Recommendation of RILEM TC 200-HTC: 'Mechanical concrete properties at high temperature – Modelling and applications'

Part 10: Restraint stress

The text presented hereunder is a general draft for general consideration. Comments should be sent to the TC Chairman Prof. Ulrich Schneider, Technische Universität Wien, Institut für Baustofflehre, Bauphysik und Brandschutz, Karlplatz 13/206, A-1040 Wien, Austria; Tel: +43 1 58801 20600; Fax: +43 1 58801 20699; Email: ulrich.schneider@tuwien.ac.at, by 30 June 2006.

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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 *restraint stress* of concrete cylinders during first heating at a constant rate "R" in the range 20°C to 750°C or above under restraint.

This document also presents test parameters and test procedures for determining the restraint stress during the transitional thermal period when the rate of heating of the specimen reduces from the constant rate "R" to "0" at a constant temperature level "T_{max}" at which point steady-state temperature tests, *e.g.* relaxation tests, will commence (see [2], Part 11).

2. SERVICE AND ACCIDENT CONDITIONS

2.1 Service Conditions

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

Boundary Condition 'd': Drying (unsealed) concrete
Boundary Condition 'nd': Non-drying (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°C 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.

3. DEFINITION

3.1 General

Restraint stress of concrete is defined as the stress resulting from dimensional constraint in the axial direction of a specimen during first time heating at a constant rate, together with any initially applied stress. The restraint stress is resulting from maintaining the length of a concrete specimen constant during the heating process. The specific definitions of restraint stress for non-drying and drying concrete are given in section 3.3.

3.2 List of symbols and notations

α = constraint stress ratio
f = strength
ε = strain $= (L - L_i)/L_i$
σ = stress
A = cross section of the specimen
D = thermal diffusivity
$F_{r,tot}$ = measured total restraint force
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)
T_s^* = surface temperature at which dT_s/dt reduces from "R"
TTP = transitional thermal period
ΔT = temperature difference $T_s - T_{ca}$
0 = superscript index for zero stress ($\sigma = 0$)
c = subscript index for compressive
ca = subscript index for location at central axis of rotation of specimen
co = subscript index for constant temperature regime
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)
r = subscript index for restraint
s = subscript index for location at surface of specimen
tr = subscript index for transient temperature regime

3.3 Restraint stress of non-drying and drying concrete

For non-drying concrete subjected to a thermal exposure with a constant restraint ε_i caused by an initial stress σ_i or an initial stress level α_i the restraint stress σ_r at a temperature T is expressed in Equation (1).

$$\sigma_r^{T,\alpha_i,nd} = \frac{F_{r,tot}}{A} \tag{1}$$

Accordingly the restraint stress can be expressed as a fraction of f_c:

$$\alpha_r^{T,\alpha_i,nd} = \frac{\sigma^{T,\alpha_i,nd}}{f_c} \tag{2}$$

α_i is defined as:

$$\alpha_i = \frac{\sigma_i}{f_c} \tag{3}$$

For drying concrete subjected to thermal exposure with a constant restraint ε_i the restraint stress σ_r at a temperature T is expressed as shown in Equation (4):

$$\sigma_r^{T,\alpha_i,d} = \frac{F_{r,tot}}{A} \tag{4}$$

and:

$$\alpha_r^{T,\alpha_i,d} = \frac{\sigma^{T,\alpha_i,d}}{f_c} \tag{5}$$

3.4 Transitional thermal period

When simulating steady state conditions at a constant temperature "T_{max}" after a heating period, the ***transitional thermal period*** is defined as the time between the end of the constant rate of heating "R" period and the beginning of the constant temperature "T_{max}" period, see [2], Part 7.

4. MATERIAL TYPE AND MIX PROPORTION

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

Mix proportion shall be determined according to the concrete design in practice.

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

Note: The development of restraint stress of concrete originates mainly from the thermal expansion of the aggregates and therefore is sensitive to the aggregate content which normally comprises 60-80% by volume. Varying the aggregate content may result in significant variations of the restraint stress.

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 (slenderness) between 3 and 5.

The specimen's minimum diameter 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

To ensure proper compaction casting should be performed in two or three steps with each specimen. 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 $20 \pm 2°C$ as follows:

- in their moulds
  - *during the first 24 $\pm$ 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 $20 \pm 2°C$ and RH of $50 \pm 5\%$
- *Moisture condition 'nd' (non-drying concrete)*
  storage within sealed bags or moulds or wrapped in water diffusion tight and non-corrosive foils at $20 \pm 2°C$.

