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Draft on the JCI Standard Test Method for Determining Tension Softening Properties of Concrete

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ABSTRACT: In this paper, draft on the standard test method for determining tension softening properties of concrete is proposed. This test method evaluates the tension softening diagram of concrete by analyzing the load-CMOD curve obtained from the three-point bending test of notched concrete beam specimen. A round robin test was performed by some JCI members in Japan in order to verifying the accuracy of proposed standard test method. A poly-linear approximation analysis method is employed to calculate the tension softening diagram by using a load-CMOD curve and this program was opened on the internet web site as a standard program.

1 INTRODUCTION

1.1 *Back ground*

In the Gifu Workshop (FRAMCOS-3, Japan), test methods for mode I fracture of concrete were discussed by the leading scientists and engineers (Kitsutaka & Mihashi 1998). In this workshop, it has been concluded that a technical committee on the standard test methods for tension softening properties of concrete should be established in RILEM and Japan Concrete Institute (JCI). Following this conclusion, a technical committee on the test method for fracture property of concrete (JCI-TC992, chairman: Y. Kitsutaka) was organized in JCI from 1999.4 to 2001.3. The purpose of this technical committee is to establish a standard test method on the fracture property of concrete. The committee focuses on three issues and has been setting up the three working groups, they were an evaluation test method for the tension softening property of concrete (WG1, chairman: Y. Uchida), an application of the test method for fiber reinforced concrete (WG2, chairman: Y. Kitsutaka), and a testing method of mixed mode fracture (WG3, chairman: Y. Kaneko). To attain these purposes, round robin tests were planed. At the end of the two-year deliberation, a report was published and a symposium has been held in order to publicize the idea of these issues.

1.2 *Outline*

In this paper, activities of the WG1 are summarized. A round robin test was performed by some JCI members in Japan in order to verifying the accuracy of proposed standard test method. In this round robin test, an organizing committee sent concrete specimens of same batches for participants, and load-crack mouth opening displacement (CMOD) curve of the specimen under three-point loading was measured and fracture energy was calculated according to the proposed standard test method. The tension softening curves were calculated from the data of a load-CMOD curve by using a standard program which was prepared by the organizing committee. This program is an inverse analysis of poly-linear tension softening curve. These test results were compared and problems on the standardization are discussed in this paper.

Considering these results, the draft on the JCI standard test method for determining tension softening properties of concrete is proposed. This test method evaluates the tension softening diagram (TSD) of concrete by using standard program and the data of load-CMOD curve obtained from the three-point bending test of notched concrete beam specimen.

2 OUTLINE OF PROPOSED DRAFT METHOD

Standard test method proposed by JCI committee consists of "Determination of the fracture energy for plane concrete specimen by measuring load-CMOD curve" and "Determination of the tension softening diagram".

2.1 *Determination of the fracture energy for plane concrete specimen by measuring load-CMOD curve*

In order to analyze the TSD, a load–displacement relationships by fracture test should be obtained. For this reason, this draft (called JCI-G_F method) of measuring load-CMOD was proposed. JCI-G_F method is basically follows RILEM G_F recommendation (RILEM 1985). Main differences from RILEM method are as follows.

2.1.1 *Specimen size*

RILEM method set a long loading span of beam in order to obtain the stable fracture. The minimum specimen size is 100×100×840mm, and this size is almost two times bigger as Japanese conventional bending specimen of 100 × 100 × 400mm. The weight of RILEM specimen becomes about 20kg, so it has problems on the treatment and on the mold. Moreover, self weight of the specimen affects seriously on the G_F value. So JCI committee modified the specimen height (D) and width (B) as 5 times and 4 times bigger than maximum aggregate size (d_a), and the loading span 3xD, considering the practical use. In case of normal concrete d_a□20mm, we can use the 100×100×400mm size beam specimen.

