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RILEM TECHNICAL COMMITTEE

Recommendation of RILEM TC 200-HTC: mechanical concrete properties at high temperatures—modelling and applications

Part 2: Stress–strain relation*

RILEM Technical Committee**

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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 stress–strain relation of concrete at constant temperature T_{max} after first heating or after cooling from T_{max} to ambient. The test temperatures range from 20°C to 750°C or above. The stress–strain relation can be determined for specimens heated with or without an externally applied constant uniaxial compressive load, see Ref. 1 and Ref. 2, Part 1.

2 Service and accident conditions

2.1 Service conditions

Service conditions normally involve long-term exposure to temperatures in the range 20–200°C and moisture states in the range between the following 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.

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*The text presented here is a draft for general consideration.

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2.2 Accident conditions

Accident conditions normally involve short-term exposure to temperatures in the range 20–750°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 stress–strain relation is defined here as the experimental curve of the average uniaxial stress under a monotonically increasing compressive strain as described in Fig. 3. This relation may be determined either out of the strain under increasing uniaxial compressive stress (stress-rate controlled), or out of the stress under increasing strain (strain-rate controlled). The latter test method allows to determine the falling branch of the material, which corresponds to a loss of load-carrying capacity after it has sustained the maximum load (softening behaviour). Consequently the stress–strain relation of concrete is referred to as

- "stress-rate controlled" stress–strain relation (see Fig. 3a),
- "strain-rate controlled" stress–strain relation (see Fig. 3b).

The stress–strain relation can be determined either in the hot state, or at ambient temperature after heating and cooling. Stress–strain relations determined at temperature T_{max} are henceforth described as "hot". Stress–strain relations determined after cooling from T_{max} are henceforth described as "residual".

Consequently, the stress–stress relation of concrete is referred to as

- hot stress–strain relation,
- residual stress–strain relation.

The stress–strain relation 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 stress–strain relation of concrete, it is proposed to distinguish two cases:

- The "hot" or "residual" stress–strain relation of specimens without loading during the temperature exposure prior to testing is henceforth defined as "unstressed".
- The "hot" or "residual" stress–strain relation of specimens which are loaded during the temperature exposure prior testing is henceforth defined as "stressed".

3.2 List of symbols and notations

α	stress ratio
ε	strain
$\dot{\varepsilon}$	strain rate
ε_{c1}	strain at the peak of a stress–strain relation
ε_{cu}	strain at the end of the descending branch of a stress–strain relation
f_c	compressive strength
f_c^T	compressive strength at temperature T
ΔL_R	measured length changes during the test (variable)
L_{Ri}	initial reference length at ambient temperature (constant)
r	radius of specimen
R	constant heating rate (dT_s/dt)
RH	relative humidity
σ	stress (constant)
$\dot{\sigma}$	stress rate
t	time
T	reference temperature (variable)
T_{max}	maximum reference test temperature (constant)
ΔT	temperature difference
0	superscript index for zero stress (σ = 0)
c	subscript index for compression
$c1$	subscript index for strain at load peak
cu	subscript index for maximum strain
d	superscript index for drying (unsealed concrete)
i	subscript index for initial
nd	superscript index for non-drying (sealed concrete)
res	subscript index for residual
T	superscript index for temperature

3.3 Stress–strain relation of concrete for stress-rate controlled tests

3.3.1 Stress–strain relation of non-drying concrete, stress-rate controlled

The "hot" stress–strain relation of "unstressed", sealed specimens is determined from the strain ε corresponding to the stress-rate $\dot{\sigma}$ according to Fig. 3a, see Sect. 6.3:

$$\sigma = \sigma^{T,\dot{\sigma},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1}^{T,\dot{\sigma},nd} \tag{1}$$

The "hot" stress–strain relation of "stressed", sealed specimens is determined accordingly, see Eq. 2:

$$\sigma = \sigma^{T,\sigma,\dot{\sigma},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1}^{T,\sigma,\dot{\sigma},nd} \tag{2}$$

The corresponding "residual" stress–strain relations for "unstressed" and "sealed" specimens are:

$$\sigma = \sigma_{res}^{T_{max},\dot{\sigma},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1,res}^{T_{max},\dot{\sigma},nd} \tag{3}$$

and for "stressed" and "sealed" specimens:

$$\sigma = \sigma_{res}^{T_{max},\sigma,\dot{\sigma},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1,res}^{T_{max},\sigma,\dot{\sigma},nd} \tag{4}$$

3.3.2 Stress–strain relation of drying concrete, stress-rate controlled

According to the Sect. 3.3.1 four types of stress–strain relations result from the different test conditions, see Fig. 3a, Sect. 6.3.

