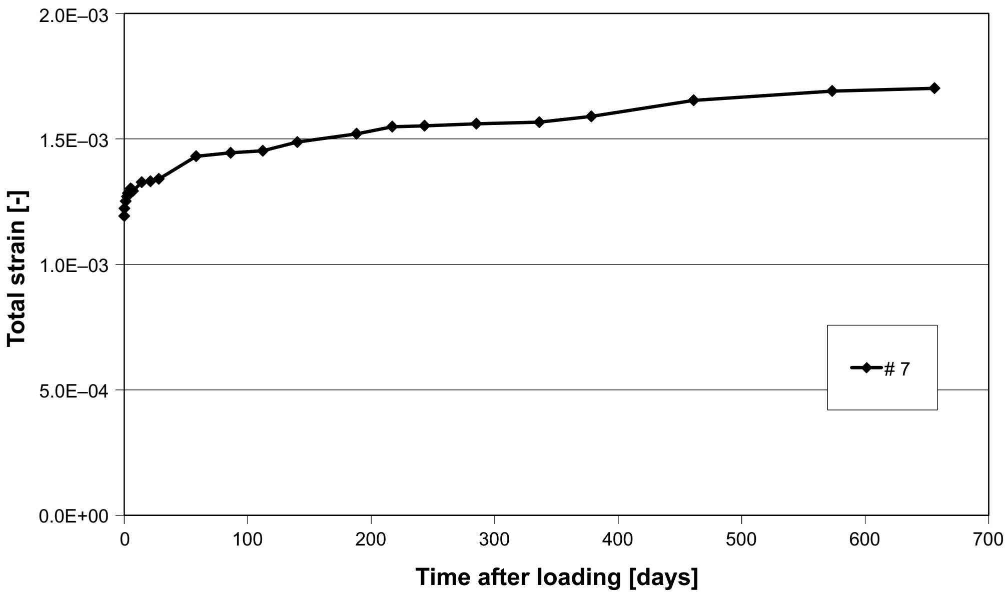

Figure B-7. *Total strain versus time after loading for creep specimen # 7.*

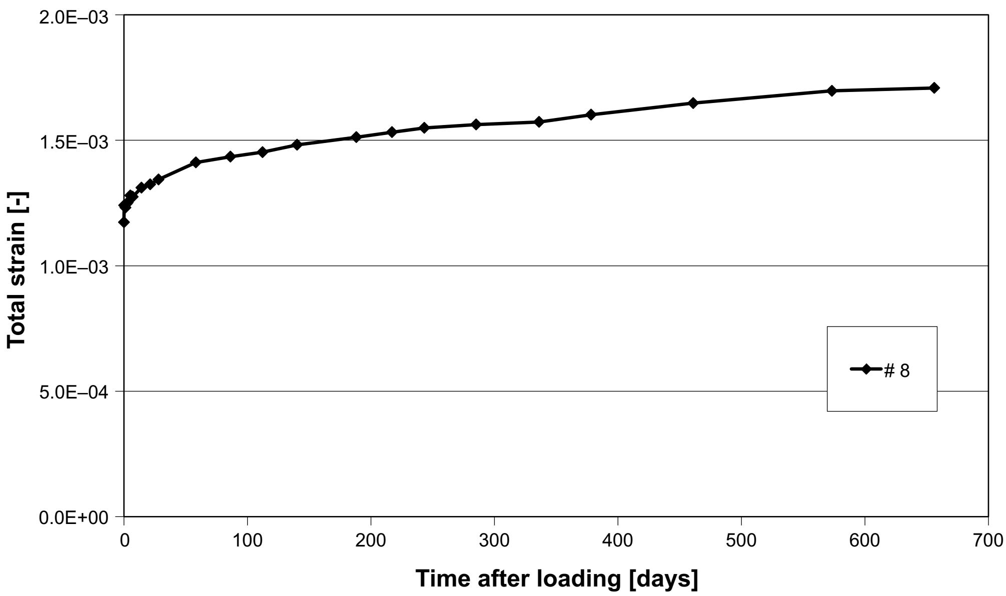

Figure B-8. *Total strain versus time after loading for creep specimen # 8.*

