Materials and Structures/Matériaux et Constructions, Vol. **33**, July 2000, pp 347-351

RILEM TC 148-SSC: STRAIN SOFTENING OF CONCRETE - TEST METHODS FOR COMPRESSIVE SOFTENING

Test method for measurement of the strain-softening behaviour of concrete under uniaxial compression

Recommendations

The text presented hereunder is a draft, which is being submitted to enquiry. Comments should be sent to the secretary of the committee Prof. Dr. J. G. M. van Mier, Delft University of Technology, Faculty of Civil Engineering and Geo-Sciences, P.O. Box 2600 GA Delft, The Netherlands, by January 2001.

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CONTENTS

1. INTRODUCTION AND SCOPE

In these recommendations a test method is described for measuring the strain-softening behaviour of concrete under uniaxial compressive loading. Strain softening is defined as the loss of load-carrying capacity of concrete after it has sustained a maximum load. Strain softening can often be measured for normal strength (gravel) concrete under displacement-controlled conditions. However, alternative measures are needed for concretes with a very high compressive strength or for lightweight concrete. When the softening diagram is very steep, or even shows simultaneously decreasing deformations and stress (snap-back behaviour), the material (or rather specimen as will become clear) is said to behave in a brittle manner. In contrast, the material is said to behave in a ductile manner when the post-peak curve approaches the strain axis gradually (see Fig. 1).

For structural analysis, knowledge of the complete stress-strain diagram under uniaxial compression, thus inclusive of the descending or softening branch, is essential. From experiments it is known that the peak stress as well as the post-peak softening curve are highly dependent on specimen geometry and boundary conditions during the experiment. For example, it was shown, [1], that the amount of frictional restraint between loading platen and concrete specimen has a significant effect on the peak uniaxial compressive stress and on the slope of the softening diagram, as depicted schematically in Fig. 2a. Increasing the boundary restraint leads to more ductile specimen behaviour.

In addition it was shown that the slope of the softening curve was dependent on the slenderness of the specimen as well [2]: increasing the slenderness leads to more brittle post-peak behaviour (see Fig. 2b). Moreover, uniaxial

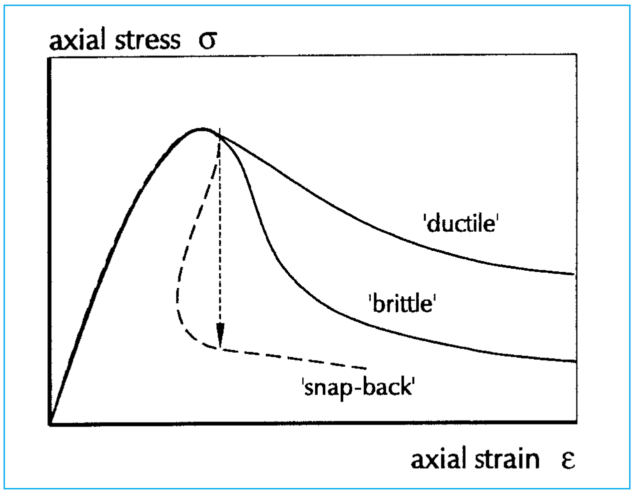

Fig. 1 – Ductile, brittle and snap-back behaviour.

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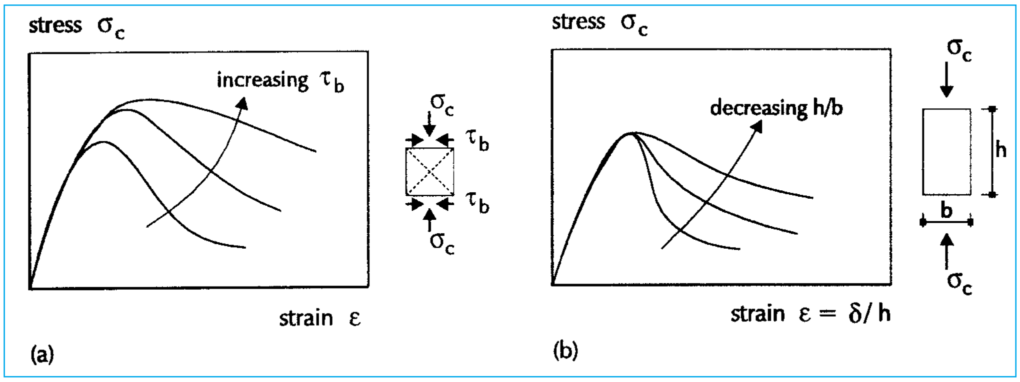

Fig. 2 – Effect of boundary restraint (a) and specimen slenderness (b) on the compressive stress-strain behaviour.

