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TI-B 102 (15)
Test Method
Strains from Creep and Early-Age shrinkage

Danish Technological Institute
Building and Construction

Test Method
Strains from Creep and Early-Age shrinkage

Descriptors:

Concrete, Creep and Early-Age Shrinkage

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Test Method
Strains from Creep and Early-Age Shrinkage

1. Scope and Area of Application

This test method is applied for determination of creep strain and/or strain caused by early-age shrinkage of concrete. The method does not include determination of strains caused by desiccation shrinkage, nor does it cover creep strains caused by tension. The strains are determined as a function of the age of the concrete. The determination takes place during a period of 28 days unless other requirements are stipulated.

2. References

DS/EN 12350-2 Testing fresh concrete - Part 2: Slump test

DS/EN 12350-7 Testing fresh concrete - Part 7: Air content - Pressure methods

DS/EN 12350-6 Testing fresh concrete - Part 6: Density

DS/EN 12390-2 Testing hardened concrete - Part 2: Making and curing specimens for strength tests

DS/EN 12390-3 Testing hardened concrete - Part 3: Compressive strength of test specimens

TI-B 101 Test Method. Expansion Coefficient of Concrete

DS 423.17 Testing of concrete - Fresh concrete - Hardening

3. Definitions

The following definitions are used in this method:

3.1 Shrinkage

Deformations caused by the hardening process of the concrete with the exception of deformations caused by temperature variations and exchange of humidity with the surroundings.

3.2 Creep

Deformations caused by action from an external load with the exception of initial elastic deformations.

4. Principle of Method

4.1 Shrinkage

The shrinkage is determined as the deformations that take place in a test specimen free from load after the hardening process has started and compensation is made for deformations originating from the temperature variations in the concrete. Exchange of humidity between the test specimens and the surroundings shall be prevented.

The compensation for temperature deformations implies knowledge of the thermal expansion coefficient of the concrete. It is assumed that the thermal expansion coefficient is independent of the age of the concrete during the relevant period. The thermal expansion coefficient may be determined in accordance with TI-B 101.

The determination of shrinkage is performed on the basis of measurements on at least two test specimens. The concrete temperature must be measured in the middle of at least one shrinkage test specimen.

4.2 Creep

Creep is determined by repeated loading and offloading of two test specimens. Exchange of humidity between the test specimens and the surroundings shall be prevented. The measured deformations are compensated for the shrinkage of the concrete and the temperature variations caused by the hardening process by means of the measurements performed on the unloaded shrinkage test specimens that hereby serve as reference specimens. Furthermore, the initial elastic deformations of the concrete are compensated for.

The two creep test specimens shall not be exposed to the same load sequences but shall be loaded and unloaded in opposite phase, see example in Annex B. The concrete temperature must be measured in the middle of at least one creep test specimen.

5. Test Specimens

The test specimens are made of concrete cast in such a way that humidity exchange with the surroundings is prevented from the time of casting. It must be ensured that the concrete is not exposed to unintentional external forces (for instance friction between the test specimen and the mould).

The test specimens are cylinders with a diameter of e.g. 130 mm and a height of e.g. 700 mm.

6. Equipment

6.1 Generel

Equipment for casting of concrete and determination of the temperature of the fresh concrete, slump, air content and density.

Moulds made of a non-absorbent material that is diffusion tight and inactive to cement.

Climate Chamber that can maintain a temperature of 20 ± 1°C.

Temperature sensors for determination of the temperature of the surroundings and the temperature in the middle of a test specimen. The accuracy shall be within ± 1°C at the absolute level. Temperature variations shall be measured within ± 0.5°C.

Deformation gauge to measure length changes. When creep is determined, the length changes shall be measured with load applied. The gauge length shall be 400 - 600 mm. The measurements are carried out on two opposite sides of the specimen. It shall be possible to compensate for possible temperature sensitivity of the deformation gauge. The strain shall be measured with an accuracy of $\pm 1 \cdot 10^{-5}$.