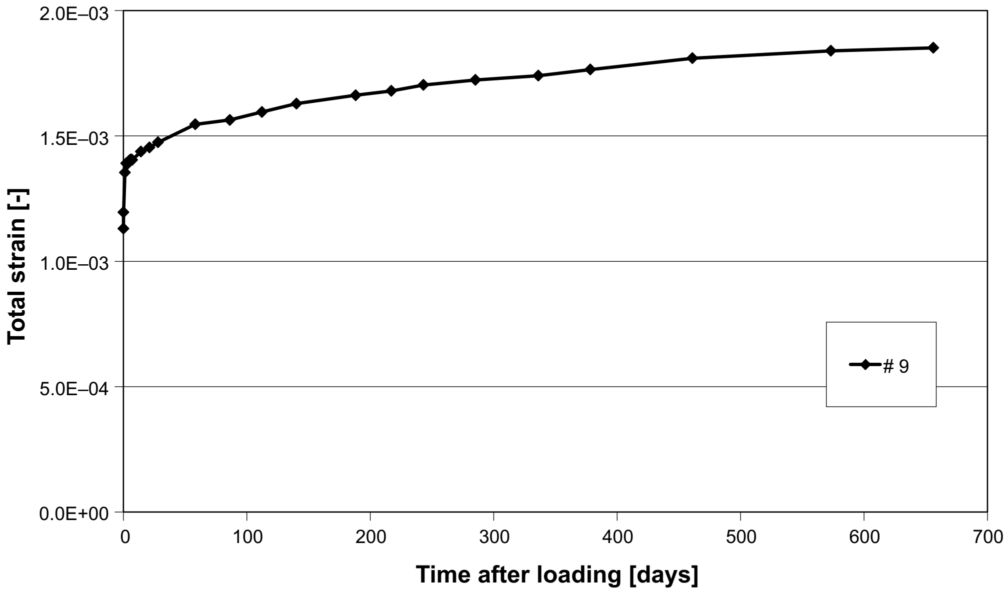

Figure B-9. Total strain versus time after loading for creep specimen # 9.

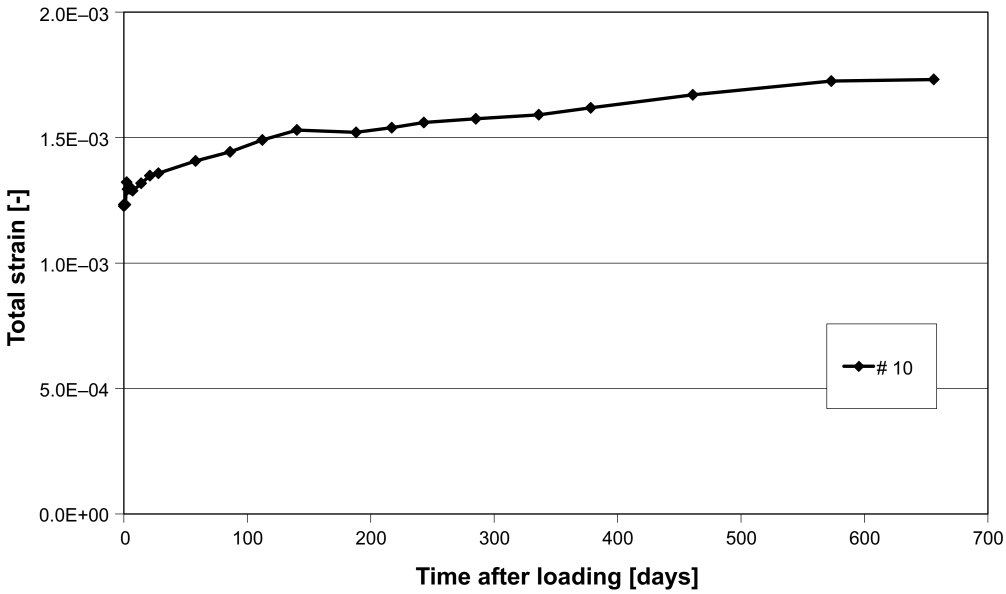

Figure B-10. Total strain versus time after loading for creep specimen # 10.

