論文 Recommendation for Test Conditions of Uniaxial Tension Test in Order to Monitor Tension Softening Behavior of Concrete

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ABSTRACT: Testing conditions for obtaining reliable tension softening behavior and fracture energy of the uniaxial tension test have been investigated. First, it is recommended that the applied load should be controlled by the strain of concrete specimen in order to maintain stable fracture during testing. Next, the generation of secondary flexure should be prevented. For this purpose, fixed platens and a force mechanism is required. Not only primary notches but also guide notches are recommended to avoid the occurrences of multiple cracks as well as overlapping cracks. The constant different elongation method can be most reliable for the uniaxial tension test.
KEYWORDS: tension softening, uniaxial tensile test, secondary flexure, multiple cracks, overlapping crack

1. INTRODUCTION

Since uniaxial tensile testing of concrete is difficult to perform in practice and observed tensile properties are in difference according to employed testing conditions, no standard test has been established yet. However, the knowledge of tensile behavior is essential to understand fundamental fracture mechanism of concrete as well as to satisfy new demands for qualifying new cementitious materials. Although many investigators suggested various testing methods, some of conditions and results were inconsistent. The difficulties to investigate tension softening behavior under the uniaxial tensile load are unstable fracture, secondary flexure generation, and multiple or overlapping crack occurrence. The main objective of this study is to provide solutions to overcome these problems. Several recommended testing conditions to obtain reliable results for the uniaxial tensile test of concrete would be addressed.

2. PROBLEMS IN THE UNIAXIAL TENSILE TEST

2.1 SELECTION OF LOAD CONTROL

Applied load can be controlled by displacement of machine platens or by strain (displacement) of specimen. If the applied load were controlled by displacement of machine platens, the entire length of a specimen should be less than the characteristic length [1]. Since the characteristic length, however, decreases rapidly as the strength of concrete increases, this method would be limited to low strength concrete or small size specimen. Additionally, rigidity reduction in platen or any attachments should be accounted for the characteristic length. This method is practically unable to avoid the generation of secondary flexure because an apparatus, which is necessary to prevent

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secondary flexure, is too difficult to be attached. While, if the load were controlled by the specimen strain (displacement), only measuring length, not entire specimen length, is taken into consideration. This method enables to test in a wide range of strength and specimen size as well as to prevent secondary flexure without any limitations. Therefore, the specimen strain (displacement) -controlled loading will be recommended.

2.2 PREVENTION OF SECONDARY FLEXURE

When local softening of concrete specimen is happened during loading, a secondary flexure (or lateral flexing) will be created. The secondary flexure produces stress reductions at the peak load not only inside but also outside of the softening zone, resulting in significant underestimation of the observed tensile strength [2]. Thus, the secondary flexure should be prevented. To satisfy this demand, a fixed platen method has been suggested [3]. This method is assumed that platens and machine have infinite rigidity, but it is impossible practically. Moreover, long specimen tends to be bent undesirably under loading. Because of these two problems, only use of fixed platens was unable to eliminate the secondary flexure completely. In order to avoid secondary flexure, a specifically designed adjusting gear system was introduced [4]. When a certain side of a concrete specimen is elongated more than the opposite side, by turning the adjusting gear the over-elongated side can be contracted until reaching a proper balance. This study employed this method.

2.3 AVOIDANCE OF MULTIPLE CRACKS

Although secondary flexure is prevented completely, the success in the observation of tension softening behavior of concrete is still unknown. One reason is the occurrence of multiple cracks, as shown in Fig. 1. Since softening behavior after generating multiple cracks becomes unreliable, the multiple crack generation should be eliminated. By employing flared type specimen, multiple cracks were prevented easily [5]. Recently, it was reported that applying notches on a prismatic specimen is enough to prevent multiple cracks [4]. It is thought that high stress concentration caused by notches may mislead to estimate the true tensile strength of concrete, while several simulation results prove that the influence of notches on the observation of the tensile strength can be negligible [6,7]. A notched prismatic specimen is recommended because of ease to fabricate. The prismatic specimen also allows monitoring all lateral deformations.