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 0.5% of the initial concrete weight determined before storage in a surface dry condition, *e.g.* by dabbing the specimens 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 or jackets, 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 and load measuring devices. 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 should be determined at 28 days and at the time of testing using samples of the same type and of the same batch. The latter shall be used as the reference strength of the specimen, see [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, 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

Changes in length relative to "L_i" are measured in the direction of the central axis of the specimen. Length is measured in the longitudinal 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 $20 \pm 2°C$ with a precision of at least 0.5%.

From the length measurements the strain increments are derived. For strain increments up to 1000 micro strain, the uncertainty should be less than 10 micro strain. For strain increments exceeding 1000 micro strain the uncertainty should be less than 20 micro strain.

Note: For the stability of the strain control it may be necessary to take the constant distance between the load platens (or end faces of the specimens) as governing control input instead of the initial reference length "L_i".

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 and in the centre of the specimen as shown in Fig. 1.

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

6.2.3 Load measurement

The initial load and the total restraint force should be measured with a precision of $\pm 1\%$.

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 (see section 6.4.2.).

The specimen shall be placed in the testing machine, centred with an accuracy of 1% of the specimen's diameter. A small compressive stress referred 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 [2], Part 5).

Then the specimen shall be subjected to three load cycles between the pre-load level ($\leq$ 0.05 MPa) and 15% or $\leq$ 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 $\leq$ 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; centring of the specimen; flatness and orthogonality of the flat ends of the specimen. Appropriate adjustments should be made and the load cycles repeated until the 20% criterion is met. If this is not possible within one hour, the specimen should be excluded from the test.

The test is started thereafter with the pre-load or a uniaxial compressive load is then applied continuously in the direction of the central axis of the specimen at a rate of the order of 0.5 ± 0.1 MPa s^{-1} up to the selected initial stress ratio α_i at ambient temperature. Following this, the strain shall be maintained at a constant value (ε_i), *e.g.* by turning the control unit from the load controlled mode to the strain controlled mode (see Fig. 3). Another possibility is to load
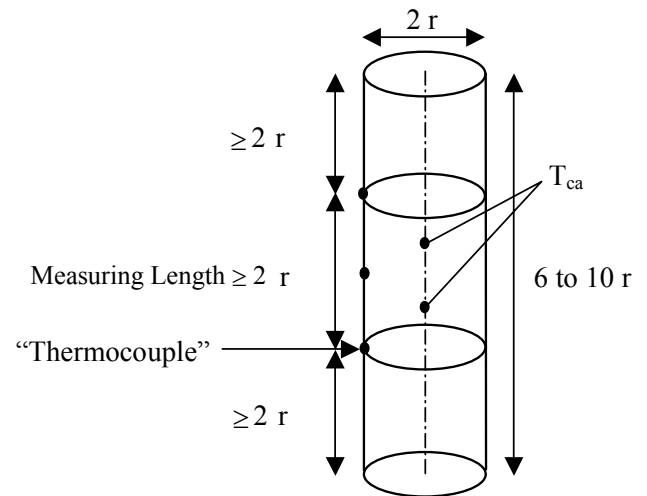

Fig. 1 - Cylindrical specimen showing the location of the temperature measuring points.
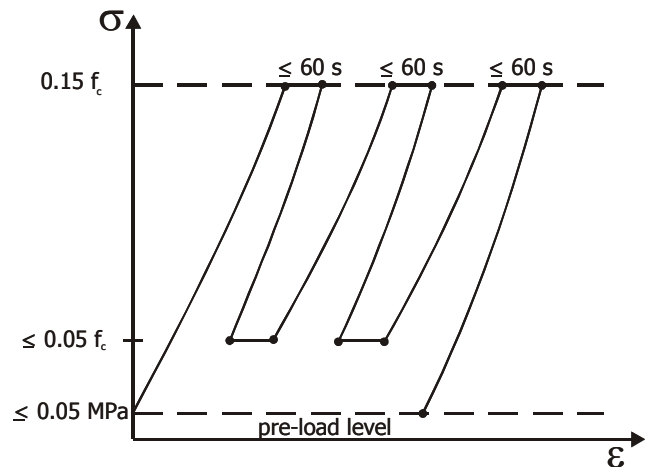