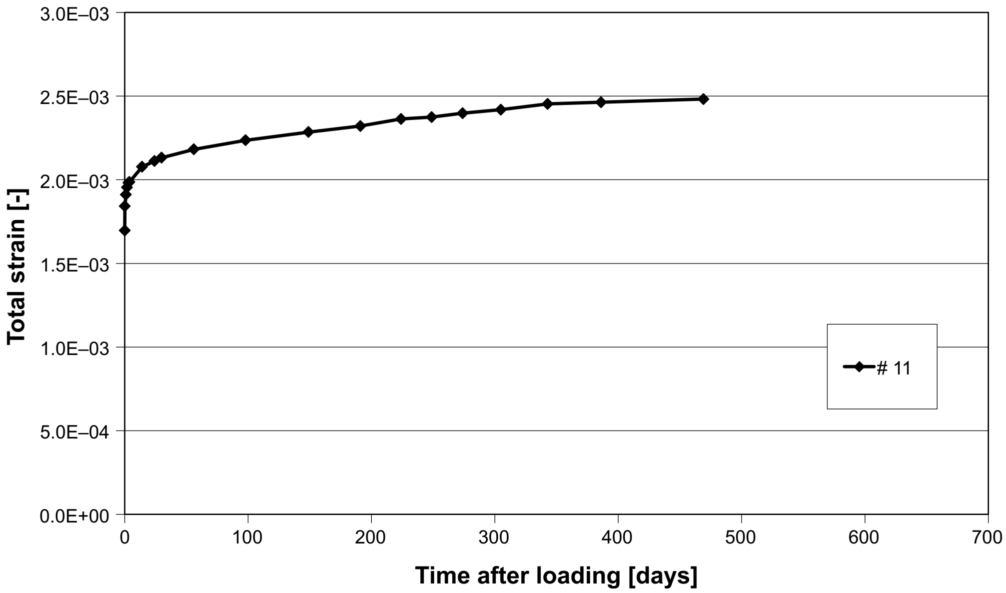

Figure B-11. *Total strain versus time after loading for creep specimen # 11.*

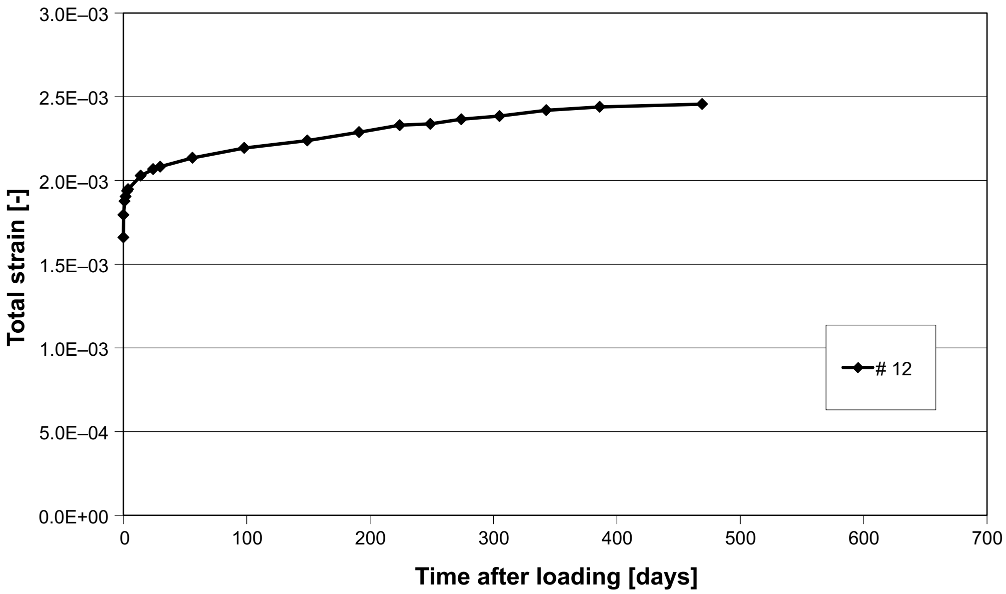

Figure B-12. *Total strain versus time after loading for creep specimen # 12.*