6.2 Creep

Additional equipment required for determination of creep:

Equipment for application of load. The equipment shall be capable of applying a load corresponding to stress in the creep test specimen of at least 15 MPa. The load shall be kept constant in the range of ± 5% during the desired measuring period.

Equipment for measuring the applied load. The accuracy shall be in the range of ± 3%.

Equipment for determination of the compressive strength of the concrete in accordance with DS/EN 12390-3.

7. Measuring Procedure

7.1 Preparation of Test Specimens

The test specimens shall, if possible, be cast of concrete from same batch. The temperature of the concrete should, if possible, be the same as that of the climate chamber at the time of casting (refer section 7.2.1).

Slump, air content and density are determined on the fresh concrete in accordance with DS/EN 12350-2, DS/EN 12350-7 and DS/EN 12350-6, respectively. Furthermore, the concrete temperature is measured. The casting shall be performed according to DS/EN 12390-2 for concrete to be vibrated. After casting, the moulds are closed and placed vertically in the climate chamber.

7.2 Procedure

A measurement comprises correlated values of time, deformations, temperatures and possibly load.
The measurements shall be carried out in a climate chamber or similar, wherein the temperature is maintained constant at 20°C ± 1°C throughout the measuring period.

<u>7.2.1 Shrinkage</u>

The measurements shall be initiated as early as possible and no later than when the heat development in the concrete starts. If the casting temperature of the concrete corresponds to that of the climate chamber, the time of initial heat development can be determined as the time where the rise in the concrete temperature exceeds the rise in the temperature of the surroundings by 1°C[1].

Measurements are made at least every 20 minutes throughout the test period.

7.2.2 Creep

The measurements shall be started no later than by the first application of load.

Prior to each application/increase of load the compressive strength is determined according to DS 12390-3 on at least one test specimen made with the same concrete and hardening as the test specimens used in the creep test. This might be omitted if the strength development of the concrete is known.

During each application and relief of load, at least five correlated values of load and deformations are recorded. Measurements are made at least every 20 minutes.

The application of load shall take place at a velocity where the initial elastic deformations do not significantly increase the creep process. This requirement will normally be met if the application of load takes place within a period of 5 minutes. The load should be applied centrally. The off-loading shall take place at the same velocity as the loading. The maximum load must not exceed 40% of the compressive strength at the time of loading.

7.3 Test Results

7.3.1 General

The Maturity M is determined from the measured concrete temperature T as:

$$M = \sum_{i=1}^{n} H\,(T_i)\,\Delta t_i$$

where:

Δt_i	=	Length of time interval i
T_i	=	Mean temperature in time interval i [°C]
H(T)	=	Velocity function defined by:

$$H(T) = exp\left[\frac{E(T)}{R}\left(\frac{1}{293} - \frac{1}{273+T}\right)\right]$$

where:

R	=	Gas constant = 8.314 [J/mol K]
E(T)	=	Activation energy of the concrete [J/mol]

The applied value for E(T) shall be stated. If the correct value is unknown, the following can be used:

E (T)	=	33.500 J/mol for T ≥ 20 °C
E (T)	=	33.500 + 1.470 (20 - T) J/mol for T < 20 °C.

The strain ε_m of the concrete corresponding to the measurement on one side of a test specimen is determined as:

$$\varepsilon_m(M) = \left(\frac{l_0 - l_M}{l_D}\right) + \varepsilon_{T,G}(M)$$

where:

$\varepsilon_m(M)$	=	Measured strain at the maturity M, positive as contraction [µm/mm]
l_0	=	Length at maturity M_0 [µm]
l_M	=	Length at maturity M [µm]
l_D	=	Measuring length [mm]
$\varepsilon_{T,G}(M)$	=	Possible increase in strain caused by temperature sensitivity of the deformation gauge at the maturity M, positive as contraction [µm/mm]

The concrete strain $\varepsilon_{m,n}(M)$ measured on test specimen No. n is determined as average of measurements on two opposite sides of a test specimen.

