Fracture Mechanics of Concrete Structures, de Borst et al (eds) © 2001 Swets & Zeitlinger, Lisse, ISBN 90 2651 825 0

Establishment of Uniaxial Tensile Test Procedure for High Strength Concrete

D.Sohn
High Technology Research Center, Tohoku Institute of Technology, Sendai, Japan

H.Akita & H.Koide
Department of Civil Engineering, Tohoku Institute of Technology, Sendai, Japan

M. Igarashi
Ube-Mitsubishi Cement Research Institute Corporation, Sendai, Japan

ABSTRACT: It is reported that the tension softening behavior of normal strength concrete was monitored reliably by a uniaxial tension test developed by the authors. The major criteria for the test procedure are maintenance of stable fracture, avoidance of secondary flexure and prevention of multiple cracks. The main purpose of this study is to examine the practicability of the uniaxial tension test on investigating tensile properties of high strength concretes. It was found that the present test procedure has an ability to investigate tension softening behavior of high strength concretes as well as normal strength concretes. As the level of concrete strengths increases, the fracture energy also increases for the present concrete. The application of guide notches is beneficial to make tension softening behavior more reliable while it may not influence tensile strength and fracture energy. The overlapping cracks frequently generated for normal concrete was not observed for high strength concretes.

1 INTRODUCTION

The distinguishing features of concrete are brittleness, low tensile strength, and easy to crack. Since the compressive strength, being the principal property in the field of concrete research, is insufficient to understand fracture mechanism and further to improve properties of concrete, the knowledge of tensile behavior of concrete is required. Tensile properties of concrete strongly influence deflection, shear, cracking and bond behavior in structures. Since cracking in tension, for instance, is a significant factor contributing to the complex behavior of reinforced concrete structures, many investigators have studied to establish the test for obtaining reliable tensile responses of concrete members. Especially, the knowledge of tension softening process of concrete is beneficial to understand fracture mechanism and further to improve properties of concrete. In spite of augmentative demands for tensile properties of concrete, yet no standard tests for the type of a uniaxial tension test have been established. Instead, to explore tensile behavior of concrete, several alternative methods, such as three-point bending, compact tension and wedge splitting test, have been adopted. However, those methods have some drawbacks – non-true-tensile stress conditions and impossibility of simultaneous monitoring of tensile strength and tension softening behavior.

There are several criteria to perform uniaxial tension test for investigation of tension softening behavior. First, a stable fracture during the test is indispensable because of easiness of fracture due to very low frequency of crack arrest and rapid crack propagation (Mehta & Monteiro 1993). Second, more important, is to avoid secondary flexure generation because it will produce a strain gradient, resulting in a misleading estimation for tensile strength, usually decreased in observation (Hordijk 1989). Next is to prevent multiple or overlapping cracks (Mier & Nooru-Mohamed, 1990). Since those cracks enlarge crack surfaces, they will mislead fracture energy to become greater. To establish a reliable test procedure, various test conditions have been proposed with respect to load control, treatment of secondary flexure, specimen conditions or applying notches (Trunk & Wittmann 1998, Mier et al. 1996, Carpinteri & Ferro 1994, Vliet & Mier 1998, Koide et al 1997).

A recently developed uniaxial tension test procedure monitored tension softening curve as well as tensile strength of normal strength concrete simultaneously with reliable grade (Sohn et al. 1999). This test adopted strain-controlled loading conditions to satisfy maintenance of stable fracture and a uniquely designed gear system to eliminate secondary flexure generation. Additionally, notches were applied to reduce occurrence of multiple cracks. The present uniaxial tension test has several advantages, such as easy to operate, use of simple shape of specimen, inexpensive equipment. However, the success of this uniaxial tension test procedure on normal concrete does not guarantee that the applicability on high strength concrete because of the greater degree of the brittleness for the high strength concrete. The high strength concrete is different fundamentally from the normal strength concrete with respect to microstructure, stress-strain relations and fracture behavior. Thus, it is required to figure out the test procedure and testing conditions for high strength concretes independently. The other main objective of this study is to explore the tension softening behavior of high strength concrete, if the test is possible.