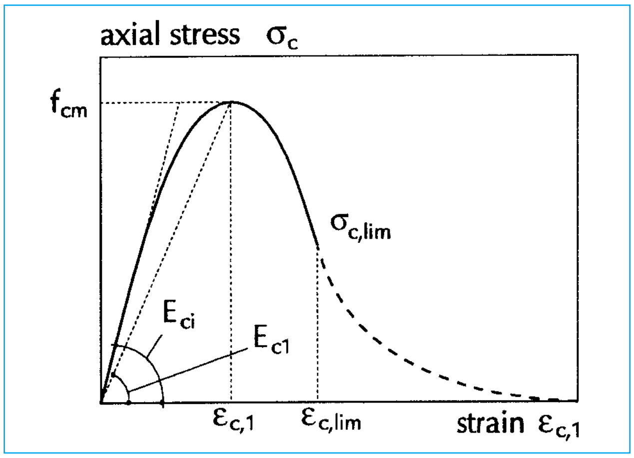

Fig. 3 – Stress-strain diagram for concrete subjected to uniaxial compression, after [4].

compression tests with varying slenderness indicate that localisation of deformations occurs in the post-peak regime, see for example references [2] and [3]. The observation that localisation of deformations occurs in the post-peak regime has important implications for structural analysis. It means that no longer a stress-strain diagram can be used in the post-peak regime, which implies that compressive failure is drawn into the realm of fracture mechanics, [2]. In the CEB model code [4] a compressive stress-strain diagram is proposed for structural analysis. The expression is based on the Young's modulus and the uniaxial compressive strength of the material.

The diagram of Fig. 3 shows the compressive diagram proposed by CEB, and is well described by:

$$\sigma_c = -\frac{\dfrac{E_{ci}}{E_{c1}}\dfrac{\varepsilon_c}{\varepsilon_{c1}} - \left(\dfrac{\varepsilon_c}{\varepsilon_{c1}}\right)^2}{1+\left(\dfrac{E_{ci}}{E_{c1}}-2\right)\dfrac{\varepsilon_c}{\varepsilon_{c1}}} f_{cm}$$

For $|\varepsilon_c| < |\varepsilon_{c,lim}|$, where E_{ci} is the tangent Young's modulus, σ_c is the compressive stress in [MPa], ε_c is the compressive strain, $\varepsilon_{c1} = -0.0022$ and E_{c1} is the secant modulus from the origin to the peak stress f_{cm} (see Fig. 3). For the descending branch, because of the aforementioned problems, it is assumed that the diagram of Fig. 3 is valid in the descending branch only for stress levels between the peak and the point $|\sigma_c|/f_{cm} = 0.5$ in the descending branch.

The fact that the softening behaviour depends on the test-environment and the specimen geometry (size), implies that fracture mechanics principles must be used for the analysis of structures where compressive failure prevails. A good example is the rotational capacity of reinforced concrete beams and plates [5, 6]. Obviously there is a need to develop a standard test for compressive softening, as well as procedures to bring into account the size dependency of the softening diagram. Based on an extensive test programme [7] and a Round-Robin analysis of over-reinforced concrete beams subjected to four-point bending [8], the following recommendation is proposed for measuring strain softening of concrete under uniaxial compression.

2. SPECIMENS

2.1 Geometry and size

The most convenient specimen shape is a prismatic specimen of constant circular or square cross-section. The size of the specimen should be such that a representative volume of the concrete is taken. A cross-section with characteristic dimension of 100 mm is suitable for most concretes, and in many cases is suitable for high strength (performance) concrete as well (in view of the capacity of available compressive loading machines). The length of the specimen should be twice the characteristic cross-sectional dimension. Thus, a rectangular prism of 100 × 100 × 200 mm^3 must be used, or cylinders of diameter 100 mm and length of 200 mm. For concretes with an exceptionally large aggregate size (larger than 32 mm), the characteristic dimension of the cross-section should be at least five times the size of the maximum aggregate size. This choice may imply that – at least for concretes with very high compressive strength – no stable softening branch can be found.