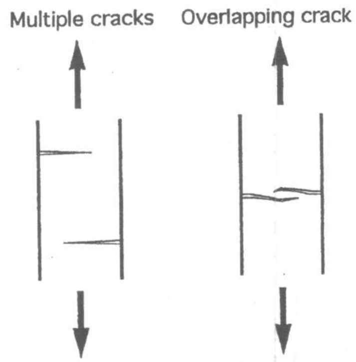


Fig. 1 Multiple and overlapping cracks

2.4 AVOIDANCE OF OVERLAPPING CRACK OCCURRENCE

Another serious problem in performing the uniaxial tensile test is overlapping cracks, as shown in Fig 1. The overlapping cracks make crack surface increase, resulting in increasing the observed fracture energy too great to be acceptable. Thus, these cracks should be prevented. Basically, the overlapping crack creation is based on the mismatch of two opposite directional cracks. If an eccentric load were applied on a specimen to make a single directional crack propagation, as van Vliet suggested [8], overlapping cracks may be avoided. However, the eccentric load affects on a specimen as same as the secondary flexure, thus the amount of the flexure should be optimized.

3. EXPERIMENTAL WORK

3.1 SPECIMEN PREPARATION

Ordinary concrete (cement : sand : aggregate = 1 : 2 : 3.8, w/c=0.5) was used. Concrete was cast into prismatic molds with dimensions of 100x100x400 mm. Four specimens were tested for each series. After demolding, specimens were cured under water at 20±1°C. Notches were made at the center of lateral faces by a diamond saw. The depth of the notch was in the range of 5-25 mm. A 70-mm gauge length extensometer was attached to each face. A cross type steel frame was attached to specimen ends by epoxy resin and embedded bolt. Details in elsewhere [9].

3.2 TESTING METHODS

Figure 2 shows testing scheme for the direct uniaxial tension test. The steel frames glued at the ends of a specimen were connected to universal joints designed to be free of bending moment. A specifically designed adjusting gear system was attached at a branch end of the steel arm of all four faces. When deformation difference of two opposite face becomes beyond the predetermined level, an additional force is applied on the over-elongated face by means of tuning the adjusting gear to tighten the steel rod. The role of the steel rod is to transport contraction generated by the gear through steel arms to the specimen. A single turn of the gear reduces 0.01 mm of the distance between two steel arms. This reduction gives an additional force on the specimen to reduce unexpected unbalanced crack propagation. When the one side was tightened, the opposite side should be completely loose. A separate strain gauge attached on each steel rod monitors the additionally applied force. All signals from four extensometers and four strain gauges were monitored by strain amplifier meters and recorded.

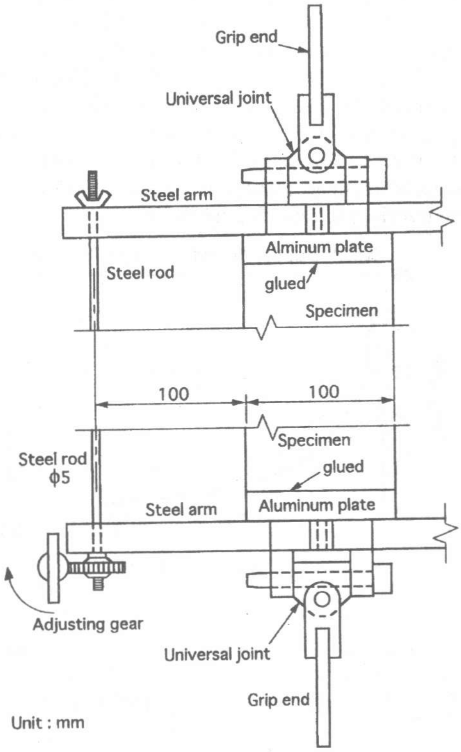


Fig. 2 Testing scheme with the gear system

The application of tensile loading was controlled by a closed-loop loading system. The testing began with a load control stage until reaching appropriately determined level of the applied load. Experimentally, 60-70% of the expected maximum load of a specimen was chosen for the level. After the first stage, the test shifted to a strain control stage. During strain control stages, the applied load was controlled by the average strain of all faces.