7.3.2 Shrinkage

The shrinkage strain $\varepsilon_{s,n}$, in test specimen No. n is determined as the measured concrete strain in the test specimen corrected for contributions from the temperature deformations of the concrete:

$$\varepsilon_{s,n}(M) = \varepsilon_{m,s,n}(M) + \alpha_c\,(T_c(M) - T_c(M_0))$$

where:

[1] If it has not been possible to cast the concrete at the same temperature as that of the climate chamber, it will be difficult to determine whether the temperature variations in the concrete have been caused by heat exchange with the surroundings or by heat development in the concrete. In that case, the starting time may be fixed as the time where the penetration resistance determined according to DS 423.17 exceeds 3.5 MPa, and the starting time as well as the setting period determined according to DS 423.17 shall be stated in the report.

$\varepsilon_{s,n}(M)$ = Shrinkage strain in test specimen No. n at maturity M, positive as contraction [µm/mm]
$\varepsilon_{m,s,n}(M)$ = Concrete strain in test specimen No. n at maturity M, positive as contraction [µm/mm]
α_c = Thermal expansion coefficient of the concrete [-]
$T_c(M)$ = Concrete temperature at maturity M [°C]
$T_c(M_0)$ = Concrete temperature at maturity M_0 [°C]

The shrinkage strain of the concrete $\varepsilon_s(M)$ is determined as average of the shrinkage strains determined on the individual test specimens.

7.3.3 Creep

The stress applied to test specimen No. n is determined as:

$$\sigma_n(M) = \frac{1000\ P_n(M)}{\frac{1}{4}\pi d^2}$$

where:
$\sigma_n(M)$ = Stress in test specimen No. n at maturity M [MPa]
$P_n(M)$ = Load applied to test specimen No. n at maturity M [kN]
d = Diameter of test specimen [mm]

The concrete strain caused by an external load to test specimen No. n is determined as:

$$\varepsilon_{l,n}(M) = \varepsilon_{m,c,n}(M) - \varepsilon_{m,s}(M)$$

where:
$\varepsilon_{l,n}(M)$ = Concrete strain caused by external load to test specimen No. n at maturity M [µm/mm]
$\varepsilon_{m,c,n}(M)$ = Strain measured in test specimen No. n at maturity M [µm/mm]
$\varepsilon_{m,s}(M)$ = Mean value of measured strain of the two shrinkage test specimens at maturity M [µm/mm]. (Note that the shrinkage test specimens are hereby applied as reference test specimens).

At the time for each loading and off-loading, the E-modulus of the concrete is determined by means of linear regression. The initial elastic deformations at the maturity corresponding to the time of loading or off-loading, M' are calculated as:

$$\varepsilon_i(M') = \frac{\Delta\sigma(M')}{E(M')}$$

where:
$\varepsilon_i(M')$ = Initial elastic strain, positive as contraction [µm/m]
$\Delta\sigma(M')$ = Change of stress applied at the maturity M´, positive as compression [MPa]
$E(M')$ = E-modulus at maturity M´ [MPa]

The creep strain $\varepsilon_{c,n}(M)$ in test specimen No. n is determined as the concrete strain caused by the external load minus the initial elastic strains.

8. Expression of results

The results are presented graphically. It applies to all graphs that the zero point for time shall correspond to the mixing time, unless information to the contrary is stated on the graph.

Several graphs can be presented on the same figure.

8.1 Shrinkage

The result is expressed as:

Graph with correlated values of maturity and the shrinkage strain of the concrete, $\varepsilon_{s,n}(M)$.

Further information:

Age at the start of the measurements given in maturity hours rounded off to the nearest 0.1 hour.

The thermal expansion coefficient used for the concrete and description of how it was determined.

Graph with correlated values of maturity and measured concrete strain, $\varepsilon_{m,s,n}(M)$.

Graph with correlated values of maturity and shrinkage strain for each test specimen, $\varepsilon_{s,n}(M)$.

Graph with correlated values of maturity and shrinkage strain of the concrete, $\varepsilon_s(M)$.

8.2 Creep

The result is expressed as:

Graph with correlated values of maturity and creep strain for each test specimen, $\varepsilon_{c,n}(M)$.