2.1.2 *Deformation measurement*

In order to calculate the G_F, an accurate load point displacement curve should be needed. To attain this purpose, a jig for fixing the LVDT is set on the specimen in general. Especially, for the TSD analysis, test method needs an extreme accurate data on the load-displacement curve. Crack opening displacement (CMOD) can be easily and accurately measured by using clip gage, without using a special jig. So JCI committee employed the CMOD measurement. For the calculation of G_F, load point displacement (LPD) is converted from CMOD data by using a follow equation.

$$\mathrm{LPD} = 0.7 \times \mathrm{CMOD} \qquad (1)$$

This equation assumed the deformation of the specimen is caused from the rotation of elastic body by a ligament compression area plays the rotation center. Fracture energy is calculated from RILEM equation by applying the load and the LPD converted from CMOD using equation (1). According to the our numerical analysis, the difference between G_F obtained by L-LPD and G_F obtained by L-CMOD is negligible.

2.2 *Determination of tension softening diagram*

JCI committee employed the poly-linear approximation method as the standard method to determine the TSD (called JCI-TSD method) because of it has the high accuracy on the prediction of tension softening diagram (TSD). This method is basically the numerical analysis using a fictitious crack model, so JCI committee opened the computer program on the internet web site as the JCI standard program.

3 ROUND ROBIN TEST

3.1 *Test outline*

In order to investigate the effectiveness of the proposed test method, the round robin test was performed by 10 organizations in Japan as follows.

(1) Kumamoto University (KU)
(2) Central Research Institute of Electric Power Industry (CRIEPI)
(3) Tokyu Construction Co. (TC)
(4) Tokyo Metropolitan University (TMU)
(5) Tohoku University (TU)
(6) Tohoku Gakuin University (TGU)
(7) Tohoku Institute of Technology (TohIT)
(8) Mie University (MU)
(9) Musashi Institute of Technology (MusIT)
(10) Gifu University (GU)

Before the round robin test, a draft of standard test method was opened on the internet web site of JCI. All concrete specimens used for the test were cast at the same laboratory to discuss problems of the test method excepting the effect of specimen variance. All specimens were made at Gifu University by four different batches of same mix proportion. Mix proportion of concrete is shown in Table 1.

The maximum aggregate size of concrete was 20 mm, and expected compressive strength at testing period was 40 N/mm^2. Specimen size was 100×100 ×400 (span 300) mm, and total numbers of specimen sent to one organization were four following the JCI-G_F method. Cylindrical specimens were made in order to measure the compressive strength and tensile strength. Specimens were cured in air for 1 day, and after remolding, specimens were cured in water at outdoor space for 1 month without temperature control, then they were sent to each organization.

Table 1. Mix proportion of concrete.

W/C	s/a	Unit weight (kg/m^3)				
(%)	(%)	W	C	S	G	Ad
65.0	46.4	178	274	820	981	2.74

Table 2. Concrete strength.

Batch	Slump (cm)	Air Cont. (%)	Comp. Strength (MPa)	Tensile Strength (MPa)	Young's Modulus (GPa)
A	9.2	3.3	37.9	2.79	31.8
B	11.2	3.9	38.4	3.11	30.9
C	6.3	3.4	40.9	3.46	31.6
D	6.5	3.9	41.8	3.34	30.3

Specimens were wrapped in wet waste and a vinyl sheet to prevent the water evaporation during the transportation.

Specimens were soaked in water immediately after send to the organization, and were cured in water about one month. Notch was made at the organization. The results of compressive test are shown in Table 2.

3.2 *Results of round robin test*

3.2.1 *Load-CMOD curve*

a) *Load-CMOD curves measured by Gifu University*
Loading tests were performed at the curing age of 2 months following the draft testing method. Load-CMOD curves measured at Gifu University (GU) are shown in Figure 1. Stable fracture was obtained and ultimate CMOD value (CMODc) could be measured for all specimens. In case of batch-A, CMODc is lager to compare to the other batches. This is because a large size coarse aggregate existing in the compressive fracture area of a beam caused the aggregate inter lock effect and specimen was not broken at the ultimate loading state. Smoothed load-CMOD curves for each batch are shown in Figure 2. It can be considered that all batches of concrete have same properties.

b) *Load-CMOD curves measured by organizations*
Smoothed load-CMOD curves obtained by all organizations are shown in Figure 2. Initial stiffness of all curves is almost same except the curve of TGU. From the result of this similarity, in order to obtain the stable mode I fracture test data, measurement of the CMOD by clip gage can be considered as an effective method. However there are some variances at the maximum load point and the softening area.