2 EXPERIMENTS

2.1 *Specimen preparation*

The concrete employed in this study is characterized by high strength as well as high fluidity. The mix proportion of concrete, which categorized A through C according to the strength levels, is shown in Table 1. Concrete was cast into cylindrical molds (100x200 mm) for a compression test and a splitting tension test (according to the Japanese Industry Standard), or dog-bone molds for the uniaxial tension test. After demolding, all specimens were cured under water at 20±1°C before testing. Table 2 shows characteristics of concretes, such as flow or slump, air content, 28-day compressive strength, and splitting tensile strength. Type A is the lowest and type C is the highest in both strength levels. The ages of concrete at the uniaxial tensile testing were varied in 29-44 day period.

Figure 1 shows the dimension of a dog-bone specimen whose entire length was 600 mm. The cross sectional area of each end of specimen was 120 mm by 100 mm, while that of the 120-mm-length center zone of a specimen was 100 by 100 mm, including 70-mm measuring length in the middle. A 3-mm–width notch, it is called a primary notch in this study, was made at the center of two side faces. The depth of the primary notch was in the range of 5-25 mm. Some concrete specimens have an additional 3-mm-width and 5-mm-depth guide notch at the center of the other two side faces (the cast and the bottom face). Each 70-mm extensometer was attached to four side faces. 0.1-mm thick steel sheets were glued on the specimen surface for 5-mm and 10-mm notched specimen in order to prevent unexpected breakage of a specimen outside of the measuring length. A cross type steel frame was attached to specimen ends.

2.2 *Apparatus*

Figure 2 shows the apparatus for the uniaxial tension test employed in this study. The steel frames at the ends of a concrete specimen were fixed by the connection pin of universal joints. An adjusting gear system was attached at the four branch ends of the steel frames of all four faces to avoid secondary flexure. Manual turns of the adjusting gears reduce the side distance of two steel arms; thereby the reduction gives an additional force on the specimen to restrict the unexpected unbalanced crack propagation. When one side is over-deformed compared to the opposite, this side is contracted by turning the gear until reaching proper balance. Each steel rod has a set of gauges on the circumference in order to estimate the additionally applied force. The true applied load on the specimen was calculated by subtracting the induced force by the adjusting gear from the measured total load. All signals from extensometers and strain gauges on the steel rod were monitored by strain amplifier meters and recorded.

The application of tensile loading was controlled by a closed-loop loading system with four sequential control stages, as indicated in Table 3. The test began with a load control stage until reaching appropriately determined level of the load, which is approximately 60-70% of predicted maximum loads of each notch depth. After the first stage, the test shifted to continuous strain control stages. During strain control stages, the applied load was controlled by the average value of all four-face strains. Based on the preliminary experiments, it was preset that the peak load should be appeared in the stage with the slowest strain rate (or stage 2). Since slope of a load-deformation curve becomes gentler after the peak load, strain rates were properly increased.

Table 1. Mix proportion of high strength concrete

Type	W/C	Cement (kg/m^3)	Aggregate (kg/m^3)		Chemical admixture
			Fine	Coarse	
A	0.35	500	832	900	9
B	0.31	580	732	934	10.5
C	0.28	692	651	941	12.5

Table 2. Characteristics of high strength concrete

Type	Flow (mm)	Air Content (%)	28-day compressive strength (MPa)	Splitting tensile Strength (MPa)
A	550x500	5.8	44.2	3.9
B	595x565	2.9	58.8	4.1
C	200(slump)	1.5	87.0	6.6

Table 3 Tensile loading control stages

Stage	Control	Duration	Rate	Deformation (mm/sec)
1	Load	Approx.	50 N/sec	Varied
2	Strain	+ $200x10^{-6}$	$0.1x10^{-6}$/sec	$7x10^{-6}$
3	Strain	+ $400x10^{-6}$	$0.2x10^{-6}$/sec	$14x10^{-6}$
4	Strain	- last	$0.4x10^{-6}$/sec	$28x10^{-6}$