Further information:

Age at the start of the measurements given in maturity hours rounded off to the nearest 0.1 hour.

Graph with correlated values of maturity and measured concrete strain, $\varepsilon_{m,n}(M)$.

Graph with correlated values of maturity and stress applied for each test specimen, $\sigma_n(M)$.

Graph with correlated values of maturity and concrete strain caused by external load for each test specimen, $\varepsilon_{l,n}(M)$.

9. Test Report

A test report shall include at least the following information:

1. Name and address of testing laboratory.
2. Date and identification of the report.
3. Name and address of client.
4. Test method (No. and title).
5. Deviations from the test method, if any.
6. Identification of the concrete.
7. Date of casting.
8. Fresh concrete properties (slump, air content, temperature, w/c-ratio).
9. Starting time for of shrinkage and creep measurements.
10. Test result (refer section 8).
11. Further information of significance for the evaluation of the result.
12. Evaluation of the result, if included in the assignment.
13. Signature.

Annex A

This annex is included only as a guide and does not form an integral part of the standard.

1. Area of Application

The present annex describes how the shrinkage development process of concrete determined during and after the hardening process can be described so that the shrinkage is included into a stress calculation of hardening concrete.

The measured shrinkage deformations can be observed by means of tests as described in TI-B 102 "Test Method. Concrete. Strains from Creep and Early-Age Shrinkage".

During the described tests, the shrinkage of a concrete specimen without water evaporation is measured as a function of maturity.

2. Scope of Test

The shrinkage developments is measured on two specimens as described in TI-B 102 "Test Method. Concrete. Strains from Creep and Early-Age Shrinkage".

3. Test Results

Figure 1 shows observations from a shrinkage test. The shrinkage strains have been compensated for temperature fluctuations, cf. TI-B 102, by means of a constant thermal expansion coefficient.

For use in calculations of stresses in structures of hardening concrete, the measured shrinkage deformations as a function of maturity can, in principle, be used directly. However, at first, possible noise from the measuring device must be removed from the recorded shrinkage deformations. This can for instance be done by selecting a number of points on the curve insuring that the measured shrinkage development is sufficiently described (Figure 1).

The first point of the curve must correspond to the start of the measurement, as described in TI-B 102. Deformations that occur before this time are not assumed to generate stresses because of the very low E-modulus.

If values of the shrinkage are needed longer than the period of measuring, this can be done in accordance with the theoretical considerations described in section 4.