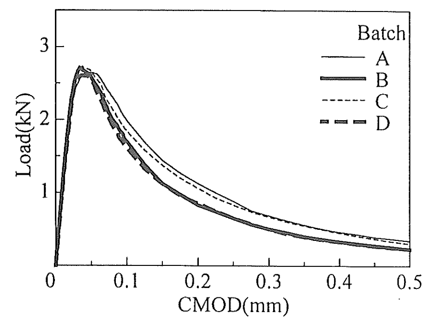


Figure 1. L-CMOD curves measured by Gifu Univ.

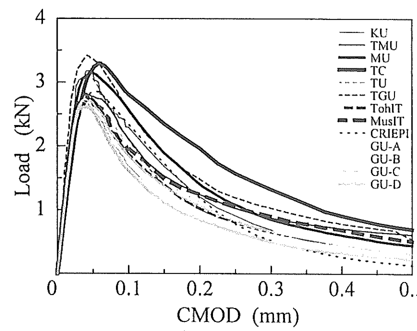


Figure 2. L-CMOD curves of all organizations.

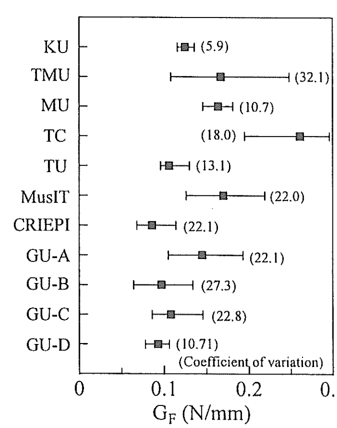
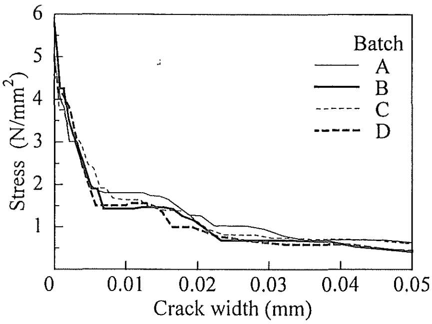


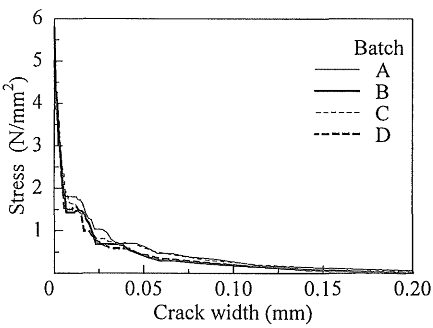
Figure 3. Fracture energy.

3.2.2 *Fracture energy*

Calculation of fracture energy proposed by this committee was following RILEM recommendation. It can be obtained by measuring the work done by both the external load and the weight of fixture plus specimen. Mean value and the standard deviation of the fracture energy obtained by 10 organizations are shown in Fig.3. Standard deviation of TMU and GU-B (batch B) are about 30% and the others are under 20%. Refer the results of Round Robin Test organized by RILEM, 20% standard deviation could be permitted. Mean values of fracture energy and standard deviation, are 0.141N/mm^2 and 19.3% respectively (data of TGU, TohIT, TC, CRIEPI were omitted because the tale part of load-CMOD curve seems to be obtained not accurately). This standard deviation value is almost same as that of the compressive strength of ordinary concrete, so this test method could be accepted as the standard method.