Fig. 2 - Schematic illustration of specimen cycling during installation at ambient temperature to verify the measurement of length change.
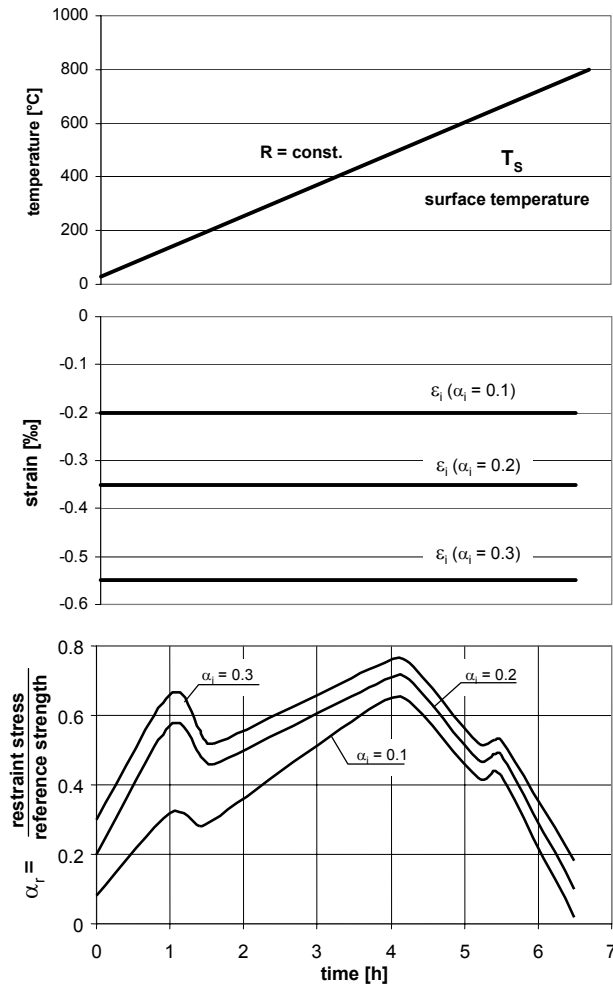
Fig. 3 - Scheme of the restraint tests.

the specimen strain controlled at a constant strain rate of appr. 0.8‰ per minute up to the selected initial stress ratio α_i, and keep the strain constant, thereafter. The specimen shall then be subjected to heating at the appropriate constant rate (see section 6.4.1), within 1 minute after reaching the selected stress ratio.

For a maximum reference test temperature "T_{max}", the test should terminate when the temperature at the central axis "T_{ca}" reaches "T_{max}", thus, ensuring that the reference temperature of the specimen "T" (see section 8.1) has also reached "T_{max}".

Recordings of force and length change shall be taken during initial load cycling (see [2], Part 5). During heating including the transitional thermal period, if relevant, recordings of length change, force and temperature shall be taken at the intervals given in Table 1.

Note: Specimen failure could occur during heating before the maximum test temperature is reached (*e.g.* for high load levels). Appropriate safety measures should be taken.

When subsequently performing a steady-state test at a temperature "T_{max}" (see [2], Part 7), the transitional thermal period TTP starts at "T_s" = "T_s^*" when dT/dt becomes less than "R" (see Fig. 4). T_s^* is to be determined as such that the temperature difference "$T_{max} - T_s^*$" should be less than 1°C at

Table 1 - Maximum recommended intervals for recording length change, force and temperature for service and accident conditions

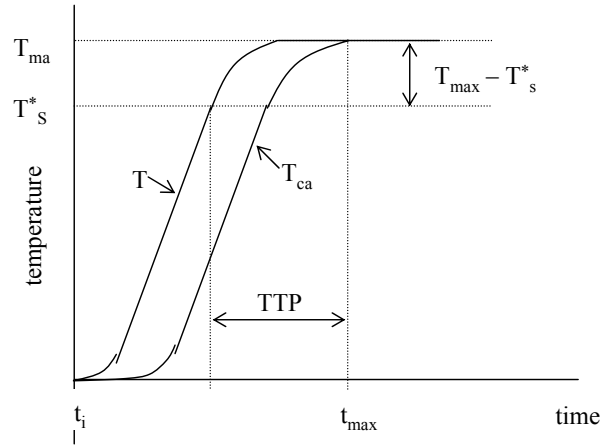| Specimen Diameter [mm]	Service conditions [min]	Accident conditions [min]
150, 100	20	4
80, 60	20	1

Fig. 4 - Definition of the Transitional Thermal Period (TTP).