"Hot" and "unstressed" stress–strain relation:

$$\sigma = \sigma^{T,\dot{\sigma},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1}^{T,\dot{\sigma},d} \tag{5}$$

"Hot", "stressed" stressed–strain relation:

$$\sigma = \sigma^{T,\sigma,\dot{\sigma},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1}^{T,\sigma,\dot{\sigma},d} \tag{6}$$

The corresponding residual stress–strain relations are for "unstressed" and "drying" specimens:

$$\sigma = \sigma_{res}^{T_{max},\dot{\sigma},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1,res}^{T_{max},\dot{\sigma},d} \tag{7}$$

and for "stressed" and "drying" specimens:

$$\sigma = \sigma_{res}^{T_{max},\sigma,\dot{\sigma},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{c1,res}^{T_{max},\sigma,\dot{\sigma},d} \tag{8}$$

3.4 Stress–strain relation of concrete for strain-rate controlled tests

3.4.1 Stress–strain relation of non-drying concrete, strain-rate controlled

The test is performed according to the description in Sect. 6.3, see Fig. 3b.

"Hot" and "unstressed" stress–strain relation:

$$\sigma = \sigma^{T,\dot{\varepsilon},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu}^{T,\dot{\varepsilon},nd} \tag{9}$$

"Hot" and "stressed" stress–strain relation:

$$\sigma = \sigma^{T,\sigma,\dot{\varepsilon},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu}^{T,\sigma,\dot{\varepsilon},nd} \tag{10}$$

The corresponding residual stress–strain relations are:

"Residual" and "unstressed" strain–strain relation

$$\sigma = \sigma_{res}^{T_{max},\dot{\varepsilon},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu,res}^{T_{max},\dot{\varepsilon},nd} \tag{11}$$

"Residual", "stressed" stress–strain relation

$$\sigma = \sigma_{res}^{T_{max},\sigma,\dot{\varepsilon},nd}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu,res}^{T_{max},\sigma,\dot{\varepsilon},nd} \tag{12}$$

3.4.2 Stress–strain relation of drying concrete, strain rate controlled

"Hot" and "unstressed" stress–strain relation: (see Fig. 3b, Sect. 6.3)

$$\sigma = \sigma^{T,\dot{\varepsilon},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu}^{T,\dot{\varepsilon},d} \tag{13}$$

"Hot" and stressed" stress–strain relation:

$$\sigma = \sigma^{T,\sigma,\dot{\varepsilon},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu}^{T,\sigma,\dot{\varepsilon},d} \tag{14}$$

"Residual" and "unstrained" stress–strain relation:

$$\sigma = \sigma_{res}^{T_{max},\dot{\varepsilon},d}(\varepsilon) \quad \text{for} \quad \varepsilon \le \varepsilon_{cu,res}^{T_{max},\dot{\varepsilon},d} \tag{15}$$

"Residual" and "stressed" stress–strain relation:

$$\sigma = \sigma_{res}^{T_{max},\sigma,\dot{\varepsilon},d}(\varepsilon) \quad \text{for} \quad \varepsilon \leq \varepsilon_{cu,res}^{T_{max},\sigma,\dot{\varepsilon},d} \qquad (16)$$

4 Material type and mix proportion

This recommendation applies to all types of concrete used in construction including high strength concrete. Mix proportions shall be determined according to the concrete design in practice.

The maximum aggregate size should not be less than 8 mm.[1]

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) equal to 3.

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, 100, 80, and 60 mm and should be taken as standard. Other diameters, when used, should be described as "non-standard".[2]

5.3 Moulds, casting, curing and storage

5.3.1 Moulds

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

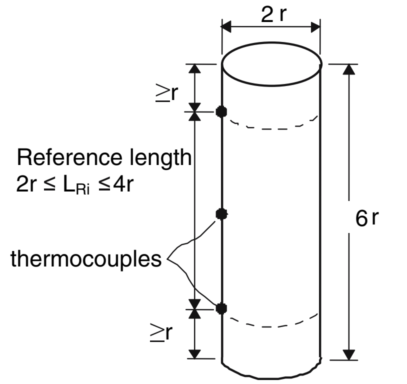

Fig. 1 Cylindrical specimen showing the location of three temperature measurement points

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 of 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 7 days after casting at a temperature of 20 ± 2°C as follows:

- in their moulds—*during the first 24 ± 4 h 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;

[1] The stress–strain relation 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 stress–strain relation.

