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RILEM TC 129-MHT: 'Test methods for mechanical properties of concrete at high temperatures'

Modulus of elasticity for service and accident conditions

The text presented hereafter is a draft for general consideration. Comments should be sent to the TC Chairman: Prof. Dr. Ulrich Schneider, University of Technology Vienna, Institut für Baustofflehre, Bauphysik und Brandschutz, Karlplatz 13/206, A-1040 Vienna, Austria; Tel.: + 43 1 58801 20600; Fax: + 43 1 58801 20699; Email: ulrich.schneider@tuwien.ac.at, by 30 September 2004.

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1. SCOPE

This recommendation is valid for structural applications of concrete under service and accident conditions.

This document presents ***test parameters*** (material and environmental), and ***test procedures*** for determining the modulus of elasticity of concrete cylinders at constant temperature T_{max} after first heating or after cooling from T_{max} to ambient. The test temperatures range from 20 to 750°C or above. The modulus of elasticity can be determined for specimens heated with or without a constant uniaxial compressive externally applied load, see Ref. 1.

2. SERVICE AND ACCIDENT CONDITIONS

2.1 Service conditions

Service conditions normally involve long-term exposure to temperatures in the range 20°C-200°C and moisture states between the two boundary conditions:

Boundary Condition 'd': Drying (unsealed) concrete

Boundary Condition 'nd': Moisture saturated (sealed) concrete.

In general, boundary condition 'd' applies to drying structures in air with a maximum thickness < 400 mm, or structures with no point which is farther than 200 mm away from a surface exposed to air.

Boundary condition 'nd' is defined for the following wet structures:

- Sealed structures independent of their dimensions.
- Zones of structures with a distance > 200 mm from the surface exposed to air.
- Structures under water.

2.2 Accident conditions

Accident conditions normally involve short-term exposure to temperatures in the range 20 to 750°C or above and transient moisture states, *i.e.* the concrete is allowed to dry during heating. In this case the moisture boundary condition is the same as the condition 'd' mentioned above, see Ref. 2 Part 3.

3. DEFINITION

3.1 General

The modulus of elasticity is defined here as "secant" modulus, described in Fig. 3. It can be determined either in the hot state, or at ambient temperature after heating and cooling. Properties determined at temperature T_{max} are henceforth described as "hot". Properties determined after cooling from T_{max} are henceforth described as "residual".

Consequently, the modulus of elasticity of concrete is referred to as

- hot modulus of elasticity or
- residual modulus of elasticity

The modulus of elasticity of concrete may be determined for sealed or unsealed specimens which are loaded or non-loaded during the thermal exposure prior to testing.

Because the stress level σ during heating influences the modulus of elasticity of concrete, it is proposed to distinguish two cases:

- The hot or residual modulus of elasticity of specimens without load during the temperature exposure prior to testing is henceforth defined as "unstressed".
- The hot or residual modulus of elasticity of specimens which are loaded during the temperature exposure prior to testing is henceforth defined as "stressed".

3.2 List of symbols and notations

ε	=	strain = ((L - Li)/Li)
$\Delta\varepsilon$	=	strain increment
$\Delta\varepsilon^{\sigma}$	=	strain increment of "stressed" specimen
σ	=	stress (constant)
$\Delta\sigma$	=	relevant stress difference of the elastic strain increment
E	=	modulus of elasticity
f_c	=	compressive strength
f_c^T	=	compressive strength at temperature T
L	=	measured length (variable)
L_i	=	initial reference length at ambient temperature (constant)
r	=	radius of specimen
R	=	constant heating rate (dT_s/dt)
RH	=	relative humidity
t	=	time (variable)
t_i	=	time at initiation of test
t_{max}	=	time when T reaches T_{max}
T	=	reference temperature (variable)
T_{ca}	=	temperature at central axis of rotation of specimen (variable)
T_{max}	=	maximum reference test temperature (constant)
T_s	=	temperature at the surface of specimen (variable)
ΔT	=	temperature difference $T_s - T_{ca}$
0	=	superscript index for zero stress ($\sigma = 0$)
c	=	subscript index for compression
ca	=	subscript index for location at central axis of rotation of specimen
d	=	superscript index for drying (unsealed concrete)
el	=	subscript index for elastic
i	=	subscript index for initial
max	=	subscript index for maximum
nd	=	superscript index for non-drying (sealed concrete)
res	=	residual
s	=	subscript index for location at surface of specimen
T	=	superscript index for temperature
th	=	subscript index for thermal