4. RESULTS AND DISCUSSION

Fig. 3 shows a typical load-deformation curve (P-δ) of concrete. The specimen had 10-mm depth notches and cured 84 days. The load increased to 21.5 kN, then decreased very rapidly 15 kN followed by a gradual decrease until the specimen was completely broken. To represent a tension softening behavior, crack opening displacement (COD) was calculated by Eq. 1.

$$w = \delta - \frac{PL}{EA} - \delta_r \qquad (1)$$

where δ: observed elongation, P: applied load, L: measuring length, A: average value of cross sectional areas of ligament and whole section, E: Young's modulus, and δ_r: residual elongation [10].

Fig. 4 shows an example of calculated tension softening curves (series 1). The curves show similar declines of tensile stress with COD except 25-mm notched case whose curve locates above the rest. By extrapolating with the tangential line at the end of each tension softening curve, fracture energy was calculated. The fracture energies for series 1, as shown in Fig. 5, are about 100 N/m for 5-mm to 15-mm notched specimens. However, the 25-mm notched specimen shows a high energy of 180 N/m. One of reasons for the high fracture energy is the occurrence of overlapping crack because of increase in the surface area of crack. Photo 1 shows serious overlapping cracks along the entire ligament section for that specimen (the 25-mm notched specimen for series 1).

The test was duplicated with 135-day aged specimens (series 2). For the series 2, overlapping cracks was observed for 5- and 15-mm notched specimens whose fracture energies were 128 and 140 N/m, respectively. For 10- and 25-mm notched cases, in which overlapping cracks were not observed, the energies were almost same as 100 N/m. Therefore, it is thought that the occurrence of crack overlapping is independent of notch depth, but unpredictable. The overlapping cracks were observed in about 50% of testing specimens. As mentioned earlier, since the overlapping crack tends to mislead results, it should be eliminated. This study will suggest two methods to eliminate the overlapping crack generation.

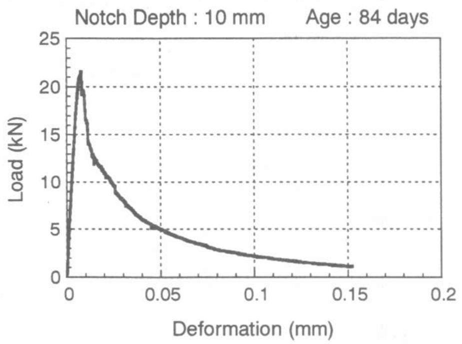


Fig. 3 Load-deformation curve

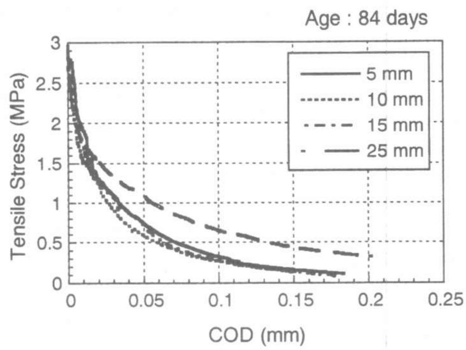


Fig. 4 Tension softening curve of series 1

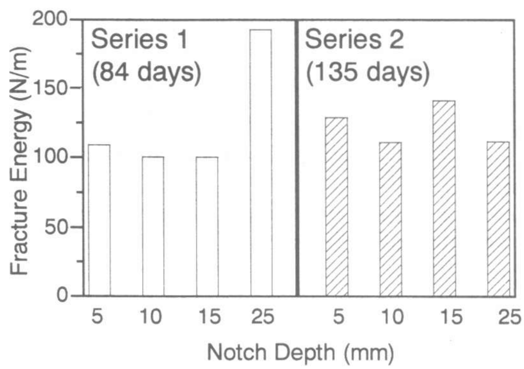


Fig. 5 Fracture energy

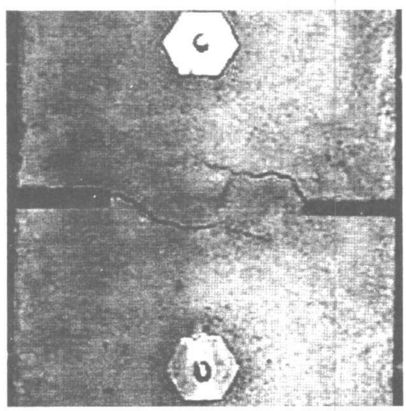


Photo 1 Crack pattern of 25-mm notch (Series 1)

