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RILEM TC 129-MHT: TEST METHODS FOR MECHANICAL PROPERTIES OF CONCRETE AT HIGH TEMPERATURES

Recommendations: Part 6 – Thermal Strain

RILEM TECHNICAL COMMITTEES

The draft of this document has been prepared by the following 10 Committee full members representing 7 countries.

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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 thermal strain, in the direction of the central axis, of cylindrical concrete specimens during first heating at a constant rate "R" without external load at temperatures in the range 20°C-750°C or above, depending on the capability of the test equipment, and during subsequent cooling [1].

2. SERVICE AND ACCIDENT CONDITIONS

2.1 Service Conditions

Service conditions normally involve a long-term exposure to test 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 a short-term exposure to temperatures in the range 20°C-750°C or above and transient moisture states, *i.e.* the test specimens are unsealed and allowed to dry during heating and cooling. In this case, the moisture boundary condition is the same as the condition 'd' mentioned above.

3. DEFINITION

Thermal strain of concrete is the strain determined during heating without external load. The specific definitions for non-drying and drying concrete are given in sections 3.2 and 3.3, respectively.

3.1 List of Symbols and Notations

ε = strain = ((L - Li)/Li)
D = thermal diffusivity
L = measured length (variable)
Li = initial reference length at ambient temperature (constant)
r = radius of specimen
R = constant heating rate (dT/dt)
t = time
T = reference temperature
T_s = temperature at the surface of specimen
T_c = temperature at central axis of rotation of specimen
ΔT = temperature difference $T_s - T_c$
i = index for initial
0 = index for zero stress ($\sigma = 0$)
c = index for location at central axis of rotation of specimen
d = index for drying (unsealed concrete)
nd = index for non-drying (sealed concrete)
s = index for location at surface of specimen
sh = index for shrinkage
th = index for thermal
tot = index for total
tr = index for transient temperature regime

3.2 Non-Drying Concrete

Thermal strain $\left(\varepsilon_{tr,\,th}^{T,\,0,\,nd}\right)$ of non-drying concrete is the strain determined during heating at a constant rate "R" (see Tables 1 and 2) without external load and without moisture loss. It is expressed as a function of the reference temperature "T". The total strain $\left(\varepsilon_{tr,\,tot}^{T,\,0,\,nd}\right)$ of non-drying concrete determined during heating without load therefore represents the thermal strain:

$$\varepsilon_{tr,\,th}^{T,\,0,\,nd} = \varepsilon_{tr,\,tot}^{T,\,0,\,nd} \qquad (1)$$

3.3 Drying Concrete

Thermal strain of drying concrete cannot be determined directly because the total strain also contains a drying shrinkage component $\left(\varepsilon_{tr,\,sh}^{T,\,0,\,d}\right)$, *i.e.*:

$$\varepsilon_{tr,\,tot}^{T,\,0,\,d} = \varepsilon_{tr,\,th}^{T,\,0,\,d} + \varepsilon_{tr,\,sh}^{T,\,0,\,d} \qquad (2)$$

Note: The shrinkage strain is influenced by the temperature in so far as the temperature influences moisture losses. Strictly, shrinkage strains are related to moisture loss.

The thermal strain of drying concrete can, therefore, only be determined after extracting the drying shrinkage strain component from the total strain:

$$\varepsilon_{tr,\,th}^{T,\,0,\,d} = \varepsilon_{tr,\,tot}^{T,\,0,\,d} - \varepsilon_{tr,\,sh}^{0,\,T,\,d} \qquad (3)$$

In practice the thermal and shrinkage strains are determined together and are normally not separable. For this reason, the total strain of drying concrete is loosely called the "thermal strain" and is taken to be so in this document.

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 provisos:

The maximum aggregate size must not exceed 25% of the specimen diameter, except for cast specimens where 20% would be preferred.

In cases where a smaller aggregate than the original maximum aggregate size in the real structure needs to be employed in the tests, the maximum aggregate size should not be less than 8 mm.

Note: The thermal strain of concrete is sensitive to the aggregate type and aggregate content by volume which normally comprises 60-80% by volume. Varying the aggregate content results in significant variations in $\varepsilon_{tr,\,th}^{T,\,0}$.