(i) Initial part



(ii) Whole part

Figure 4. TSDs obtained by Gifu Univ.

3.2.3 *Tension softening diagram*

TSDs calculated by the poly-linear approximation analysis method using load-CMOD data obtained by Gifu University are shown in Figure 4. Same TSDs can be obtained from four different batches. TSDs obtained by organizations are shown in Figure 5. Almost same TSDs can be obtained. TSDs of TC and MU show large cohesive stress to compare with other TSDs. This difference corresponded to the difference of measured load-CMOD curve. From the results of round robin test, there is no serious problem to use the poly-linear approximation analysis method.

4 CONCLUSION

From the results of round robin test performed by 10 organizations using same batch specimens, follow conclusions are obtained.

(1) Measured load-CMOD curves are almost same. There are no problems for the stability of fracture by adopting short loading span of 300mm.

(2) Effectiveness of measuring CMOD by clip gage instead of measuring load point displacement is confirmed.

(3) Standard deviation of fracture energy measured by JCI-G_F method is about 20%, so this method can be apply to a standard test.

(4) Tension softening diagrams calculated by the JCI-TSD method are almost same.

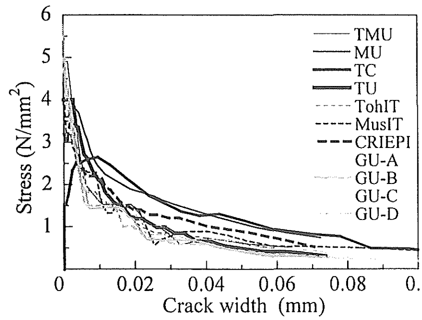


Figure 5. TSDs of all organizations.

References

Kitsutaka, Y. & Mihashi 1998. Quantitative Evaluation Methods for Toughness and Softening Properties of Concrete, *Proceedings of FRAMCOS-3 Pre-Conference.*

RILEM Draft Recommendation 1985. Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beams, *Materials and Structures*, 18(106), 285-290.

Appendix

In this section, the full draft documentation is shown. (note : This method is not yet formally authorized by Japan Concrete Institute, JCI)

Draft Determination of Tension Softening Diagram of Concrete

A.1 Scope

This recommendation specifies an analysis method for the evaluation of the tension softening diagram of concrete by using a stable load-displacement curve obtained from a mode I fracture test of a notched specimen. Tension softening diagram is defined as the relation of cohesive stress and crack opening displacement as the constitutive law for the fictitious crack model analysis applied for mode I fracture of concrete (Hillerborg et al. 1976).

A.2 Theoretical background

This evaluation method is based on the poly-linear approximation analysis of tension softening diagram (Kitsutaka 1993). This method belongs to the inverse analysis using the fictitious crack model analysis. Tension softening diagram of concrete is evaluated according to the flow chart shown in Figure 6. In this method, for each crack propagation by one node, the tension softening diagram is extended step by step as shown in Figure 7. The extended part of the tension softening diagram is chosen so that the analytical load-displacement curve fitted with the experimental one. The determined tension softening diagram is used as the constitutive law in the next step analysis and the whole shape of the tension softening diagram is evaluated uniquely, because the crack opening displacement (COD) increases monotonously. The load-displacement curve used for the analysis should be stable and smooth, because the analysis result is very sensitive to the smoothness of the load-displacement curve. If the measured load-displacement curve is not smooth, the appropriate smoothing technique should be adopted.

A.3 Determination of Young's modulus

The Young's modulus is determined so that the initial slope of the analytical load-displacement curve fitted with the one of the experimental load-displacement curve. In this calculation, initial load-displacement relation is assumed elastic deformation. The analytical load (P_{cr}) and displacement (δ_{cr}) are calculated by using the suitable Young's modulus (E_{c1}) by the calculation result of linear elastic fracture mechanics, FEM, numerical analysis, etc (Tada 1985, Murakami 1987). E_{c1} is determined by fitting the initial slope of experimental result to the analytical result.