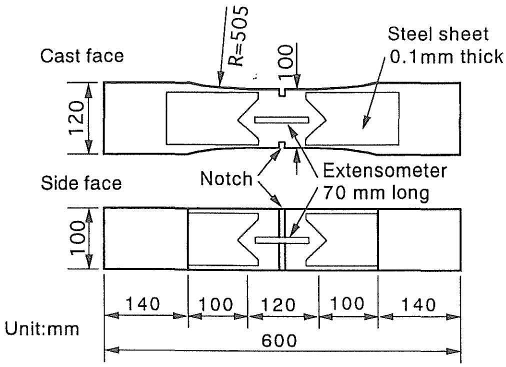


Figure. 1 Dog-bone specimen

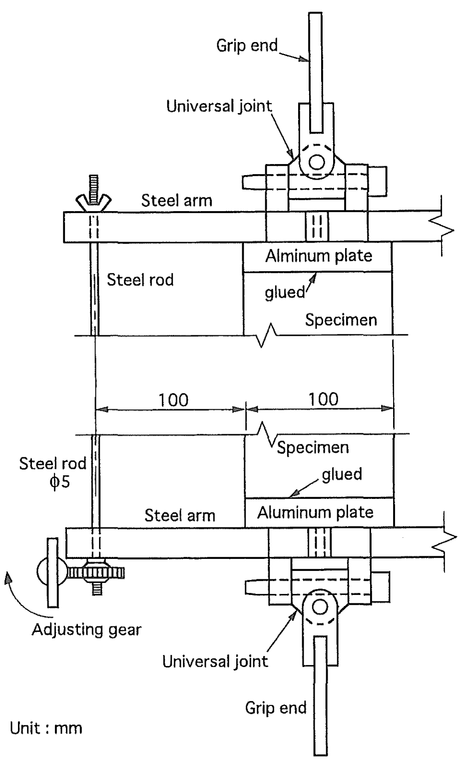


Figure 2 Experimental Set-up

3 RESULTS AND DISCUSSIONS

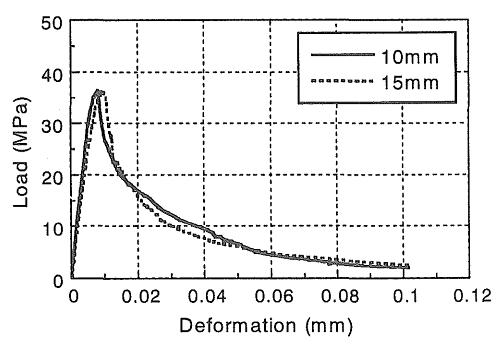
3.1 *Text and indenting*

The test results with respect to the depth of primary notches and concrete type are indicated in Table 4. The failure means that trial cannot provide sufficient tension softening curve because of too early breakage. However, tensile strengths were obtained for all concrete specimens in this study. The testing was failed only one time among 22 trials regardless applying guide notches. Thus, it is thought that the present uniaxial test enables to monitor the tensile properties of not only normal strength but also high strength concrete. When guide notches were applied, the test became easier and the test results are more reliable because the guide notch would induce the crack propagation to reduce the occurrence of weird responses, as shown in Figure 3, demonstrating typical examples of curves. All curves for specimens having guide notches are declined smoothly as deformation after the maximum load (See Figure 3 (a)) while the curves sometimes shows a serrate pattern without guide notches (See Figure 3 (b)). Since steady and smooth decline within softening range of load-deformation curve is desirable, the guide notch application is recommendable to obtain reliable results. The overall shapes of curves are very similar to those of normal concrete specimens (Sohn et al. 1999).