5. SPECIMEN

5.1 Introduction

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

5.2 Specimen Shape and Size

The concrete specimens shall be cylindrical with length/diameter ratio between 3 and 5 (slenderness).

The specimen's minimum diameter shall be four times the maximum aggregate size for cored samples and preferably 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, and Curing

Moulds shall be cylindrical and should meet the general recommendations of RILEM. The same applies to casting and curing of the specimens.

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.

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

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 top. Other possibilities include storage:

- in a room with a vapour saturated environment (relative humidity > 98%);
- in an air-tight plastic bag containing sufficient water to maintain 100% RH;
- wrapped in self-adhesive aluminium sheaths;
- under water (preferably water saturated with $Ca(OH)_2$).

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 foil at 20 ± 2°C.

In each case, the moisture loss of specimens over the storage period should be determined by weighing. The weight loss should not exceed 0.5% of the concrete weight for the case of sealed specimens.

5.4 Specimen Preparation

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

If necessary, the concrete specimen shall be prepared so that its ends are nominally parallel, 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 Strength

The standard cube or cylinder strength at ambient temperatures 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, The latter shall be used as the reference strength of the specimen.

6. TEST METHOD AND PARAMETERS

6.1 Introduction

The following test parameters are recommended as "standard" to allow consistent generation and comparison of test results. However, other test parameters may be substituted when information is required for specific applications. The "non-standard" test conditions 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 cross-sections shall be perpendicular to the central axis and at least one diameter away from each flat end of the specimen. The initial reference length shall be at least one diameter. The initial reference length shall be measured at 20 ± 2°C with a precision of at least 0.5%.

During the test, changes in the length are normally measured. From these measurements strains are derived. For strains up to 1,000 microstrain, the uncertainty should be less than 10 microstrain. For strains exceeding 1,000 microstrain, the uncertainty should be less than 20 microstrain.

6.2.2 Temperature Measurement

Surface temperature measurements shall be made at three points on the surface of the specimen, at the centre and at the level of the two cross-sections (section 6.2.1), by a temperature measuring device such as suitable thermocouples protected from direct radiation. Temperature measurements at the central axis of rotation shall be made at two points located at one third points between the measuring length cross-sections. The accuracy 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 weighted average temperature of the three measurements taken on the surface of the specimen determined according to equation (6) (section 8.1). The mean central temperature is the simple average of the two measurements taken on the central axis of rotation of the specimen. The reference temperature of the specimen "T" is calculated from the mean surface and central temperatures using equation (4) (section 8.1).

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 testing.

If necessary, a small compressive stress not exceeding 0.01 MPa can be applied prior to heating in the direction of the specimen's central axis.

Note: This limit is specified so that its influence on the deformational behaviour of the specimen during heating is negligible.

The specimen shall then be subjected to heating at the appropriate rate (see section 6.4.1), commencing no later that one hour after being placed in the testing device.

When simulating accident conditions, maximum surface temperature, when reached, should be maintained for 60 ± 5 minutes. If the hold time deviates from this period, this should be referred to as a "non-standard" test condition. Cooling shall take place in the testing device at a rate "R" given in Table 2.

When simulating service conditions, maximum temperature, when reached, should be maintained for 60 ± 5 minutes unless further tests are planned at that temperature (*e.g.* steady-state creep). Cooling shall take place in the testing device at a rate given in Table 2.

Changes in length (see section 6.2) are measured in the direction of the central axis of the specimen from at least two points on the surface of the specimen per cross-section. These points should be at least one diameter away from each flat end of the specimen.

Recordings of temperature and length change, during heating and cooling, shall be taken at the intervals given in Table 1. At constant temperature, recordings shall be taken every 5 minutes.

Table 1 – Maximum recommended intervals for recording temperatures and length changes during heating and cooling for service and accident conditions

Specimen Diameter (mm)	Service Interval (min)	Accident Interval (min)
150, 100	20	4
80, 60	20	1

6.4 Test Parameters

6.4.1 Heating and Cooling Conditions

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

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

Specimen Diameter (mm)	Service R (°C/min)	Accident R (°C/min)
150, 100	0.1	0.5
80, 60	0.1	2.0

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.