3.3 Non-drying concrete

The hot modulus of elasticity of "unstressed", sealed specimens is determined from the strain component $\Delta\varepsilon$ corresponding to the stress interval $\Delta\sigma$ according to Fig. 3, see section 6. 3.

$$E^{T,nd} = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (1)$$

The hot modulus of elasticity of "stressed", sealed specimens is determined according to Equation (2):

$$E^{T,\sigma,nd} = \frac{\Delta\sigma}{\Delta\varepsilon^{\sigma}} \quad (2)$$

The corresponding residual moduli of elasticity are referred to as $E_{res}^{T,nd}$ or $E_{res}^{T,\sigma,nd}$.

3.4 Drying concrete

The hot modulus of elasticity of "unstressed", unsealed specimens is determined from the strain component $\Delta\varepsilon$ corresponding to the stress interval $\Delta\sigma$ according to Fig. 3, see section 6.3

$$E^{T,d} = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (3)$$

The hot modulus of elasticity of "stressed", unsealed specimens is determined according to Equation (4).

$$E^{T,\sigma,d} = \frac{\Delta\sigma}{\Delta\varepsilon^{\sigma}} \quad (4)$$

The corresponding residual moduli of elasticity are refered as $E_{res}^{T,d}$ or $E_{res}^{T,\sigma,d}$.

4. MATERIAL

4.1 Material type

This recommendation applies to all types of concrete used in construction including high performance concrete.

4.2 Mix proportions

Mix proportions shall be determined according to the concrete design in practice with the following proviso:

The maximum aggregate size should not be less than 8 mm.

Note: The modulus of elasticity of concrete is sensitive to the aggregate content which normally comprises 60-80% by volume. Varying the aggregate content may result in variations of the modulus of elasticity.

5. SPECIMEN

5.1 Introduction

The specimens referred to in this recommendation may be laboratory cast, field cast or taken as cores and should conform to the recommendations given below.

5.2 Specimen shape and size

The concrete specimens (see Fig. 1) shall be cylindrical with a length/diameter ratio between 3 and 4 (slenderness).

The specimen's minimum diameters shall be four times the maximum aggregate size for cored samples and five times for cast specimens.

The recommended diameters of the test specimen are 150 mm, 100 mm, 80 mm, and 60 mm to be taken as standard. Other diameters, when used, should be described as "non standard".

5.3 Moulds, casting, curing and storage

5.3.1 Moulds

Moulds shall be cylindrical and should meet the general recommendations of RILEM.

The moulds should preferably be constructed from sufficiently stiff, cylindrical or semi-cylindrical shells made of steel or polymer. The assembled moulds should be watertight so as to prevent leakage of the cement paste or water during casting. If polymer moulds are used, the polymer should not be water absorbent.

5.3.2 Casting

Casting should be performed in two or three stages. The compaction of the concrete in the mould should be done preferably using a vibrating table.

5.3.3 Curing

All specimens shall be stored during the first seven days after casting at a temperature of 20 ± 2°C as follows:

- in their moulds - *during the first 24 ± 4 hours after casting*
- under conditions without moisture exchange - *during the next 6 days*

This can be achieved by several means. The recommended method is to keep the specimens in their moulds adding a tight cap on the top. Other possibilities are the curing:

- in a room with a vapour saturated environment (relative humidity > 98%);
- in a plastic bag containing sufficient water to maintain 100% RH;
- wrapping the specimen in a metal foil, e.g. self-adhesive aluminium sheaths;
- under water (preferably water saturated with $Ca(OH)_2$).

5.3.4 Storage

The further storage conditions up to the beginning of testing shall be chosen to simulate the moisture conditions of the concrete in practice. The following storage conditions are proposed:

- *Moisture condition 'd' (drying concrete)* storage in air at 20 ± 2°C and RH of 50 ± 5%
- *Moisture condition 'nd' (non-drying concrete)* storage within sealed bags or moulds or wrapped in water diffusion tight and non-corrosive foils at 20 ± 2°C.