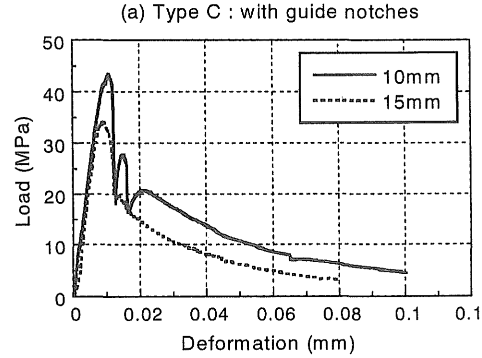
Table 4 Success or failure in testing

Type		A		B		C	
Guide notch		with	w/o	with	w/o	with	w/o
Primary notch	5	S	F	S	S	S	N/A
	10	S	S	S	N/A	S	S
	15	S	S	S	S	S	S
	25	S	S	S	S	S	S

* S: Success in testing , F: Fail, N/A: data is not available



(a) Type C : with guide notches



(b) Type C : without guide notches

Figure 3 Load-deformation curve

Crack opening displacement (COD; w in the equation) was calculated by Equation [1]:

$$w = \delta - (PL)/(EA) - \delta_r \qquad (1)$$

where δ = observed elongation; P = applied load; L = measuring length; A = average cross sectional area of ligament; E = Young's modulus; and δ_r = residual elongation, as illustrated in Figure 4. For the equation, it was assumed that concrete specimen except softening zone is deformed elastically during the entire test.

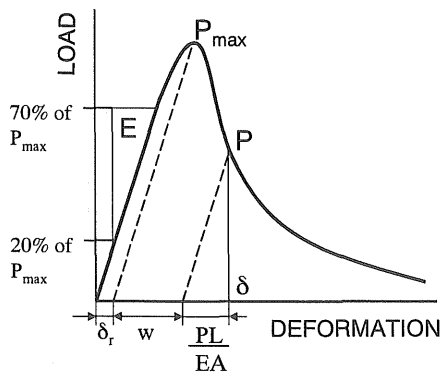
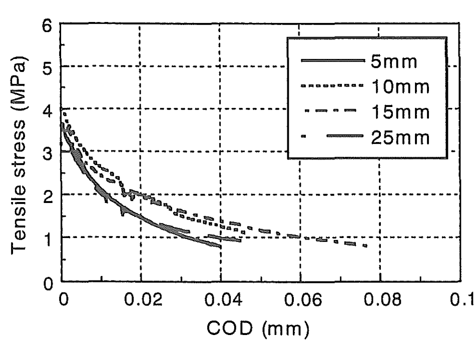
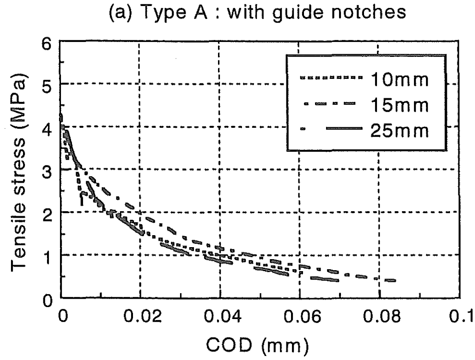