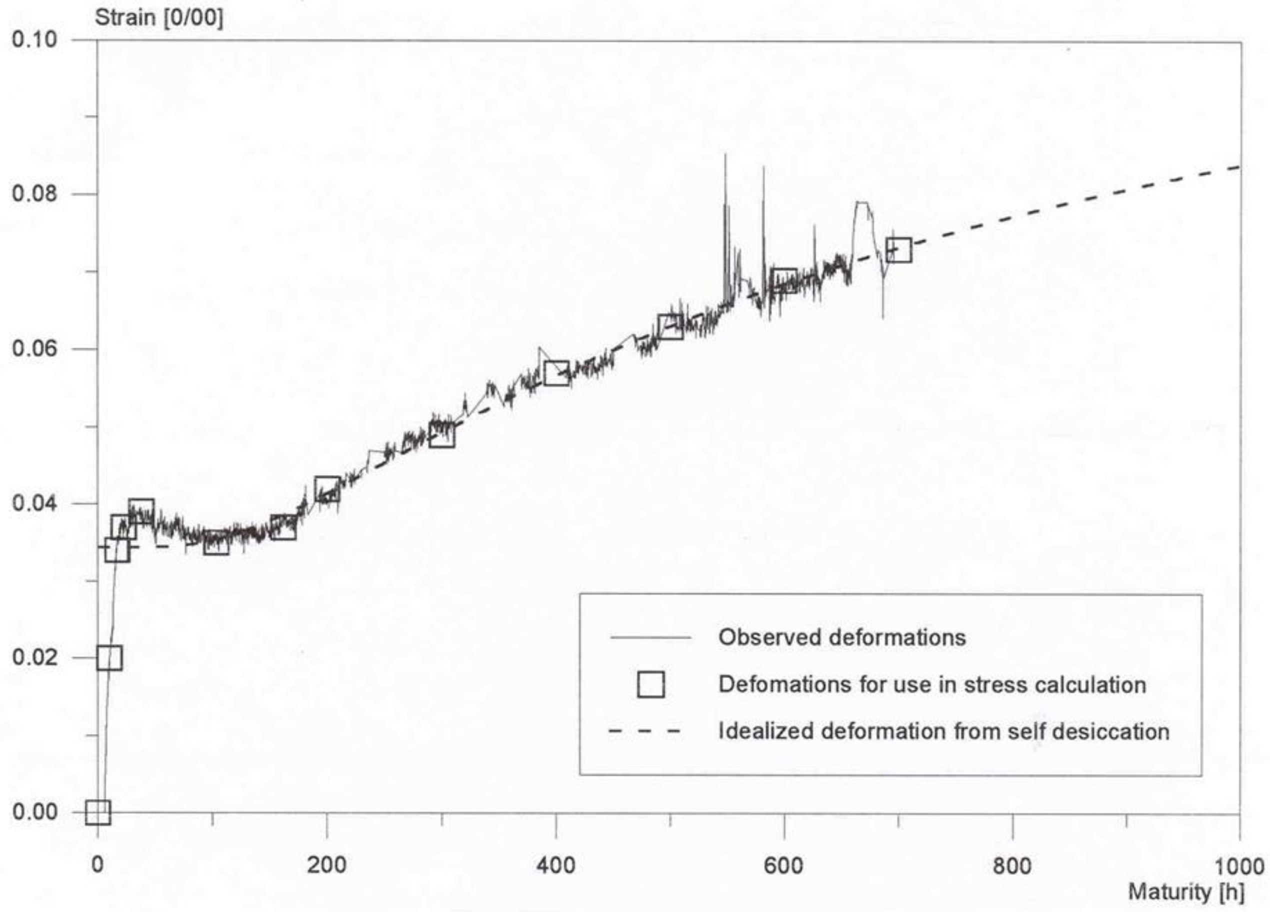

Figure 1 Development of shrinkage

4. Theoretical Considerations

The observed deformations can be divided into two groups:

1) When a concrete with a low w/c-ratio is involved, the capillary water will be used up as water reacts with cement. This will result in a desiccation shrinkage corresponding to the shrinkage observed by desiccation of non-sealed concrete. Calculations based on w/c-ratios and the heat development curves show that shrinkage originating from self-desiccation is observed only after 40 - 100 maturity hours depending on the concrete mix in question.

2) Deformations that are not related to self-desiccation shrinkage can be observed in early-age concrete (Figure 1). Reference to this type of deformations is found in the literature. The only explanations found are that it might be a result of chemical shrinkage and/or of a thermal expansion coefficient that varies during the hydration stage.

The self-desiccation starts when the capillary water V_k has been used up during the reaction with cement. From Powers phase conversion, it is seen:

$$V_k = p - 1.4\,(1-p)\,r$$

where:

p is the specific volume of water before the reaction starts
r is the degree of reaction

The degree of reaction r_{max} corresponding to initial self-desiccation is then

$$r_{max} = \frac{p}{1.4\,(1-p)}$$

The w/c-ratio is introduced by:

$$\frac{p}{1-p} = \frac{\rho_c}{\rho_v}\,v/c - r_{max} = \frac{\rho_c}{\rho_v}\,\frac{v/c}{1.4}$$

where:
ρ_c and ρ_v are the density of cement and water, respectively.

The maturity is introduced by means of the adiabatic thermal development

$$r_{max} = \frac{Q}{Q_\infty} = exp\left(-\left(\frac{\tau_e}{M}\right)^{\alpha}\right)$$

where:
Q_∞, τ_e and α are parameters from the heat development curve of the concrete.