In each case, the moisture loss of specimens over the storage period should be determined by weighing. For the case of non-drying concrete, the weight loss should not exceed 0.2% of the initial concrete weight determined before storage in a surface dry condition, *e.g.* by dabbing the specimen in water absorbent paper until no traces of humidity appear on the paper.

5.4 Specimen preparation

The length, diameter and weight of the specimen shall be measured before testing.

The concrete specimen shall be prepared so that each end is flat and orthogonal to its central axis. This shall be done at an age of at least 28 days and not later than 2 months before testing.

Specimens representing non-drying concrete shall be sealed by polymer resin, metal or polymer foils, or rigid encasement depending upon the maximum test temperature. The encasement shall not influence the deformation of the specimen or the contact between the specimen and the strain measuring device. The time for the preparation of sealed specimens under laboratory conditions should not exceed 4 hours.

5.5 Age at testing

The specimen should be at least 90 days old before testing.

5.6 Standard and reference compressive strength

The standard cube or cylinder compressive strength at ambient temperature shall be determined at 28 days, and at the time of testing, according to national requirements. In addition the compressive strength of the test specimen according to section 5.2 shall also be determined at 28 days.

The compressive strengths (ambient and hot or residual as appropriate (see Ref. 2, Part 3) of the specimens according to section 5.2 shall be determined at the time of testing. The result shall be used as reference strength of the specimens.

The related reference strength specimens shall come from the same set of batches and shall be tested under the same temperature and load condition, see Ref. 2, Part 3.

6. TEST METHOD AND PARAMETERS

6.1 Introduction

The following test parameters are recommended as "standard" to allow a consistent generation and comparison of test results. However, the test parameters may be altered to suit specific applications. This should be described as "non-standard" and should be carefully detailed in the test report.

6.2 Measurements

6.2.1 Length measurement

Length is measured in the direction of the central axis of the cylindrical specimen, and shall be determined by measuring the distance between two cross-sections on the surface of the specimen with at least two measuring points per cross-section. The measuring points shall be symmetrically arranged on the cross section. The cross-sections shall be perpendicular to the central axis and at least one diameter away from each flat end of the specimen (see Fig. 1). The initial reference length shall be at least one diameter. The initial reference length "L_i" shall be measured at 20 ± 2°C with a precision of at least 0.5%.

Changes in length relative to "L_i" are measured in the direction of the central axis of the specimen.

From the length measurements the strain increments are derived. For strain increments up to 1 000 micro strain, the uncertainty should be less than 10 micro strain. For strain increments exceeding 1 000 micro strain the uncertainty should be less than 20 micro strain.

6.2.2 Temperature measurement

Thermocouples or other types of temperature measuring devices may be used. In special cases it may be necessary to protect the surface thermocouples against radiation.

Temperature measurements shall be made during heating and, when required, during cooling at three points on the surface of the specimen, at the centre and at the level of the two cross-sections as shown in Fig. 1.

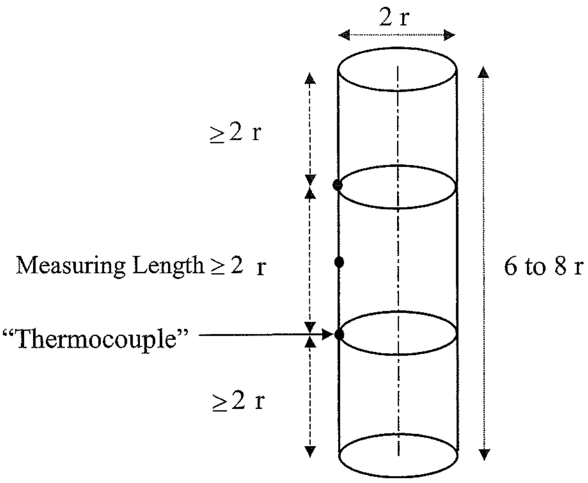

Fig. 1 - Cylindrical specimen showing the location of three temperature measuring points.

The precision of the temperature measurements should be at least 0.5°C or 1% of the measured values whichever is the greater.

The mean surface temperature is the simple average temperature of the three measurements taken on the surface of the specimen.

Load Measurement

The load applied shall be measured with a precision of ± 1%.

6.3 Test procedure

The specimen shall not be removed from the curing environment more than two hours for unsealed specimens and four hours for sealed specimens before the commencement of heating.