4.1 GUIDE NOTCH METHOD

The first attempt to eliminate overlapping cracks is to apply additional guide notches on unnotched faces. For this study, 5-mm deep guide notch was chosen. Thus, two main notches were made on two primary faces on which cracks began to propagate and two 5-mm guide notches were made on two secondary faces to control the path of crack propagation. As a result, tension softening curves were successfully obtained for all trials. However, 25% of all specimens shows overlapping cracks, while they were not serious like Photo 1. Fig. 6 shows fracture energy of two different age specimen. For series 3, short overlapping cracks were observed on 5-mm notched specimen, resulting in high energy. For the same series, 10- and 15-mm notched specimens had almost same levels of fracture energy of the 5-mm case in spite of no observation of overlapping cracks. Despite of identical condition including the same notch depth of 10 mm and no observation of overlapping cracks for series 4 in Fig 6, the fracture energies were varied. The crack propagation pattern in Photo 2 can explain it. If crack propagates along the guide notches (Type A in Photo 2), the calculated fracture energy is small. If crack propagates tortuously like Type B in Photo 2, the energy is large as shown in Fig 7. Since the Type A is desirable for more reliable and reproducible results, modification in testing method is necessary.

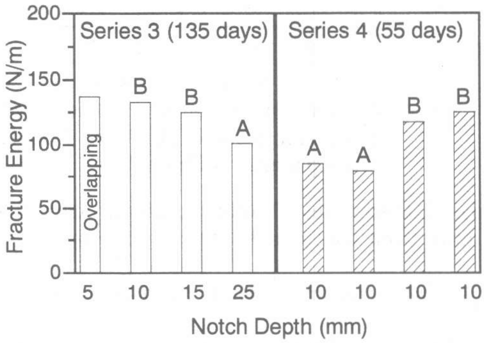
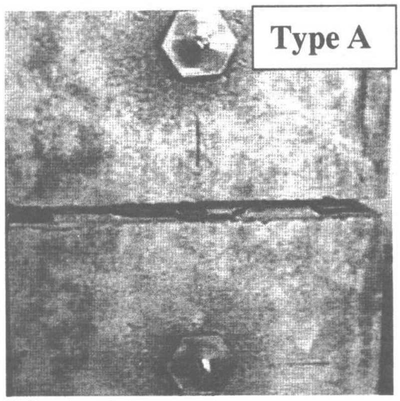
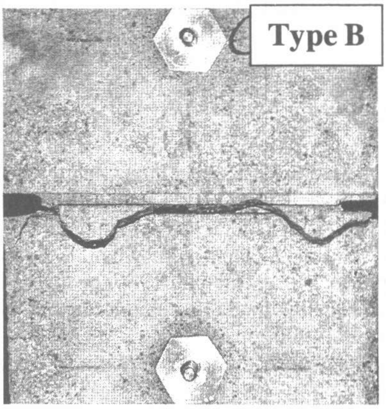


Fig. 6 Fracture energy using guide notch method. A and B indicate crack patterns in Photo 2.





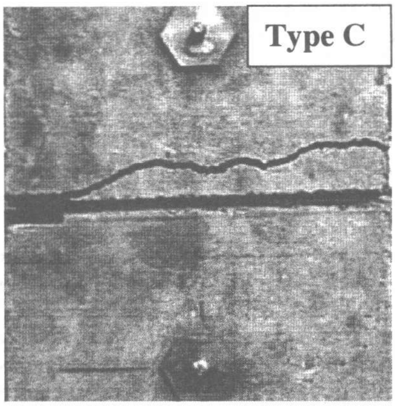


Photo 2 Crack propagation patterns

4.2 CONSTANT DIFFERENT ELONGATION METHOD

The other way to prevent the occurrence of overlapping cracks is to make a one-directional crack propagation. This method was proved by computer simulation [7]. For this purpose, it is required to maintain a constant difference of elongation on two primary notched faces. The notch depths were also changed from the same depth (for instance, 10mm-10mm) to 15mm-5mm. The guide notches were applied. The elongation of 15-mm face was always controlled to be arbitrary 90 μm greater than the opposite side.