[2] The slope of the softening branch depends significantly on the specimen geometry (slenderness and size). Because of thermal requirements a fixed slenderness of 3 is proposed.

- 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 h.

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 Sect. 5.2 shall also be determined at 28 days.

The compressive strength at ambient (see Ref. 2, Part 3) of the specimens according to Sect. 5.2 shall be determined at the time of testing. The result shall be used as reference strength for the specimens heated under stressed conditions.

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*

The 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 arranged symmetrically to each cross-section. The cross-section shall be perpendicular to the central axis and one radius apart from each flat end of the specimen (see Fig. 1). The initial reference length L_{Ri} shall be two diameters of the specimen.

Before loading the initial reference length shall be measured at 20 ± 2°C with a precision of at least 0.5%. The length changes during the test ΔL_R shall be measured in the direction of the central axis of the specimen. Changes in length are measured relative to the initial reference length at the initiation of the test.

From the length measurements the strain is derived:

$$\varepsilon = \Delta L_R / L_{Ri} \quad (17)$$

For strain increments of the ascending branch up to 1,000 micro strains the uncertainty should be less than 10 micro strains; for strain increments exceeding 1,000 micro strains the uncertainty should be less than 20 micro strains.

For strain increments of the descending branch the uncertainty should be less than 40 micro strains.[3]

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.

The temperature measurements shall be made during heating and, when required, during cooling at three points on the surface of the specimen. The measuring points shall be located on the concrete surface at the centre and at the level of the two cross-sections. L_{Ri} should be at least $2r$ and preferable $4r$ as maximum length (see 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.

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

6.2.3 *Load measurement*

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

[3] In cases were mainly the softening branch is investigated it is possible to perform the strain measurements in residual tests at ambient temperatures according to RILEM TC 148-SSC "Strain Softening of Concrete—Test Methods for Compressive Softening" (see Ref. 3). The method does not allow the determination of the stress–strain-relation at high temperatures and may lead to different results compared to the test results of strain-rate controlled tests described above.

6.3 Test procedure

The specimen shall not be removed from the curing environment more than 2 h for unsealed specimens and 4 h 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 Sect. 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 σ_i 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 Fig. 2).

Then the specimen shall be subjected to three load cycles between the pre-load level (≤ 0.05 MPa) and 15% or between ≤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. The hold time at ≤5% and 15% load levels should be less than 60 s. At the end of the load cycling 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

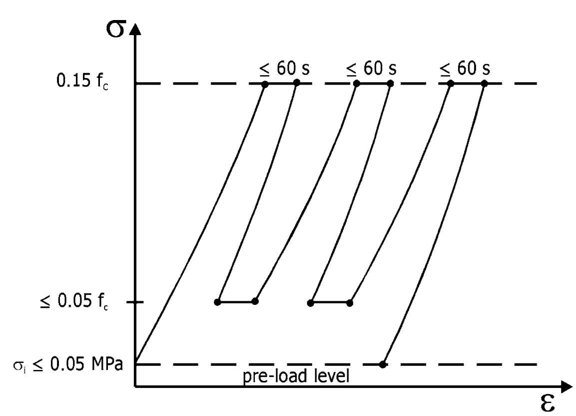

Fig. 2 Schematic illustration of specimen cycling during installation at ambient temperature

and the load cycle repeated until the 20% criterion is met. If this is not possible within 1 h, the specimen should be excluded from the test.

For specimens which are stressed during heating, or during 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 α at 20°C immediately prior to heating. The load level α must be kept constant according to Sect. 6.2.3.

The specimen shall be subjected to heating at the appropriate constant rate (see Sect. 6.4.1), commencing not later than 2.0 ± 1.0 min after reaching the required pre-load level ("unstressed" specimen) 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 Sect. 6.4.1 and tested at ambient.

Before testing, the load level α of the "stressed" specimens shall be $\sigma_i \leq 0.05$ MPa. Within ±1 min after reaching this stress level the stress-rate controlled tests should be commenced with a loading rate of 0.5 MPa/s until f_c^T or $f_{c,res}^{T_{max}}$ is reached (see Fig. 3a).

