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A database for prediction of the tension softening curve of concrete made from crushed andesite

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ABSTRACT: The authors have developed a uniaxial tension test method minimizing the inevitable flexure completely during the test using adjusting gear systems. The purpose of this paper is to propose a database for the prediction of the tension softening curve of any concrete made from crushed andesite based on the experimental results. With such a database, anyone can predict the tension softening curve without performing the test only when the mixture of the concrete is known. The database consists of the data obtained from 15 reference mixtures and a linear interpolation combined to the least square method is adopted for the prediction. Using an example concrete, it was shown that the present database gives a very good prediction of the tension softening curve.

1 INTRODUCTIONS

The tension softening curve is essential for the analysis of crack behavior or fracture behavior of concrete and concrete structures. The best way to obtain the tension softening curve is to perform an uniaxial tension test. This test directly provides the tension softening curve and tensile strength from an identical specimen without any inverse analysis. However, there are only few investigators to perform the test. Because, the test needs an expensive loading machine and special equipments to minimize some inevitable flexures that occur during the test.

Special attention should be paid to the fact that gluing both ends of the specimen to the loading platens cannot minimize the flexures. The reason is that only a rotation angle of 10^{-4} is enough (Akita et al. 2002) to allow such flexures and loading platens cannot avoid such small rotation. In addition, avoiding load's eccentricity is not enough to avoid flexure. As the weakest zone will be softened and elongated, i.e. flexed by the heterogeneity of concrete when the applied load increases, the flexure appears even if there is no eccentricity between specimen and applied load. Thus, a real time minimization process is essential to avoid the flexure during the test.

The authors have developed such an uniaxial tension test method minimizing the flexure completely by means of adjusting gear systems. The test provides the exact tension softening curve and exact tensile strength which cannot be obtained unless the flexures are minimized completely.

The purpose of this paper is to propose a database for the prediction of the tension softening curve of a concrete made from crushed andesite based on the experimental results obtained by the authors. With such a database, anyone can predict the tension softening curve without performing the test only when the mixture of the concrete is known. Such database should be very beneficial for researchers and designers who want to analyze crack behavior or fracture behavior of some concrete structures.

2 BASIC FUNCTION

In order to determine a basic function to express the tension softening curve, 21 tension softening curves shown in Figure 1 were adopted. They were obtained from the experiments using the specimens of an identical mixture during 2001 to 2005. The curves are expressed by such a normalized form of σ_N and w_N in order to make it easy to get the average of the curves. Where σ_N equals σ/f_t, σ is tensile stress or cohesive stress and f_t is tensile strength, and w_N equals w/w_c, w is crack opening displacement (COD) and w_c is critical crack opening displacement. Some basic functions were proposed by Reinhardt et al. (1986), Li et al. (2002). However, both of the proposed functions do not match the experimental curves directly. Thus, the following basic function (Eq. 1) was assumed by improving the function proposed by Li et al.

$$\sigma_N = E + \frac{C}{w_N + D} - EXP\left(-\left(\frac{B}{w_N}\right)^A\right) \tag{1}$$

where A to E are constants. After the 21 curves were averaged in 11 points (open circles) shown in Figure 2, these constants were determined by applying the least square method to fit the curve to the points.

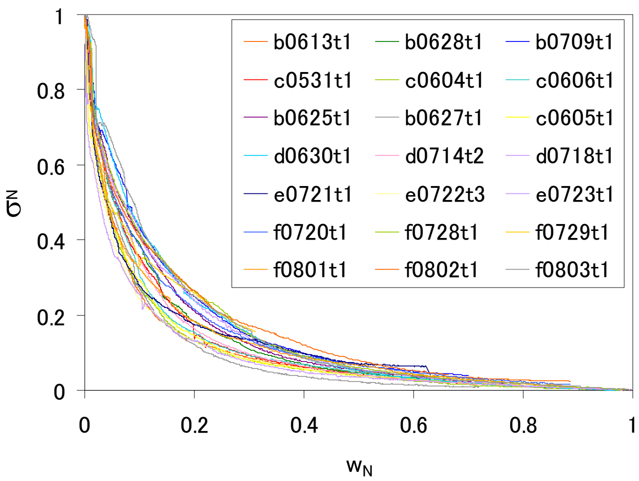

Figure 1. 21 basic tension softening curves.