2.2 Manufacturing method and storage of the specimens

The manufacturing of the specimens should be done as carefully as possible in order not to introduce additional errors in the measurements. The specimens can be manufactured following two different methods. Either one can decide to cast specimens directly of the size

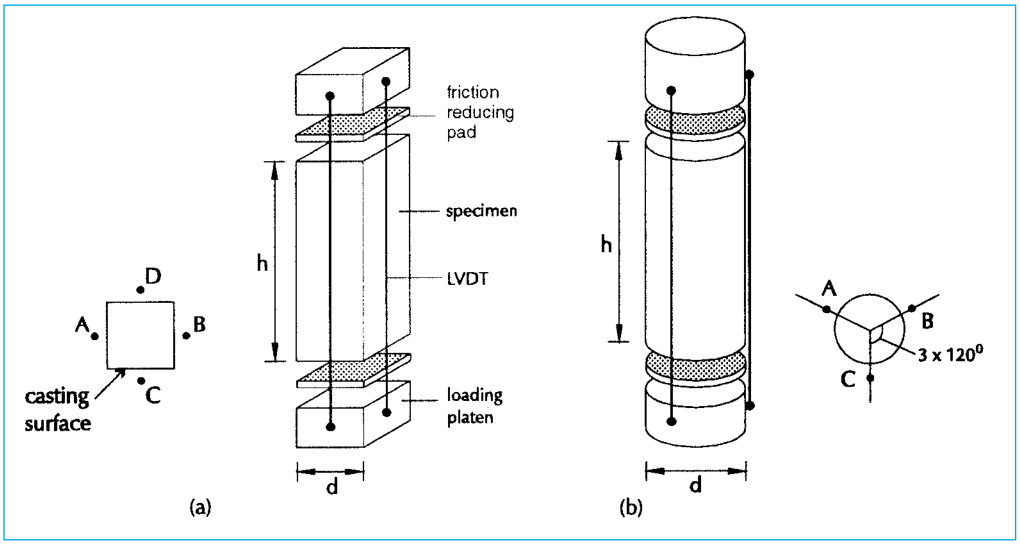

Fig. 4 – Test configuration for prisms (a) and cylinders (b), after [9].

required in the tests, or as a (preferred) alternative, the specimens can be sawed from larger blocks. In the first case, stiff formwork is needed, preferably of steel. The specimens should be cast in a horizontal position to assure that the two loading surfaces are flat and parallel. A maximum deviation of 0.05 mm can be accepted with regard to the flatness and skewness of the loading surfaces. The casting surface, *i.e.* the upper surface of the specimen when cast should be finished some time (approx. 1-2 hours) after casting before the concrete starts to set. After casting and finishing the specimen should be covered by plastic sheets or by wet cloths. Two days after casting, the specimen should be demoulded and placed in a fog room (99% RH and 20°C). For prismatic specimens with square cross-section, there is no constraint to prepare the specimens in a horizontal position. For cylinders, however, vertical casting is essential, and the casting surface must ground flat such that it is parallel to the lower loading surface.

As a (preferred) alternative, the prismatic specimens can be sawed (prisms) or cored (cylinders) from larger blocks. The dimensions of these blocks should larger by at least two aggregate sizes. Thus if prisms of 100 mm of concrete with 16 mm are manufactured, the minimum block size is 132 × 132 × 232 mm. The best quality control is possible on the flatness and parallelness of the surfaces when specimens are prepared in this way. Grinding of the loading surfaces is needed to ensure flatness of these surfaces and a good contact with the loading platen in the compression machine. Sawing the specimen 0.1-0.2 mm larger than required on all sides and removal of the excess material by grinding will generally lead to a good result. The casting surface, i.e. the upper surface of the specimen during casting should be marked. There is no need to use capping between the specimen and the loading platen.

All dimensions of the specimen should be measured before the beginning of the test. The axial dimension is the average length of the specimen from four measurements at the corners or along the circumference of the prism or cylinder respectively. The diameter of the specimen should be measured along three positions over the height; the lateral dimensions of the prisms should be taken at the two ends as the average of four measurements at each side.

The specimens should be stored in a fog room (99% RH at 20°C) until testing at 28 days. The sawing and grinding of the specimens should be done between 14 and 28 days. After sawing and grinding the specimens are to be returned to the fog room.

3. INSTRUMENTATION

LVDTs or extensometers are mounted between the loading platens (for measurement of deformations in axial direction) or with a device clamped with springs over the specimen diameter platens (for measurement of deformations in lateral direction). For cylindrical specimens three measuring devices should be mounted at 120-degree intervals along the circumference of the specimen. When prisms are used, four LVDTs or extensometers can be mounted between the loading platens, one at each side. The range of the LVDTs or extensometers should be at least 2 mm. The arrangement of the axial measuring devices is shown in Fig. 4 for prisms and cylinders respectively.