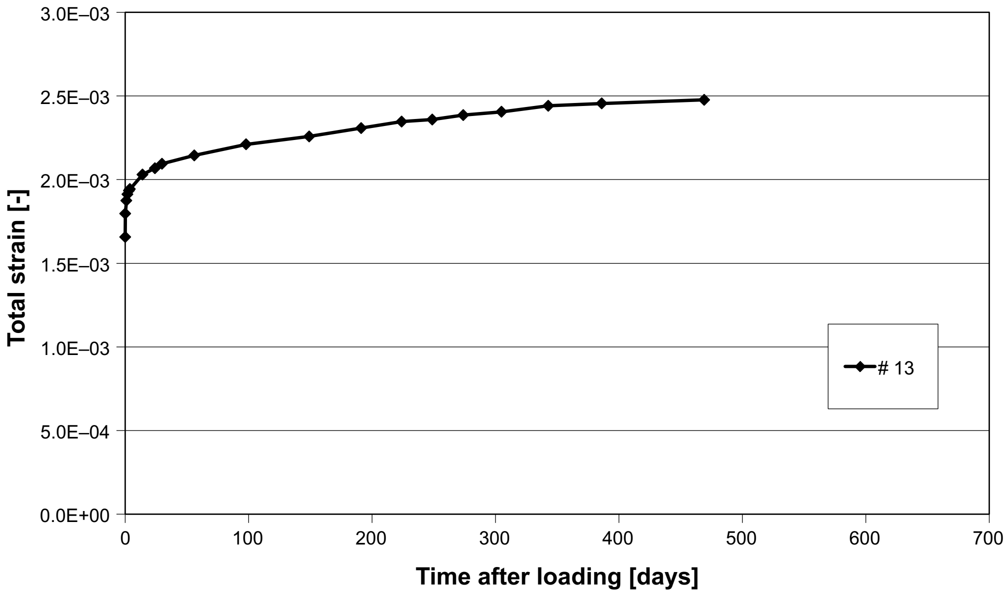

Figure B-13. *Total strain versus time after loading for creep specimen # 13.*

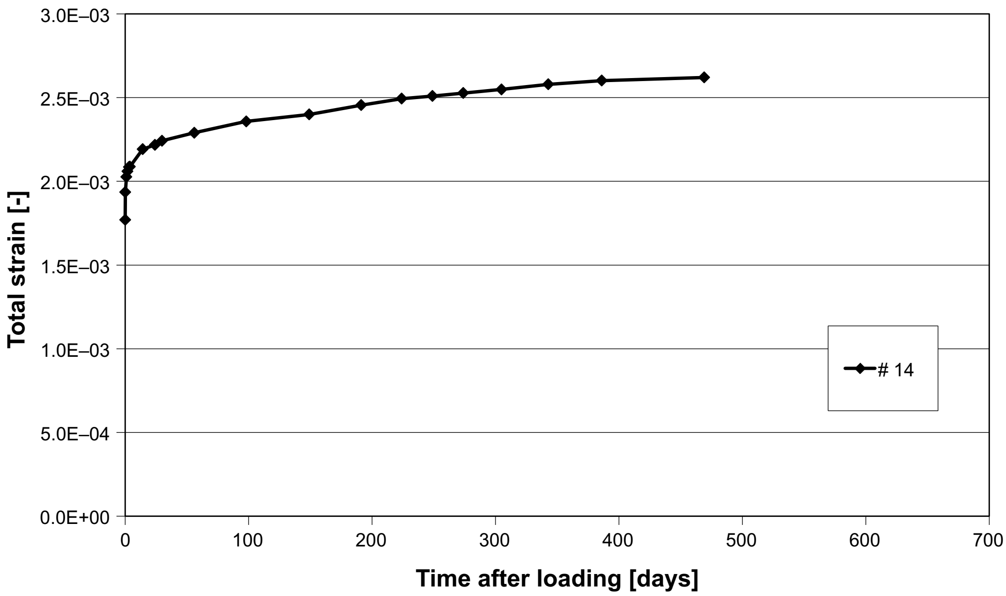

Figure B-14. *Total strain versus time after loading for creep specimen # 14.*

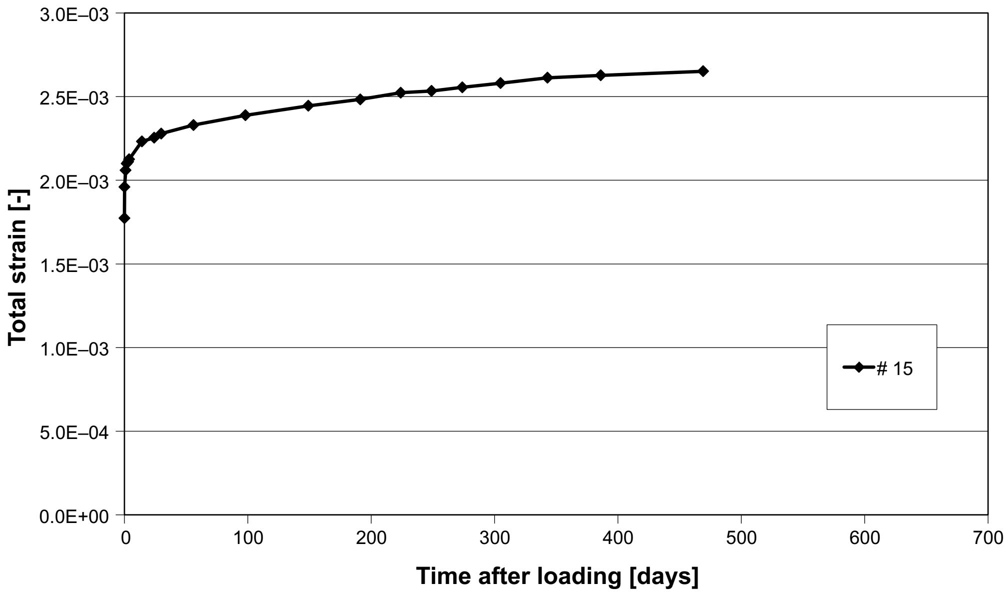