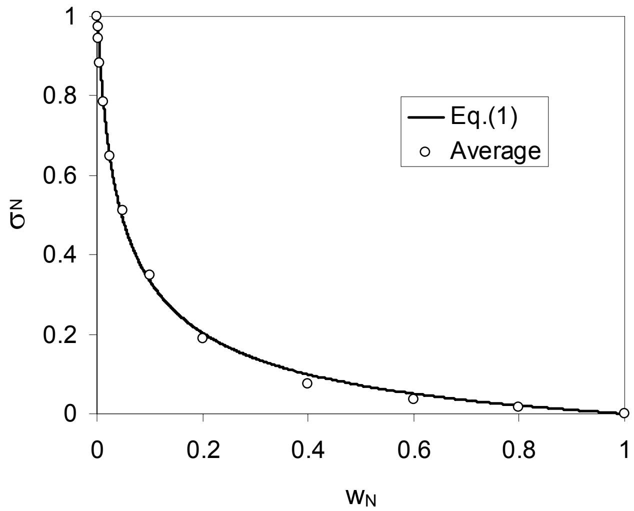

Figure 2. Approximation curve by least square.

The resulting curve agrees with the points precisely and is shown in Figure 2. In Figure 3 & 4, the initial parts of the curves in Figure 1 & 2 are multiplied and shown, respectively. Because of the convex shape of the initial part of these curves, the last term in Equation 1 was adopted. In addition, it is supposed that Equation 1 can be applied to any concrete made from crushed andesite when the constants A to E are appropriately chosen.

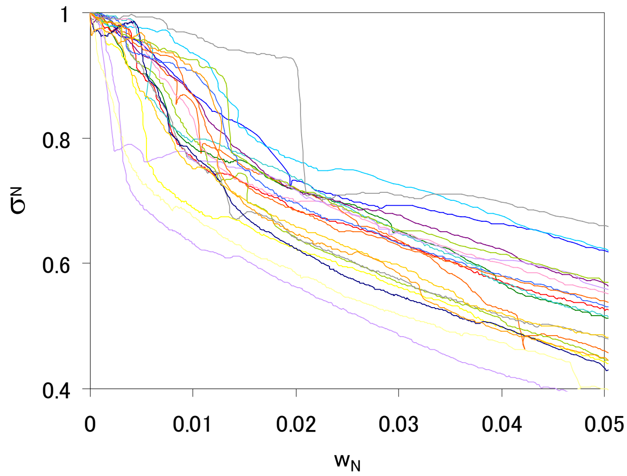

Figure 3. Initial parts of 21 tension softening curves.

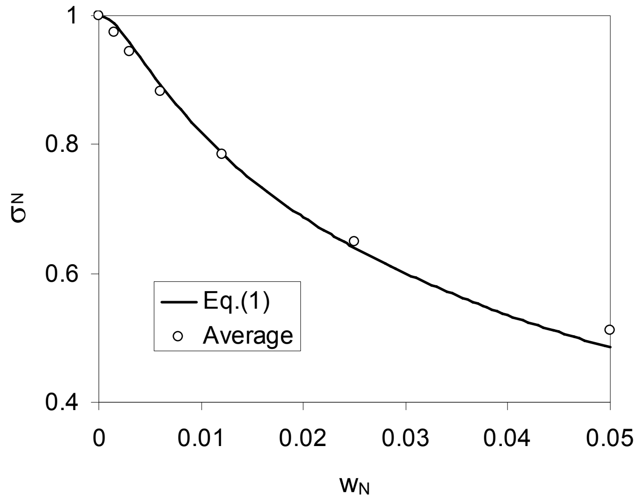

Figure 4. Initial part of the approximation curve.