The measuring devices for axial deformation measurement should be fixed directly to the loading platens. This is essential, and under no circumstance may they be attached to the concrete because severe macrocracking in the post-peak regime may lead to instability of the extensometers. Consequently the test may become unstable because it must be controlled over these LVDTs or extensometers. The measuring devices should be installed such that the measurement direction is parallel to the loading direction. Offsets by small angles up to 0.5 degrees can be allowed, see Fig. 5.

The axial deformation measured between the loading platens can not be used for determination of the Young's modulus of the concrete tested. For a proper determination of the pre-peak stress-strain curve and the Young's modulus, strain gauges or extensometers should be fixed to the middle one third of the specimen length. At least the aver-

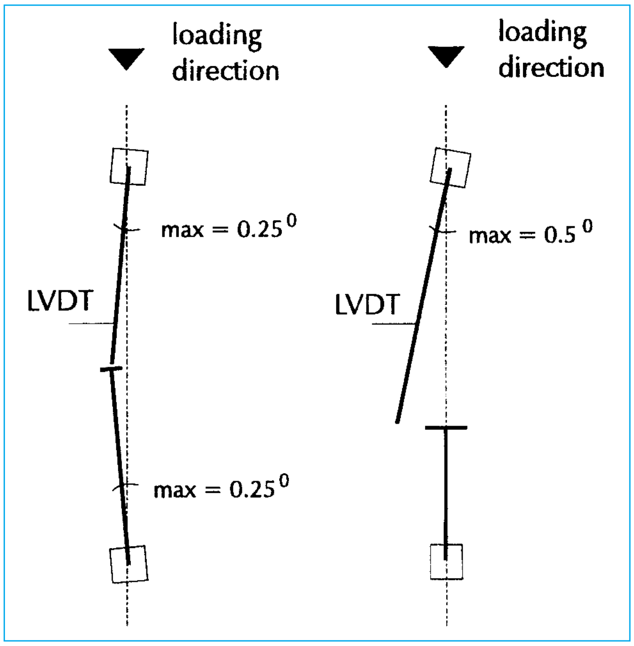

Fig. 5 – Allowed deviation of extensometers or LVDTs used for the measurement of axial deformations from loading direction.

age of three gauges should be used to determine the pre-peak strains. Note that this method cannot be used in the post-peak regime, because of the aforementioned macro-cracking and surface spalling in the post-peak regime.

For the measurement of lateral deformations no guidelines are given, only the following suggestions are made. If needed, a spring type extensometer can be clamped at half height to the prism or cylinder. The extensometer should be fixed on two opposite sides of the specimen. For cylinders commercially available gauges can be used that measure the radial or circumferential expansion of the specimen. One warning is in order. In the post-peak regime the specimen breaks in a number of smaller and larger parts. This means that a relatively large scatter in lateral deformations can be found [2]. It is therefore essential to perform lateral deformation measurements at a sufficient number of places. The use of at least six lateral gauges is recommended.

4. TEST APPARATUS

No special demands are made for the testing machine, except that the loading capacity is sufficient, and that it fulfils the specification outlined in [10]. A servo-controlled system is needed. The loading platens should have the same size as the specimen cross-section. By no means can they be smaller. A slightly larger dimension is acceptable, but no more than 2 mm at each side. The loading platens should be attached securely to the compression machine. The thickness of these loading platens should be in the order of 50 to 100 mm. The requirement that the loading platens have the same size as the specimen cross sections allows for easy placement of the axial measuring devices as described in section 3. One of the loading platens should be able to rotate freely at the beginning of a test; the other platen must be fixed at all time. Between the specimen and loading platens a friction reducing pad is inserted as described in section 5.2.

5. TEST PERFORMANCE

5.1 Installing the specimen

At the beginning of the test, the specimen is placed on the lower loading platen. A friction-reducing pad is placed between the specimen and the loading platen, see section 5.2. The specimen should be placed exactly in the centre of the loading platen. This is easy to check because the loading platens have the same size as the specimen. A second friction-reducing pad is placed on top of the specimen. The upper platen is lowered such that a very small load of 0.5-1 kN is exerted on the specimen. Allow for adjustment of the upper loading platen, and secure that the upper loading platen is placed centrically on the upper surface of the specimen. The LVDTs or extensometers are mounted between the loading platens as described before. The load can be increased to approximately 10 kN, and the control can now be switched to displacement control. Loading must be increased at a rate of 1 μm/s, with an accuracy of ± 10%.