20°C, less than 3°C at 100°C, and less than 20°C at 750°C. For intermediate temperatures, the maximum permitted value for "$T_{max} - T_s^*$" shall be calculated by linear interpolation.

6.4 Test parameters

6.4.1 Heating conditions

The recommended constant heating rates for service and accident conditions are given in Table 2.

Maximum axial temperature differences between any two of the three surface temperature readings (Section 6.2.2) 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: If – after termination of the restraint test – other tests, *e.g.* thermal strain during cooling, residual strength test etc., are to be performed the maximum cooling rate should not exceed the maximum heating rate.

Note: The recommended specimen diameters and heating rates have been specified to ensure the maximum specimen radial temperature differences normally do not exceed 20°C during heating (see sections 6.2.2 and 8.1).

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

Table 2 - Recommended heating rates "R" at the surface of the specimen for service and accident conditions

Specimen Diameter [mm]	Service conditions R [°C/min]	Accident conditions R [°C/min]
150, 100	0.1	0.5
80, 60	0.1	2.0

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.

6.4.3 Strain condition

The specimen shall be subjected during heating to a constant strain applied in the direction of the specimen's longitudinal axis.

For comparison of data between different laboratories, a constant strain, which is caused by an initial uniaxial compressive load or stress of 30% of the reference strength ($\alpha_i = 0.3$, see section 5.6) is recommended.

6.4.4 Number of Tests

A minimum of two "replicate" specimens shall be tested for any unique combination of test and material parameters. If the test results differ more than 20% a third or more specimens should be tested. The simple mean of two or more specimens should be determined. If the result of a single specimen differs more than 20% of the mean value of all specimens it should be excluded from the evaluation. The related reference strength specimens (see [2], Part 3) should come from the same set of batches.

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, during the period of heating at a constant rate and during the transitional thermal period, from the mean surface and central axis temperatures using:

$$T = T_s - \Delta T / 2 \tag{6}$$

where ΔT represents the temperature difference between the surface temperature "T_s" and the temperature at the central axis of rotation "T_{ca}", *i.e.*:

$$\Delta T = T_s - T_{ca} \tag{7}$$

where "T_{ca}" is the simple average of the two measurements taken on the central axis of rotation of the specimen at one third points between the measuring length cross-sections (sections 6.2.2), and "T_s" is the mean surface temperature of the specimen calculated as a weighed average of the three temperature readings (section 6.2.2) according to the formula:

$$T_s = (T_1 + 2 T_2 + T_3) / 4 \tag{8}$$

where "T_2" is the measured centre surface temperature.

Note: An approximation to ΔT can be made for the period during heating at a constant rate using the formula $\Delta T = Rr^2/4D$, where D = thermal diffusivity of the concrete, r = radius of the specimen, R = rate of heating. The thermal diffusivity "D" varies significantly with temperature and type of concrete.

8.2 Evaluation of restraint stress results

8.2.1 General

For both the constant rate of heating and the transitional thermal period the restraint stress is the measured stress versus reference temperature during heating under a constant strain induced by an initial stress σ_i or stress ratio α_i.

8.2.2 Non-drying concrete

For non-drying concrete the restraint stress or stress ratio is:

$$\sigma_r^{T,\alpha_i,nd} \quad \text{or} \quad \alpha_r^{T,\alpha_i,nd} \tag{9}$$

8.2.3 Drying concrete

For drying concrete the restraint stress or stress ratio is:

$$\sigma_r^{T,\alpha_i,d} \quad \text{or} \quad \alpha_r^{T,\alpha_i,d} \tag{10}$$

8.2.4 Average restraint stress

The restraint stress of the concrete is the *average restraint stress* evaluated as the arithmetic mean of the values of the replicate specimens (see section 6.4.4).

8.3 Test report

8.3.1 General

The restraint stress of concrete for each combination of parameters is the measured stress versus temperature during heating under a constant strain (see section 8.2) obtained from the specimens tested for this combination. The mean values and the individual test results shall be reported.

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

8.3.2   Mix proportion

Cement type and source, cement replacements, additives, cement content, water/cement or water/binder 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, 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. Initial stress or initial stress ratio.

The following should be reported as functions of time during heating: individual measured temperatures, 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), and strain changes.

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

For service conditions: Transitional thermal period, maximum constant test temperature "T_{max}",
    $T_{max} - T^*_{s}$, deviation from T_{max} with time of both T_S and T_{ca}.

8.3.7   Strain during initial load cycling

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

8.3.8   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

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