The maturity corresponding to initial self-desiccation is then

$$M_{max} = \frac{\tau_e}{(-\ln(2.22\,v/c))^{\frac{1}{\alpha}}}$$

The measured self-desiccation shrinkage may be approximated by:

$$\varepsilon_{sd} = (\varepsilon_\infty - \varepsilon_0)\exp\left(-\left(\frac{\tau}{M}\right)^{\alpha}\right)$$

where:

ε_0	=	The level corresponding to the zero point of the self-desiccation shrinkage
ε_∞	=	The level corresponding to total self-desiccation
M	=	Maturity
τ, α	=	Curve parameters

The values of ε_0, ε_∞, τ and α are determined on the basis of the temperature compensated shrinkage strains as a function of maturity (Figure 1) by means of the method of least squares. Figure 1 shows the resulting curve. The total self-desiccation shrinkage of the concrete is determined as $\varepsilon_\infty - \varepsilon_0$.

Annex B

This annex is only included as a guide and does not form an integral part of the standard.

1. Area of application

TI-B 102 describes the technical aspects of a method for determination of coherent values of load, deformation and time. The present annex describes how the planning of such test and the subsequent data processing may be carried out, when the objective is to establish a mathematical creep model for stress calculations of hardening concrete.

It is expected that the annex will be revised as more experience is collected.

It is assumed that creep deformations of concrete can be described by means of a rheological creep model as shown on Figure 1. When a test specimen (see TI-B 102) is exposed to repeated loads and relief of loads, the properties of the viscous pistons and the spring can be determined, including the variation in time.

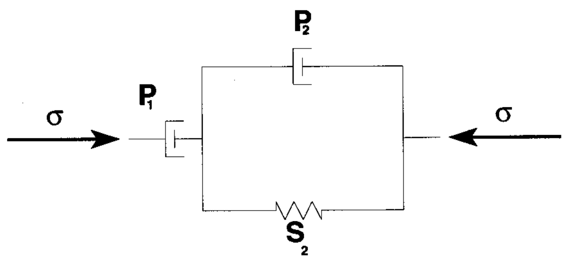

Figure 1. Rheological model for creep strains

2. Scope of Test

Test setup and execution of test according to TI-B 102 "Test method. Concrete. Strains from Creep and Early-Age Shrinkage".

Tests are carried out on two test specimens, the load periods and load levels are chosen so that the test specimens are continuously exposed to load and relief of load. The two test specimens shall be exposed to the load and relief of load sequence alternatively - in the beginning rather short load periods and longer load periods as the concrete matures.

The exposure to load and relief of load shall take place alternatively between two specimens.

The maximum load is 40% of the compressive strength and the first load shall take place as early as possible. An example of a load sequence for two test specimens is shown in Figure 2.

Furthermore, the shrinkage strains are measured on two test specimens not exposed to load, see section 4.1.1 in TI-B 102. These measurements are used to compensate the measurements on the loaded specimens for shrinkage and temperature deformations.