The initial moisture content just before testing shall be determined using control specimens (sealed or unsealed) from the same batch cured and stored under the same conditions as the test specimens. The evaporable moisture content is determined according to section 6.4.2.

The specimen shall be placed in the testing machine and centred with an accuracy of 1 % of the specimen's diameter.

A small compressive stress referred to as "pre-load level", not exceeding 0.05 MPa shall be applied in the direction of the specimen's central axis prior to testing (see Fig. 2).

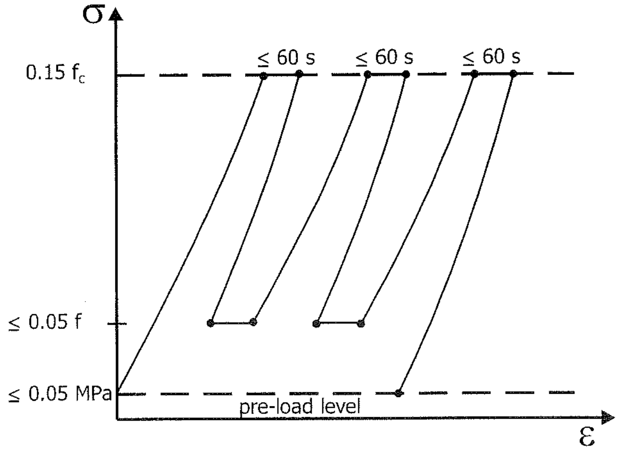

Fig. 2 - Schematic illustration of specimen cycling during installation at ambient temperature to verify the measurement of length change.

Then the specimen shall be subjected to a load cycle between the pre-load level (≤5%) and 15% or ≤5% and 15% of the reference strength, see Fig. 2. The loading and unloading should be performed at a rate of 0.5 ± 0.1 MPa s^{-1}. The hold time at ≤5% and 15% load levels should be less than 60 s. At the end of the loading process the changes in length, as recorded at two or more locations on the surface of the specimen, shall not exceed 20% of the mean value. If this difference exceeds 20%, then the following should be checked: strain measuring device; centering of the specimen; flatness and orthogonality of the flat ends of the specimen. Appropriate adjustments should be made and the load cycle repeated until the 20% criterion is met. If this is not possible within one hour, the specimen should be excluded from the test.

For specimens which are stressed during heating or heating and cooling a uniaxial compressive load is applied continuously in the direction of the central axis of the specimen at a rate of 0.5 ± 0.1 MPa/s to the required constant load level at 20°C immediately prior to heating. The load level must be kept constant according to section 6.2.3. The specimen shall be subjected to heating at the appropriate constant rate (see section 6.4.1), commencing not later than 2.0 ± 1.0 min after reaching the required pre-load level or load level ("stressed specimen).

After reaching the test temperature T_{max} as indicated by the mean surface temperature, the temperature should be maintained for a period of 60 ± 5 min. After the hold time period the specimen may be tested immediately or cooled down to ambient temperature at a specified rate according to section 6.4.1 and tested at ambient.

Before testing the pre-load of the stressed specimens shall be reduced or adjusted to 0.05 MPa. Within ± 1 min after reaching this stress level the test should be commenced.

The test procedure is illustrated on Fig. 3.

The testing commences with a cycling of the specimen according to Fig. 3. The cycling shall be performed with an upper level of stress of 0.3 f_c^T or 0.3 $f_{c,res}^T$ and a lower level of stress of 0.05 f_c^T or 0.05 $f_{c,res}^T$ (see Ref. 2, Part 3). The hold time at 0.05 or 0.3 of the appropriate reference

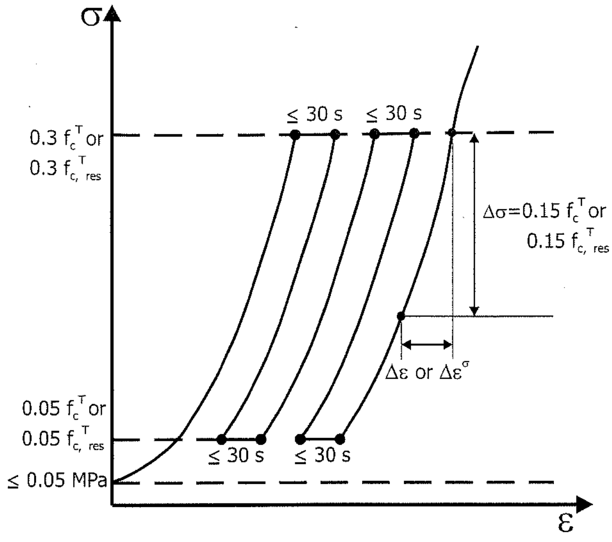

Fig. 3 - Schematic illustration of the test procedure showing how the reference, hot or residual modulus of elasticity is determined.

strength level should be ≤ 30 s. The rate of loading and unloading shall be 0.5 ± 0.1 MPa s^{-1}.