3 REFERENCE MIXTURES

The reference mixture of concrete to predict tension softening curve of an arbitrary mixture were determined as follows. Three factors of mixture such as water cement ratio W/C, sand aggregates ratio s/a and the maximum size of coarse aggregate G_{max} were selected, because they were considered to affect most the tensile properties of concrete. As an ordinary concrete is within the range of W/C=40% to 60%, s/a=35% to 45% and G_{max}=15mm to 25mm, the range is shown like the inside of the rectangular prism in Figure 5 by 3-dimensional expression. Experiments were performed for 8 mixtures correlating to the apices of the rectangular prism, 6 mixtures correlating to the centers of all faces and 1 mixture correlating to the center of the prism. Crushed andesite was adopted as coarse aggregates, because it was the most common in Japan.

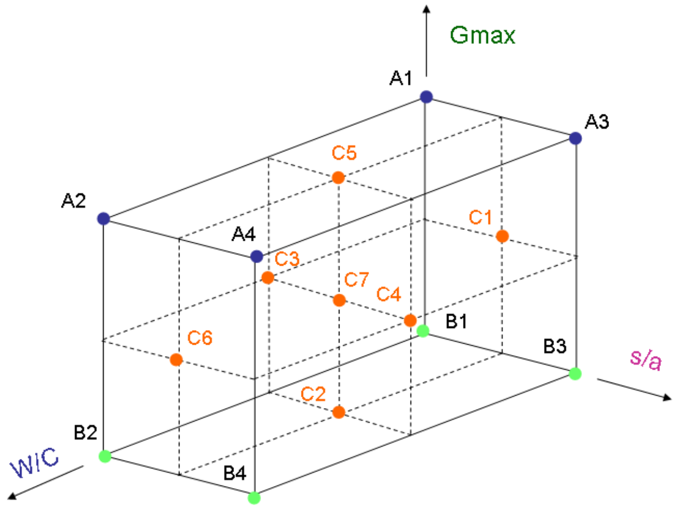

Figure 5. 3-D expression of 15 mixtures.

Table 1. Mixtures of the reference concrete.

Mix	W/C	s/a	G_{max}	W
	(%)	(%)	(mm)	(kg/m^3)
A1	40	35	25	142
A2	60	35	25	143
A3	40	45	25	150
A4	60	45	25	155
B1	40	35	15	160
B2	60	35	15	146
B3	40	45	15	160
B4	60	45	15	160
C1	40	40	20	160
C2	50	40	15	158
C3	50	35	20	146
C4	50	45	20	152
C5	50	40	25	153
C6	60	40	20	157
C7	50	40	20	163
C8	50	37	20	165

4 PROCEDURE OF PREDICTION

In order to calculate the value V inside of the prism in Figure 5, Equation 2 was adopted.

$$V = a + bx + cy + dz + exy + gyz + gzx + hxyz \qquad (2)$$

where a to h are constants and x, y and z mean arbitrary values of W/C, s/a and G_{max}, respectively. The value V means all of the constants A to E in Equation 1, f_t and w_c. Equation 2 is equivalent to a linear Lagrange interpolation formula modified to a 3-dimensional form. The constants a to h are determined by the least square method referring to 15 values of the reference mixtures shown in Figure 5 as A1 to A4, B1 to B4 and C1 to C7. When all constants A to E are predicted by Equation 2, the normalized tension softening curve is obtained by Equation 1. Then, f_t and w_c are also predicted by the same way and finally the tension softening curve without normalization is obtained.

5 EXPERIMENT

The 15 reference mixtures and one example mixture for the present experiment are shown in Table 1. Five cylinders of ϕ100x200mm for the compression test, the same 5 cylinders for the splitting tension test and 5 prisms of 100x100x400mm for uniaxial tension test were cast from one mixture.