A.4 Determination of tensile strength

The tensile strength (the stress of starting point of the tension softening diagram) is determined through following method. The initial part of the tension softening diagram is assumed to be perfect plastic as shown in Figure 8 (Uchida et al. 1995). The tensile strength (the starting point in Figure 8) is determined to be the perfect plastic stress when the fictitious crack length in the analysis becomes the longest within an allowable error (difference between experimental and analytical values of load). The crack opening at the terminal point of the perfect plastic tension softening diagram (the second point in Figure 8) is determined to be the fictitious crack width when the crack length becomes the longest.

A.5 Standard programs for this method

(1) FORTRAN program of poly-linear approximation analysis by Y. Uchida.
Download site : Japan Concrete Institute
Committee for evaluation method of fracture characteristic of concrete

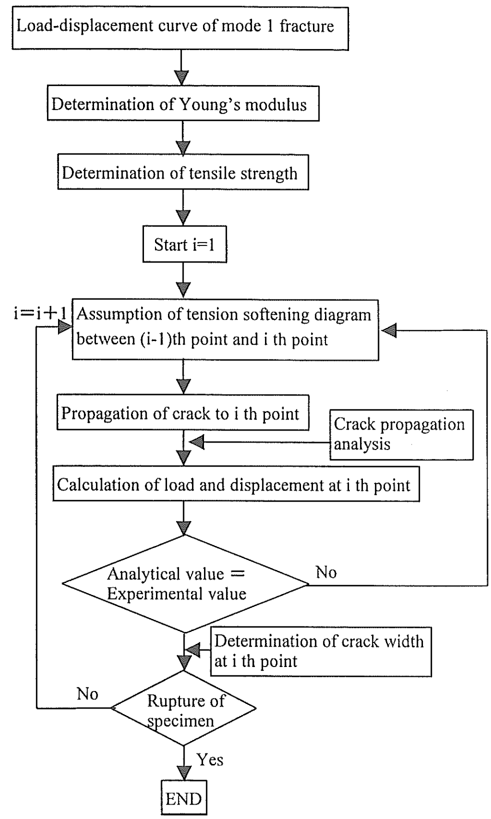


Figure 6. Flow chart of draft evaluation method of tension softening diagram.

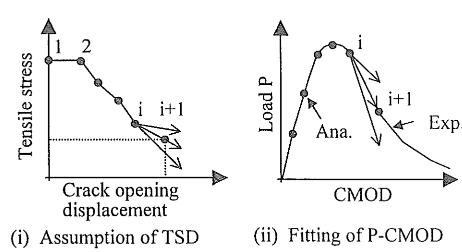


Figure 7. Poly-linear inverse analysis method.

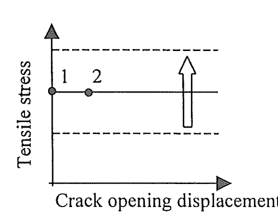


Figure 8. Perfect plastic tension softening diagram.

http://c-pc8.civil.musashi-tech.ac.jp/teacher/jci-fm/index.html

(2) Web site program on inverse analysis of tension softening diagram by Y. Kitsutaka.
This program is limited to analyze the load-CMOD data obtained by proposed JCI-G_F method.
http://www.ecomp.metro-u.ac.jp/~kitsu/fmpana.html

A.6 Terminology

Various technical terms is often used to express one phenomenon and their terms are not always unified. In this chapter, technical terms about the tension softening diagram in particular are unified as follows.

Tensile stress : The vertical axis of the tension softening diagram (Other expressions : cohesive stress, transferred stress, transmitted stress, etc)

Tensile strength : The stress of starting point of the tension softening diagram and the stress at which the crack is created and starts to open (Other expressions : initial cohesive stress, etc)

Crack opening displacement (COD): The horizontal axis of the tension softening diagram (Other expressions : (fictitious) crack width, crack opening (of cohesive force model), etc)

A.7 References

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