In the case of a strain-rate controlled test the control unit should be switched from the load controlled mode to the strain controlled mode and the test should be commenced immediately thereafter with a strain rate of 0.1 ± 0.05 ‰/s (see Fig. 3b).

The test procedures for stress-rate and strain-rate controlled tests are illustrated in Fig. 3.

In the case of a stress-rate controlled test, the test ends if the maximum compressive strength f_c^T or $f_{c,res}^{T_{max}}$ are reached. During the load increase the strain should be preferably recorded continuously or at intervals not longer than 0.2 s. The measured strain at f_c^T is called ultimate strain ε_{c1}^T and at $f_{c,res}^{T_{max}}$ ultimate residual strain $\varepsilon_{c1,res}^{T_{max}}$.

In the case of a strain-rate controlled test, the test ends with the failure of the specimen or when the stress has decreased to $0.2f_c^T$ or $0.2f_{c,res}^{T_{max}}$. The measured strain at $0.2f_c^T$ or $0.2f_{c,res}^{T_{max}}$ on the descending branch is called ε_{cu}^T or $\varepsilon_{cu,res}^{T_{max}}$. The measured strain at the maximum of compressive strength f_c^T is called ultimate strain ε_{c1}^T and at $f_{c,res}^T$ ultimate residual strain $\varepsilon_{c1,res}^{T_{max}}$.

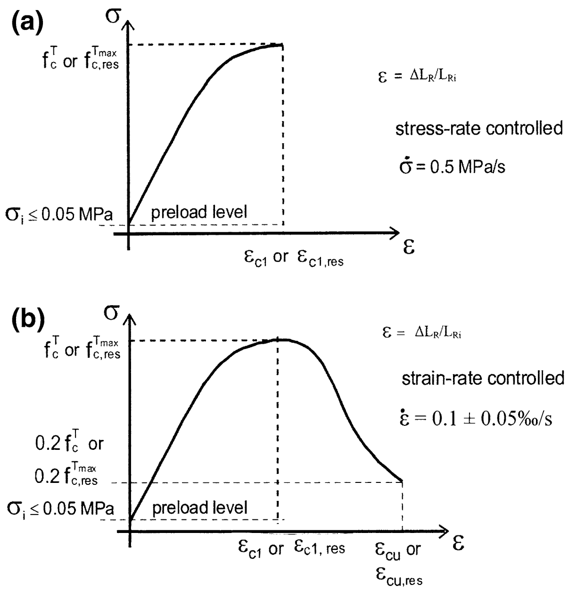

Fig. 3 Stress–strain relation of concrete under uniaxial compression determined by (**a**) stress-rate controlled tests (**b**) strain-rate controlled tests

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.[4]

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

[4] 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 is the thermal diffusivity of the concrete, R is the rate of heating, r is the specimen radius. The thermal diffusivity D varies significantly with temperature and type of concrete.

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

by linear interpolation between the two adjacent points.[5]

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 h), 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 specimens 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]

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 with respect to f_c^T or $f_{c,res}^{T_{max}}$ differ more than 20% of the mean a third or more specimens should be tested. If the result of a single specimen differs more than 20% from the mean 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 Sect. 6 for the test parameters and the levels of precision.[7]

8 Evaluation and reporting of results

8.1 Evaluation of the reference temperature

The reference temperature of the specimen "T" or test temperature T_{max} is calculated from the mean surface temperatures using:

$$T = (T_1 + T_2 + T_3)/3 \qquad (18)$$

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

8.2 Evaluation of stress–strain relations

8.2.1 Average stress–strain relation

The average stress–strain relation of concrete shall be evaluated, based on the normalisation of two or more of the recorded stress–strain relations, in accordance with the procedures given in Sect. 6. The

[5] Concrete can spall explosively when heated. Precautions should therefore be taken to avoid damage or injury.

[6] 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 h the evaporable moisture is unlikely to escape totally from the specimens, i.e., specimens with a boundary moisture condition "d" may contain different amounts of moisture 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 1 h.