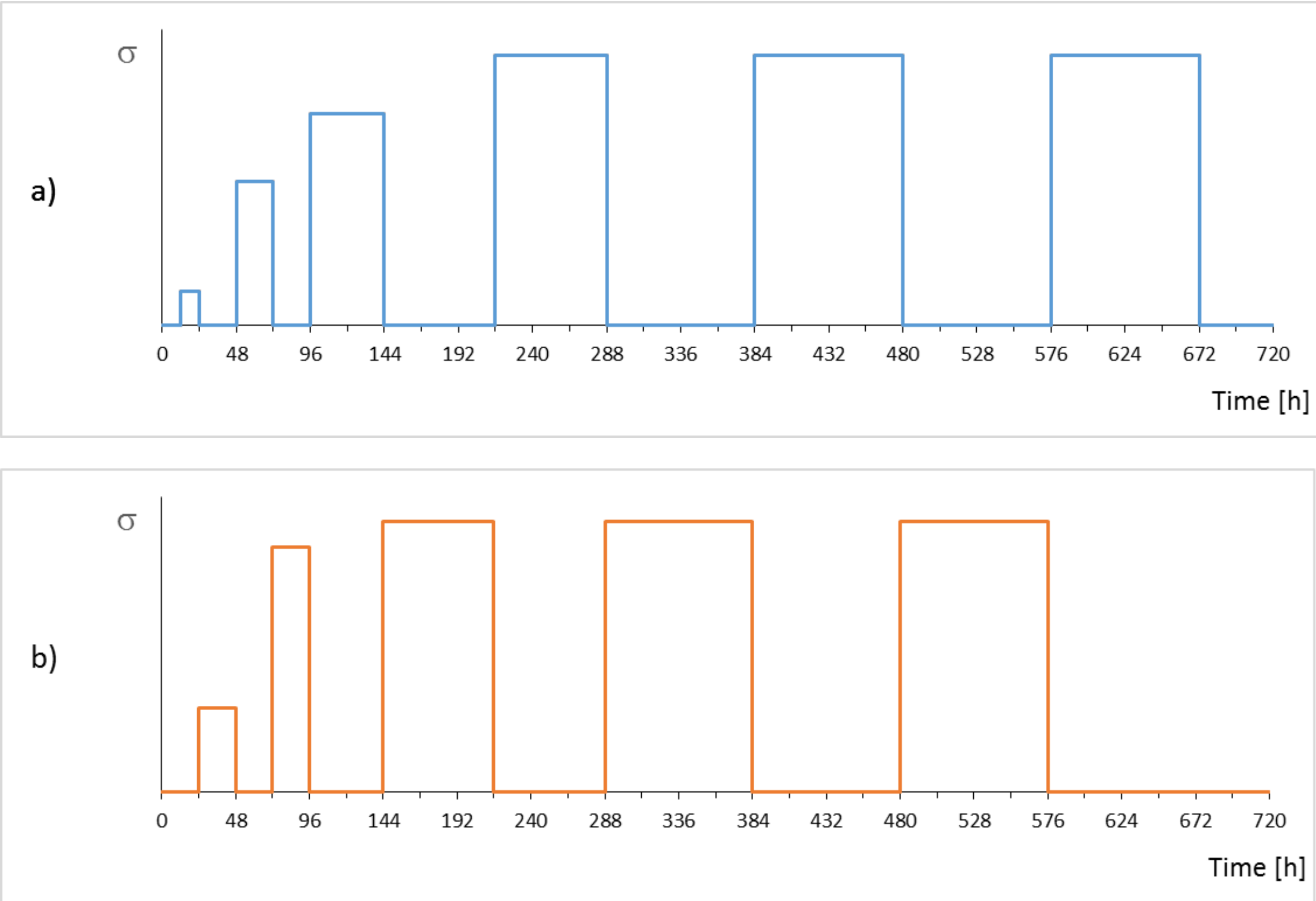

Figure 2 *Example of Load sequences*
Load-level = 40% of actual compression strength
Time = 0: time of mixing.

The load sequences a) and b) provide information for the determination of the properties the creep model in Figure 1, i.e. the properties of the parallel-coupled units and the outer piston.

3. Processing of Test Results

The deformation measurements as a function of time are compensated in accordance with TI-B 102 for the shrinkage movements and temperature fluctuations of the measuring equipment. Furthermore, the creep deformations are isolated from the initial-elastic deformations.

By means of the rheological model, the rate of creep strains can be determined by:

$$\dot{\varepsilon} = \frac{\sigma}{\eta_2} - \frac{E}{\eta_2}\varepsilon_2 + \frac{\sigma}{\eta_1}$$

where:

$\dot{\varepsilon}$ = is the total rate of creep strains
ε_2 = is creep strains in the parallel-coupled units (refer Figure 1)
η_1 = is the viscosity of the piston P_1
η_2 = is the viscosity of the piston P_2
E = is the spring constant for the spring S_2

It is assumed that the development of the viscosities and the spring constant can be expressed by

$$property = a\ time^b$$

The constants (a and b) of the development of the properties can be determined by the method of least squares performed on all the tests simultaneously.

By means of the development of the concrete temperature measured during the creep test, the creep properties are finally converted into a function of maturity instead of time.