Note: The maximum radial temperature differences should be about 20°C during heating and cooling (see sections 6.2.2 and 8.1).

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

6.4.2 Moisture Condition

The initial moisture content just before testing shall be determined using reference specimens (sealed or unsealed) cured under the same conditions as the test specimens. The evaporable moisture content is determined by drying at 105°C until constant weight is achieved (when moisture loss does not exceed 0.1% of the specimen's weight over a period of 24 ± 2 hours), by measuring the maximum weight loss.

Unsealed specimens shall be tested in a heating device where the moisture can freely escape from the specimen and from the testing device.

Sealed and autoclaved specimens shall be heated and tested with a total moisture loss during the test of less than 0.3% by weight of a similar specimen dried at 105°C.

*Note: In the test temperature range from 20 to 150°C, the determination of moisture loss after the test is recommended in the case of unsealed concrete specimens. This is because during the hold time of one 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 moisture values in this temperature range). At higher temperatures, it can be assumed that 95% of the moisture loss occurs during heating at the hold time of one hour.*

6.4.3 Number of Tests

- **Strain Tests**

A minimum of two specimens shall be tested for any unique combination of test and material parameters. The total number of specimens tested shall be at least 2 for one batch and at least 3 for more than one batch.

- **Compressive Strength Tests**

A minimum of 3 specimens shall be tested for each combination of test parameters. For each batch, a minimum of 2 specimens shall be tested. The total number of specimens tested shall be at least 3 for one batch and at least 4 for more than one batch.

7. TEST APPARATUS

The test apparatus normally comprises a heating device and instruments for measuring temperature and length change 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, for the period during heating or cooling at a constant rate, from the mean surface and central temperatures using:

$$T = T_s - \Delta T / 3 \qquad (4)$$

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

$$\Delta T = T_s - T_c \qquad (5)$$

where "T_c" 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 (section 6.2.2), and "T_s" is the mean surface temperature of the specimen calculated as a weighted average of the three temperature readings (see section 6.2.2) according to the formula:

$$T_s = (T_1 + 2T_2 + T_3)/4 \qquad (6)$$

where "T_2" is the measured centre surface temperature.

Note: An approximation to T_c can be made for the period during heating or cooling 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 Strain Results

8.2.1 Non-Drying Concrete

The thermal strain $\left(\varepsilon_{tr,\,th}^{T,\,0,\,nd}\right)$ of non-drying sealed concrete specimens is evaluated in accordance with equation (1) and is equal to the total strain $\left(\varepsilon_{tr,\,tot}^{T,\,0,\,nd}\right)$ determined in accordance with the procedures given in section 6.

8.2.2 Drying Concrete

The "thermal strain" of drying unsealed concrete specimens is considered to be equal to the total strain $\left(\varepsilon_{tr,\,tot}^{T,\,0,\,d}\right)$ (see section 3.3) determined in accordance with the procedures given in section 6.

Note: Due to the contribution of shrinkage, it is possible for $\varepsilon_{tr,\,tot}^{T,\,0,\,d}$ to have a negative value when a concrete of very low thermal expansion is heated.

8.3 Test Report

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

8.3.1 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.

8.3.2 Fresh Concrete

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

8.3.3 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).

8.3.4 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.

8.3.5 Test Parameters

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

The following should be reported as functions of time during heating/cooling: 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, cooling rate, loading rate, load level during heating) shall also be reported separately as "non-standard".

8.3.6 Thermal Strain Results

The thermal strain results $\left(\varepsilon_{tr,\,th}^{T,\,0,\,nd}, \varepsilon_{tr,\,tot}^{T,\,0,\,d}\right)$ of each set of readings from every specimen shall be reported in tabular and/or graphical form as a function of the reference temperature. The "average thermal strain" for each specimen shall also be reported.

8.3.7 Place, Date, Operator

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

9. 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, pp.72.

[2] RILEM TC 129-MHT '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; Part 4 – Tensile strength; Part 5 – Modulus of elasticity; Part 6 – Thermal strain; Part 7 – Transient creep; Part 8 – Steady-state creep and creep recovery; Part 9 – Shrinkage; Part 10 – Restraint; Part 11 – Relaxation.