The compressive strength f_c^T or $f_{c,res}^T$ referred to shall be determined according to Ref. 2, Part 3.

The third ascending branch of the test is being used to determine the strain increment $\Delta\varepsilon$ or $\Delta\varepsilon^{\sigma}$, see sections 3.3 and 3.4.

The strain increment shall be determined in the stress interval from 0.15 to 0.3 of f_c^T or $f_{c,res}^T$.

6.4 Test parameters

6.4.1 Heating and cooling conditions

For normal weight concrete, the recommended heating and maximum cooling rates as well as the temperature recording intervals for service and accident conditions are given in Table 1.

Note: For all types of concrete, the radial temperature differences in the cylindrical part of the specimen should not exceed 20°C during heating or cooling. An approximation of this temperature difference during a heating or a cooling at a constant rate can be made using the formula $\Delta T = Rr^2/4D$, where D = Thermal diffusivity of the concrete, R = rate of heating, r=specimen radius. The thermal diffusivity D varies significantly with temperature and type of concrete.

The heating of the concrete specimen should be performed in a way that a uniform temperature is ensured around the circumference of the test specimen and axially along the reference length. Maximum axial temperature differences between any of the three surface temperature readings shall not exceed 1°C at 20°C, 5°C at 100°C and 20°C at 750°C. For intermediate values, the maximum axial temperature differences permitted shall be calculated by linear interpolation between the two adjacent points.

Note: Concrete can spall explosively when heated. Precautions should, therefore, be taken to avoid damage or injury.

Table 1 - Recommended heating and maximum cooling rates and maximum temperature recording intervals at the surface of the specimen on the reference length

Maximum diameter of the cylindrical part (mm)	Rate of heating or cooling (°C/min)	Temperature recording interval (min)
150	0.5	16
100	1.0	8
80	2.0	4
60	4.0	2

6.4.2 Moisture condition

The moisture content just before testing shall be determined using a reference specimen cured and stored under the same conditions as the test specimen. The moisture content is the loss in weight related to the weight of a dried specimen. It is determined by drying at 105°C until constant weight is achieved (when the change of weight due to moisture loss does not exceed 0.1% of the specimens weight over a period of 24 ± 2 hours), and by measuring the maximum weight loss.

During testing the drying specimens shall be heated in a heating device where the moisture can freely escape from the specimen and the heating device.

Non-drying specimens shall be heated and tested with a total moisture loss during the test less than 0.5% by weight of a similar specimen dried at 105°C.

Note. In the test temperature range from 20°C to 150°C the determination of moisture loss after the test is recommended in the case of drying concrete specimens. This is because during the hold time of 1 hour the evaporable moisture is unlikely to escape totally from the specimens, i.e., *specimens with a boundary moisture condition "d" may comprise different absolute values in this temperature range. At higher temperatures it can be assumed that more than 95 % of the moisture loss occurs during heating within the hold time of one hour.*

6.4.3 Number of tests

A minimum of two "replicate" specimens shall be tested for any unique combination of test and material parameters. The simple mean of two or more specimens should be determined. If the test results differ more than 20% a third or more specimens should be tested. If the result of a single specimen differs more than 20% from the mean value of all specimens it should be excluded from the evaluation.

7. APPARATUS

The test apparatus normally comprises a heating device, a loading device, and instruments for measuring temperature, load and length changes of the specimen.

The test apparatus must be capable of fulfilling the recommendations given in section 6 for the test parameters and the levels of precision.

8. EVALUATION AND REPORTING OF RESULTS

8.1 Evaluation of the reference temperature

The reference temperature of the specimen "T" is calculated from the mean surface temperatures using:

$T = (T_1 + T_2 + T_3)/3$ (5)

where T_1, T_2 and T_3 are the measured surface temperatures.