5.2 Boundary conditions

The friction reducing pad consists of two sheets of PFTE (polytetrafluorethylene, better known under the trade name Teflon) foil with a thickness of 100 μm. In between the two sheets a layer of 50 μm of bearing grease is added as shown in Fig. 6. One of the Teflon sheets is placed in a steel block containing a depression of 150 μm deep. With a flat scraper the depression is filled with grease, and the second Teflon sheet is carefully placed on top of the grease layer. Next the sandwich can be placed between the specimen and the loading platens.

5.3 Test-control

The test must be carried out in displacement control. When cylinders are tested, the control signal is the average signal of the three LVDTs mounted along the cir-cum-ference of the cylinder (*i.e.* devices A, B and C in Fig. 4b). When prisms are used, the average of the two LVDTs mounted at the 'side' surfaces of the specimen adjacent to the casting surface should be used (*i.e.* measuring devices A and B, see Fig. 4a). The axial deformations can be used as control signal for conventional normal gravel concretes, *i.e.* with a uniaxial (prism/cylinder) compressive strength of 60-70 MPa. Beyond that limit, special precautions should be taken.

Three alternatives exist for testing above the strength limit of 60-70 MPa, or for brittle lightweight concretes, namely control over the circumferential or lateral deformation [11], control over a combination of axial load and

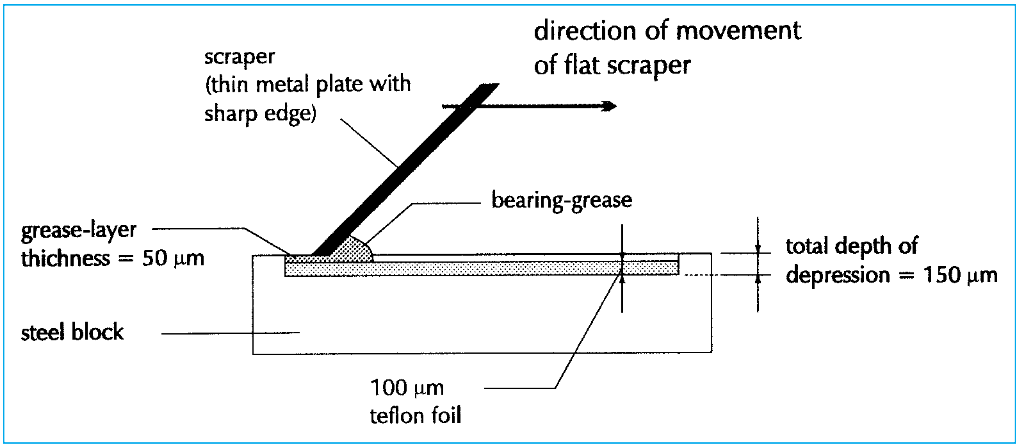

Fig. 6 – Device for applying a layer of 50 µm of bearing grease on top of a 100 mm thick Teflon foils. The shape of the depression in the steel block (which should have a minimum thickness of approximately 10-12 mm) matches that of the cross-section of the prismatic concrete specimen, *i.e.* 100 mm square or 100 mm circular, after [9].

axial deformation [12], or control over a combination of axial and lateral deformations [13]. No method is prescribed in this test recommendation.

6. TEST RESULTS

At least three identical tests must be carried out for a given concrete. Results are presented as axial stress- axial strain diagrams. The axial stress is computed by dividing the total load over the net cross-sectional area of the specimen. The net cross-sectional area must be measured at the beginning of the test as mentioned in section 2. The axial deformation is the total axial deformation corrected for the deformation of the steel in the measuring range of the LVDTs. The axial strain is the average axial deformation (from three of four LVDTs for cylinders and prisms respectively) divided by the specimen length.

7. TEST REPORT

The test report contains the axial compressive stress, being the average maximum stress reached in the three experiments. The average maximum stress is called the uniaxial compressive strength. Moreover, the report contains the three axial stress-strain curves. Stresses are given in [MPa]; strains in [mm/mm].

8. CONCLUDING REMARKS

The proposed recommendations are aimed at obtaining repeatable, uniaxial stress-strain response of concrete. The emphasis has been on the post-peak strain-softening response. As indicated in the report, this response is dependent on the length of the specimen as a result of the localised nature of failure. Post-peak stress-*deformation* curves are unique for specimens of different length, see also [2]. To use the measured stress-strain curve (or the stress-deformation curve) for the structural analysis and design, several approaches are possible. The descriptions of these are not within the scope of this report. The test method recommended here will yield a repeatable and reliable set of property measurements, which can then be used for design.

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