Figure B-15. *Total strain versus time after loading for creep specimen # 15.*

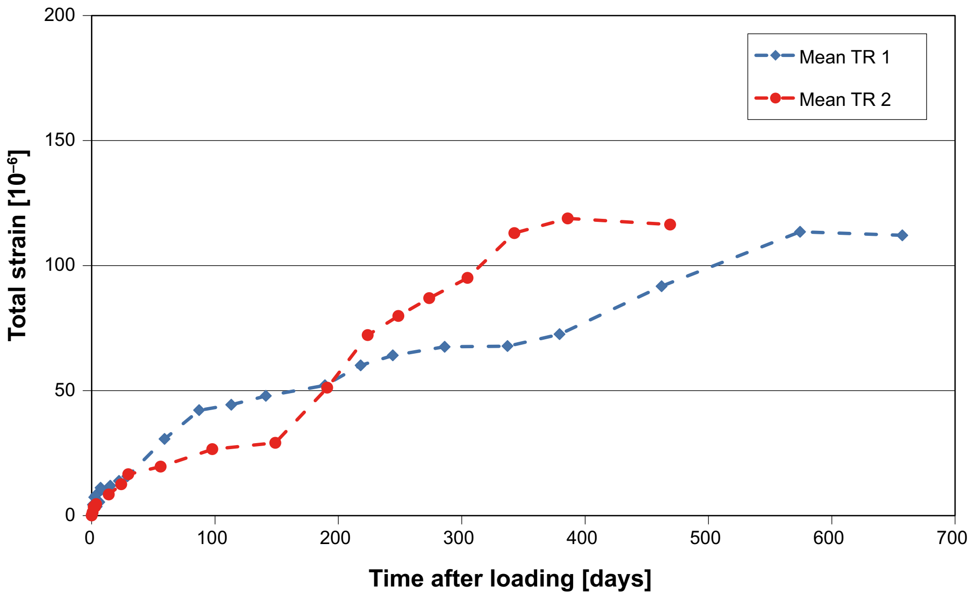

Figure B-16. *Mean value of strain measurements of the five control specimens in the first (TR 1) and the second test run (TR 2).*