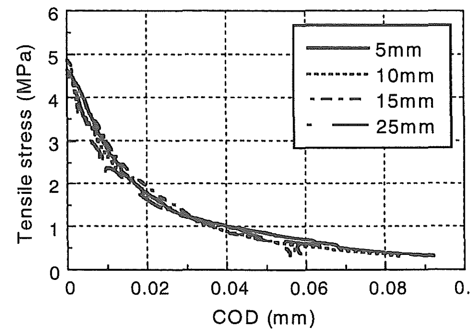
Figure 4 Calculation of COD



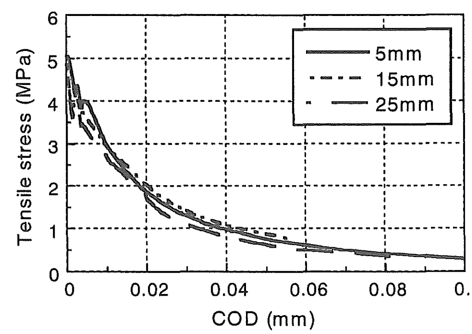
(a) Type A : with guide notches



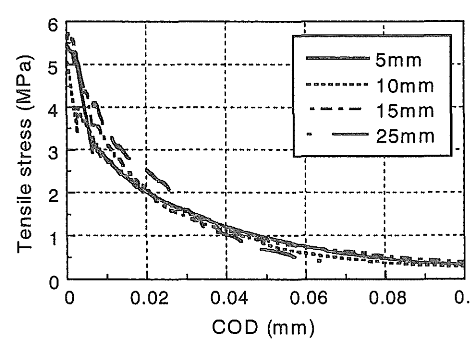
(b) Type A : without guide notches



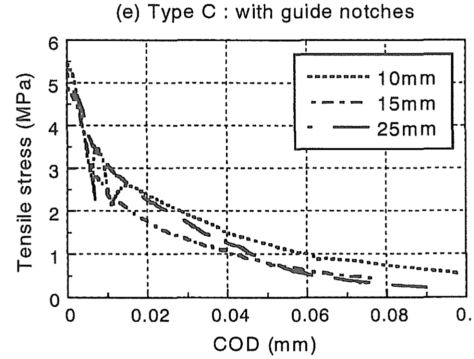
(c) Type B : with guide notches



(d) Type B : without guide notches



(e) Type C : with guide notches



(f) Type C : without guide notches

Figure 5 shows the calculated tension softening curves for various notch depths with respect to concrete type and guide notch application. The tensile strength of high strength concrete would not be influenced by notch depths and guide notch. Type B and C show satisfied degree of curve extensions while curves for type A are relatively short, which directly related to confidence of fracture energy analysis. Any significant deviation of curve was not observed for all cases, correlating to no finding of serious overlapping cracks in crack patterns. The other observation is that the slope of the early stage of curves becomes steeper as strength increases because high strength material usually sacrifices its toughness.

By extrapolating with the tangential line at each end of tension softening curves, fracture energy was calculated, as shown in Table 5. It shows that there are low data scatterings observed for the case of type B and C because the relatively satisfied developments of tension softening curves for these concretes, mentioned earlier, reduce the error of values. In spite of data scattering, especially for type A, the average fracture energies of type A and B concrete is similar while the type C concrete shows remarkably high fracture energy. It might be possibly concluded from the fracture energy observation that the fracture energy increases as the strength level of concrete increases, but it seems to be a hasty conclusion because there is a possibility that the high fracture energy of type C is casual consequence..

Tensile strength estimated by the splitting tension test is approximately 5 to 15% higher than the values by the direct tension test (Neville 1996, Mindess & Young 1981), while a contrary result was also reported (Yoshimoto 1983). However, since incomplete avoidance of secondary flexure tends to reduce the observed tensile strength by using the direct tension test, the comparison of these observed tensile strengths is rather meaningless without knowledge of secondary flexure occurrence. Since the present uniaxial tensile test is able to prevent secondary flexure efficiently, it would be helpful to address the relationships between both tensile strength. The relationships between uniaxial tensile strength versus splitting tensile strength were shown in Figure 6 (indents on left-upper side). The error bars indicate the standard deviation of each case. For relatively low strength level (normal, type A and B), the observed tensile strengths obtained by both tests were very close to each other, while splitting tensile strengths are higher than uniaxial tensile strength for high strength (type C). Two feasible explanations would be suggested. One is that there is possibly a linear relationship according to the strength level of concrete. The other is that the behavior of relationship shows just a scatter not a sort of bias because of lacks of data available or differences in specimen dimensions for both tests. Thus, further research is necessary. On the same figure, the relationships between uniaxial tensile strength versus 28-day compressive strength are also presented (indents on the right-upper side). The higher compressive strength is, the greater uniaxial tensile strength becomes with apparently nonlinear dependence.