[7] For the measurement of complete stress–strain relations there are special requirements with respect to the type of loading device and load control. After the load maximum is reached, i.e., in the falling branch, the stored elastic energy of the loading device is transferred to the specimen and may lead to a sudden rupture. The effect occurs especially if "soft" loading devices are used and can be avoided if strain-rate controlled tests are performed using a loading device allowing a load control without time delay during the decrease of force. Hydraulic machines should not be used if there are large piston friction losses.

normalisation is based on the measured strength f_c^T or $f_{c,res}^{T_{max}}$ and strain ε_{c1}^T or $\varepsilon_{c1,res}^{T_{max}}$. Each point of the normalised average stress–strain relation is derived from the mean of the calculated normalised stresses at the same normalised strain (see Fig. 4a). In order to match the average ε_{cu} values of the descending branch a different normalisation procedure may be used after the peak (see Fig. 4b).

For the sake of reliability the stress–strain relation should be determined in one test for each specimen and evaluated according to Sect. 6.4.3.

8.2.2 Average compressive strength

The uniaxial compressive strength of the concrete is the simple *average* evaluated as the arithmetic mean of the measured f_c^T or $f_{c,res}^{T_{max}}$ values of two or more accepted specimens (see Sect. 6.4.3).

8.3 Test report

8.3.1 General

The method of evaluating the stress–strain relation of concrete shall be described including any deviation from the standard. The measured stresses with respect to strain

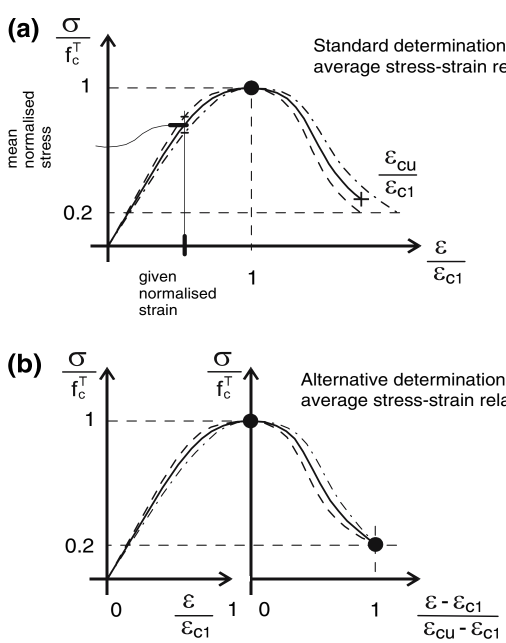

Fig. 4 Methods for the determination of the average stress–strain relation

of each specimen tested shall be reported together with the mean stress–strain relation for stress-rate controlled tests or for stress-rate controlled tests as follows:

- unstressed specimens: $\sigma^{T,\dot{\sigma},nd}$ or $\sigma^{T,\dot{\sigma},d}$ and $\sigma_{res}^{T_{max},\dot{\sigma},nd}$ or $\sigma_{res}^{T_{max},\dot{\sigma},d}$ as a function of strain
- stressed specimens: $\sigma^{T,\sigma,\dot{\sigma},nd}$ or $\sigma^{T,\sigma,\dot{\sigma},d}$ and $\sigma_{res}^{T_{max},\dot{\sigma},nd}$ or $\sigma_{res}^{T_{max},\dot{\sigma},d}$ as a function of strain

For strain-rate controlled tests the report of stress with respect to strain shall be presented as follows:

- unstressed specimens: $\sigma^{T,\dot{\varepsilon},nd}$ or $\sigma^{T,\dot{\varepsilon},d}$ and $\sigma_{res}^{T_{max},\dot{\varepsilon},nd}$ or $\sigma_{res}^{T_{max},\dot{\varepsilon},d}$ as a function of strain
- stressed specimens: $\sigma^{T,\sigma,\dot{\varepsilon},nd}$ or $\sigma^{T,\sigma,\dot{\varepsilon},d}$ and $\sigma_{res}^{T_{max},\sigma,\dot{\varepsilon},nd}$ or $\sigma_{res}^{T_{max},\sigma,\dot{\varepsilon},d}$ as a function of strain

The report shall include the items which are given in italics 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. Pre-load level or stress level during heating/cooling.

The following should be reported as functions of time during heating: *individual temperature measurements, mean surface temperature, reference temperature, rate of heating, axial 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 (Sect. 6.3).

8.3.8 Concrete strength and ultimate strain

The concrete strength and ultimate strain results for non-drying and drying concrete of every specimen shall be reported in tabular form as function of the test temperature (reference temperature).

The average strength and ultimate strain values 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

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