8.2 Evaluation of strain results

8.2.1 Non-drying concrete and drying concrete

The *strain difference* $\Delta\varepsilon$ or $\Delta\varepsilon^{\sigma}$ of a each concrete specimen is evaluated, as the arithmetic mean of two or more of the recorded strain values, in accordance with the procedures given in section 6. If the difference of the mean value and a single value measured exceeds 20 % the result for this specimen has to be excluded.

8.2.2 Average modulus of elasticity

The modulus of elasticity of the concrete is the simple *average* evaluated as the arithmetic mean of the values of two or more accepted specimens (see section 6.4.3).

8.3 Test report

8.3.1 General

The method of evaluating the modulus of elasticity of the concrete shall be described including any deviation from the standard. The valid result of each specimen tested shall be reported together with the mean modulus of elasticity as follows:

- unstressed specimens: $E^{T,nd}$ or $E^{T,d}$ and $E_{res}^{T.nd}$ or $E_{res}^{T,d}$
- stressed specimens: $E^{T,\sigma,nd}$ or $E^{T,\sigma,d}$ and $E_{res}^{T,\sigma,nd}$ or $E_{res}^{T,\sigma,d}$

The report shall include the items highlighted by underlining below. The other items listed below should be reported when available.

8.3.2 Mix proportions

Cement type and source, cement replacements, additives, cement content, water/cement ratio, maximum aggregate size, aggregate/cement ratio, aggregate grading, mineralogical type of aggregate, aggregate content by volume of concrete.

8.3.3 Fresh concrete

Air content, bulk density, slump (or equivalent).

8.3.4 Hardened concrete and specimen details

Curing regime, age at testing, initial moisture content of reference specimen, assumed thermal diffusivity "D", standard cube strength or cylinder strength, reference compressive strength, reference modulus of elasticity at ambient, diameter and length of specimen, mode of preparation of the flat surfaces of the specimen, method of sealing (if applicable), weight before and after testing (excluding the weight of items such as thermocouples).

8.3.5 Test apparatus

The apparatus used shall be described unless it is in accordance with a published standard, in which case the standard should be referenced.

8.3.6 Test parameters

Time between removal of specimen from the curing environment and initiation of heating. Time between end of loading and start of heating. Initial reference length. Level of the restraining load (if applicable).

The following should be reported as functions of time during heating: individual temperature measurements, mean surface temperature, mean centre temperature, reference temperature, rate of heating, axial and radial temperature differences, and changes in the measured length (including any adjustments made for movements of any or all components of the length measuring device).

Any deviation from the recommended test parameters (*e.g.* heating rate, loading rate, load level during heating) shall also be reported separately as "non-standard".

8.3.7 Strain during initial load cycling

Strains during initial two load cycles measured for each location at ambient temperature (section 6.3).

8.3.8 Modulus of elasticity results

The modulus of elasticity results for non drying concrete $E^{T,nd}$, $E_{res}^{T,nd}$, $E^{T,\sigma,nd}$ and $E_{res}^{T,\sigma,nd}$ or drying concrete $E^{T,d}$, $E^{T,\sigma,d}$, $E_{res}^{T,d}$ and $E_{res}^{T,\sigma,d}$ of every specimen shall be reported in tabular form as function of the reference temperature.

The average modulus of elasticity (see section 8.2.2) shall also be reported.

8.3.9 Place, date, operator

Country, city and institution where the experiment was carried out. The dates of the experiment and report. Name of the operator.

REFERENCES

[1] Schneider, U. and Schwesinger, P. (Ed.), 'Mechanical testing of concrete at high temperatures', RILEM Transaction 1, February 1990, ISBN: 3-88122-565-X, Kassel, 1990.

[2] RILEM TC 129-MHT Committee, 'Test methods for mechanical properties of concrete at high temperatures', The Committee is in the process of preparing the following documents:
Part 1: Introduction
Part 2: Stress-strain relation
Part 3: Compressive strength (published, 1995)
Part 4: Tensile strength (published, 2000)
Part 5: Modulus of elasticity
Part 6: Thermal strain (published, 1997)
Part 7: Transient creep for service and accident conditions (published, 1998)
Part 8: Steady-state creep and creep recovery (published, 2000)
Part 9: Shrinkage (published, 2000)
Part 10: Restraint
Part 11: Relaxation