As a result, overlapping cracks were not observed for all specimens of this method. It is thought that adopting the constant different elongation method can solve the problem of overlapping crack generation. Compared with Fig. 6, the calculated fracture energies obtained by the present method, as shown in Fig. 7, seems to be more reliable because the paths of crack propagation of

Type Bs were usually less tortuous than the previous cases, resulting in being close energy values to type A. Interestingly, the crack patterns of Type C in Photo 2 were observed, which describe that crack was propagated outside of the guide notch zone not tortuously but straightly. The fracture energy of Type C specimen was rather decreased (See Fig. 9). The further investigation of Type C crack propagation is on demand. Consequently, the constant elongation method is the most recommended method.

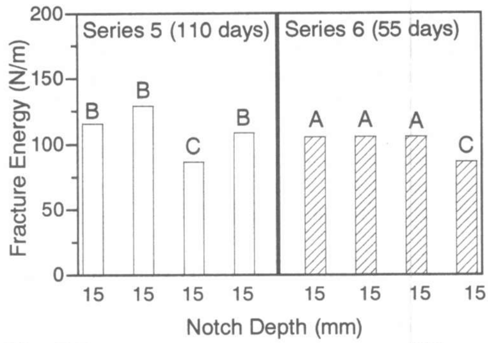


Fig. 7 Fracture energy using constant different elongation method. A, B and C indicate crack patterns in Photo 2.

5. CONCLUSIONS

In this paper, the testing conditions for uniaxial tension test in order to obtain more reliable tension softening behavior and fracture energy have been considered. Several recommendations are as follows:

1. The specimen strain (displacement) controlled loading is recommended to maintain stable fracture during testing.
2. A force mechanism designed for controlling elongation in the measuring length of a specimen is necessary to prevent secondary flexure.
3. Applying notches on a specimen is recommended to avoid multiple cracking.
4. Applying guide notch is recommended to reduce overlapping cracks.
5. To obtain reliable tensile behavior, the present study recommends adopting the constant different elongation method on a uniaxial tension testing.

REFERENCES

1. Petersson, P. E., "Crack Growth and Development of Fracture Zone in Plane Concrete and Similar Materials," Technical Report TVBM 1006, Lund Institute of Technology, Lund, 1981, pp.174.
2. Hordijk, D. A., Reinhardt, H. W. and Cornelissne, H. A. W., "Fracture Mechanics Parameter of Concrete from Uniaxial Tensile Test as Influenced by Specimen Length," in: Shah, S. P. and Swartz, S. E. eds., "Fracture of Concrete and Rock," Soc. Exp. Mechanics, Bethel, 1987, pp.138-149.
3. van Mier, J. G. M., Schlangen, E. and Vervuut, A., "Tensile Cracking in Concrete and Sandstone: Part 2 – Effect of Boundary Rotations," Mater. Struct., 29, 1996, pp.87-96.
4. Akita, H., Koide, H., Tomon, M. and Sohn, D., "A Practical Method for Uniaxial Tension Test of Concrete," submitted to Concrete Science Engineering.
5. Carpinteri, A. and Ferro, G., "Size Effects on Tensile Fracture Properties: A Unified Explanation Based on Disorder and Fractality of Concrete Microstructure," Mater. Struct., 27, 1994, pp.563-571.
6. Zhou, F. P., "Influences of Notch Size, Eccentricity and Rotational Stiffness on Fracture Properties Determined in Tensile Test," in: Wittmann, F. H., ed., "Fracture Mechanics of Concrete Structures," AEDIFICATIO Publishers, Freiburg, 1995, pp.65-74.
7. Akita, H., Sohn, D. and Ojima, M., "Computer Simulation of Tensile Strength Behavior under Various Conditions of Secondary Flexure," in preparation.
8. van Vliet, M. R. A. and van Mier, J. G. M., "Experimental Investigation of Size Effect in Concrete under Uniaxial Tension," in: Mihashi, H and Rokugo, K., eds., "Fracture Mechanics of Concrete Structures," AEDIFICATIO Publishers, Freiburg, 1998, pp.1923-1936.
9. Sohn, D., Akita, H. Koide, H. and Tomon, M., "A Study of Test Conditions for Uniaxial Tensile Test of Concrete," Cement Science and Concrete Technology, No. 54, 1999, pp. 607-613.
10. Akita, H. Koide, H. and Tomon, M., "A Practical Method for Direct Tensile Test of Concrete," Proc. Japan Concrete Institute, Vol. 2, No. 2, 1999, pp. 643-648.