Table 5 Fracture energies (N/m)

Type		A		B		C	
Guide notch		with	w/o	with	w/o	with	w/o
Primary notch	5	80	-	128	131	144	-
	10	122	98	113	-	140	171
	15	151	125	111	119	152	120
	25	103	98	114	109	128	139
Average		114	107	116	120	141	142

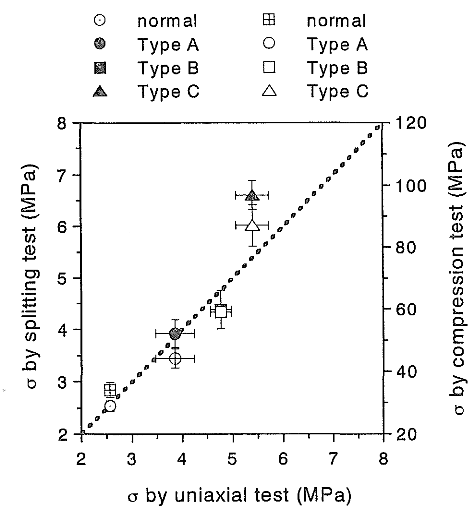


Figure 6 Comparison in tensile strengths

4 CONCLUSIONS

The present study investigating the application of the uniaxial tension test on the high performance concrete led to the following conclusions.

1. The present test procedure is able to investigate tension softening behavior as well as tensile strength of several levels of high strength concretes.
2. The application of guide notches will provide more reliable test results of the tension softening behavior.
3. A serious crack overlapping was not observed unlike normal concrete.
4. As the strength levels of concrete increases, the fracture energy also increases for the present concrete specimens.

5. The average values of fracture energy seems to be unaffected by guide notch application, but the guide notched specimens shows less data scattering.

REFERENCES:

Carpinteri, A. & Ferro, G. 1994. Size Effects on Tensile Fracture Properties: A Unified Explanation Based on Disorder and Fractality of Concrete Microstructure. Material Structure. (v. 27):pp. 563-571.

Hordijk I.D.A. 1989. Deformation-Controlled Uniaxial Tensile Test on Concrete, Technical Report 25.5-89-15/VFA, Delft University of Technology: pp.118.

Koide, H., Akita, H., & Tomon, M. 1997. A Direct Tension Tests for Obtaining Tension Softening Curves of Unnotched Concrete Specimens. Proceedings of International Symposium Brittle Matrix Composites. (no.5): 366-375.

Mehta, P.K. & Monteiro, P.J.M. 1993. Concrete: Structure, Properties, and Materials (2nd ed.). New Jersey: Prentice Hall.

Mindess, S. & Young, J.F. 1981. Concrete (1st ed.). New Jersey: Prentice Hall.

Neville, A.M. 1996. Properties of Concrete (4th ed.). London: John Wiley.

Sohn, D., Akita, H., Koide, H & Tomon, T. 1999. A Study of Test Conditions for Uniaxial Tensile Test of Concrete, Cement Science and Concrete Technology. (no. 53): 650-656.

Trunk, B.& Wittmann, F.H. 1998. Experimental Investigation into the Size Dependence of Fracture Mechanics Parameters. Fracture Mechanics of Concrete Structures. Freiburg: AEDIFICATIO Publishers: pp. 1937-1948.

Van Mier, J.G.M. & Nooru-Mohamed M.B. 1990. Geometrical and Structural Aspects of Concrete Fracture. Engineering. Fracture Mechanics (v. 35): pp. 617-628.

Van Mier, J.G.M., Schlangen, E. & Vervuut, A. 1996. Tensile Cracking in Concrete and Sandstone: Part 2 – Effect of Boundary Rotations. Material Structure. (v. 29): pp. 87-96.

Van Vliet M.R.A. & Van Mier, J.G.M. 1998. Experimental Investigation of Size Effect in Concrete under Uniaxial Tension. Fracture Mechanics of Concrete Structures, Freiburg: AEDIFICATIO Publishers. pp. 1923-1936.

Yoshimoto, A. 1983. Relation between Direct Tensile Strength and Modulus of Rupture of Concrete and Mortar. Cement & Concrete (no. 435)pp. 42-48.