The compression test and splitting tension test were performed at the age of 28 days following after the Japan Industry Standard. The uniaxial tension test was performed using a strain-controlled loading ma-chine as shown in Figure 6. Flexures caused by load eccentricity and heterogeneity of concrete were both minimized by adjusting gear systems. In Figure 6, the adjusting gear systems and extensometers on

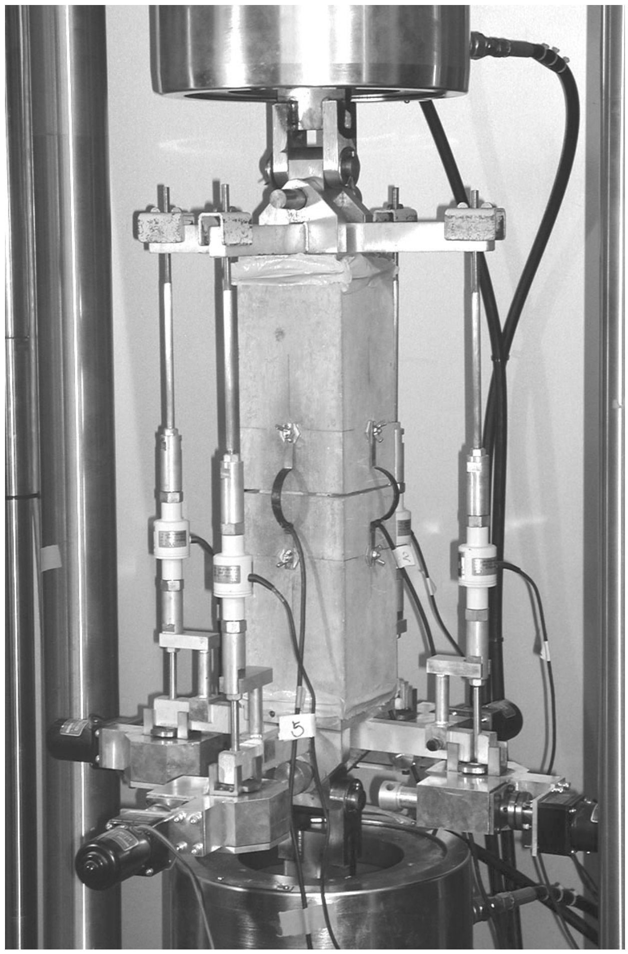
Figure 6. Experimental set-up.

four side faces are shown. The minimization of flexures is executed as follows during the test. When a certain side of a specimen is elongated more than the oppo site side, the more elongated side should be contracted by turns of its adjusting gear until reaching a proper balance in elongation. Such a real time execution is indispensable to minimize flexures caused of the heterogeneity of concrete. Three hours

Table 2. Constants, tensile strength and critical crack opening displacement of each mixture.

Mix	A	B	C	D	E	f_t	w_c
A1	0.6850	0.03421	0.00598	0.0598	0.9000	2.652	0.371
A2	0.5541	0.02130	0.01042	0.0858	0.8786	2.365	0.315
A3	0.5802	0.01381	0.00666	0.0773	0.9139	2.966	0.378
A4	0.5447	0.01832	0.01509	0.1253	0.8796	2.202	0.330
B1	0.6101	0.02853	0.00645	0.0566	0.8860	2.973	0.295
B2	0.5676	0.03328	0.00722	0.0510	0.8582	2.449	0.309
B3	0.7012	0.02243	0.00828	0.1106	0.9251	2.753	0.216
B4	0.6439	0.01699	0.00632	0.0834	0.9242	2.453	0.262
C1	0.6364	0.03309	0.00932	0.0799	0.8834	2.807	0.270
C2	0.5299	0.02826	0.01802	0.1153	0.8436	2.703	0.215
C3	0.4451	0.04754	0.02158	0.0874	0.7529	2.696	0.205
C4	0.6509	0.02904	0.00737	0.0723	0.8981	2.417	0.274
C5	0.5123	0.02286	0.00962	0.0671	0.8566	2.670	0.324
C6	0.5200	0.02530	0.01053	0.0715	0.8528	2.156	0.317
C7	0.5354	0.03328	0.01322	0.0818	0.8384	2.642	0.264
C8	0.6605	0.02740	0.00517	0.0552	0.9064	2.758	0.396

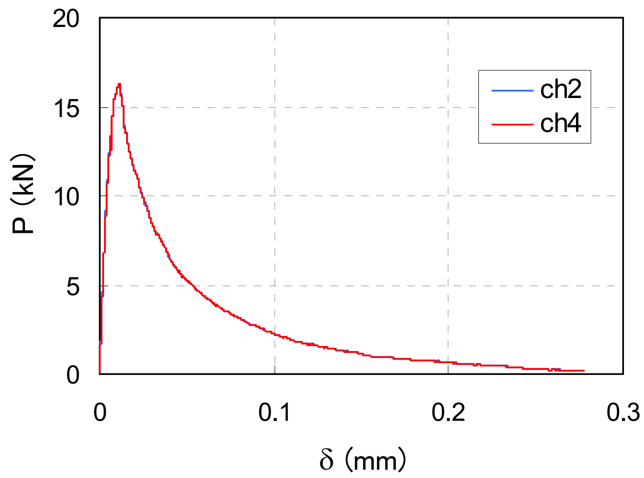

Figure 7. Load-deformation curves (H1019T1).

were spent for one specimen including necessary preparation. Thus, the tension tests of 5 specimens were performed on the age of 29 and 30 days.

6 TEST RESULTS

An example of load-deformation (P-δ) curves directly obtained from the uniaxial tension test is shown in Figure 7. Ch2 and ch4 in the Figure mean two opposite face deformations and coincidence of the two curves indicates that flexures are completely minimized. Figure 8 shows an example of 5 tension softening curves derived from the load-deformation curves of mixture B3. These curves were expressed by normalized form of σ_N and w_N. The representative tension softening curve of this mixture was determined as the same way as in chapter 2, i.e. five curves were averaged in 11 points and constants A to E in Equation 1 were determined by the least square method.

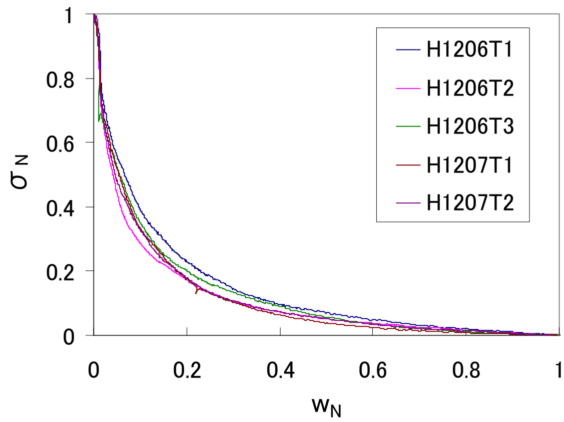

Figure 8. Tension softening curves (Mix B3).

The constants A to E of the tension softening curves determined as mentioned above in each mixture and one example mixture are shown with f_t and w_c in Table 2. In these constants, variation of D in W/C is shown in Figure 9 to 11. In order to avoid complexity, it is shown by three Figures, namely the cases when s/a=35% in Figure 9, when s/a=40% in Figure 10 and when s/a=45% in Figure 11. By these three Figures, all the variations of constant D in the prism including 15 reference mixtures are expressed. In the Figures, marks express the experimental values in reference mixtures and lines express the predicted values by Equation 2. The values in the apices of the prism, namely in A1 to B4 correlate well, but those in centers, namely in C1 to C7 show a little deviations, especially in C2 in Figure 10.

Figure 12 shows the variation of constant B, indicating that the experimental results (marks) and prediction (lines) correlate well. Figure 13 shows the variation of f_t. Every line shows a descending ten dency in increasing W/C and marks correlate well to

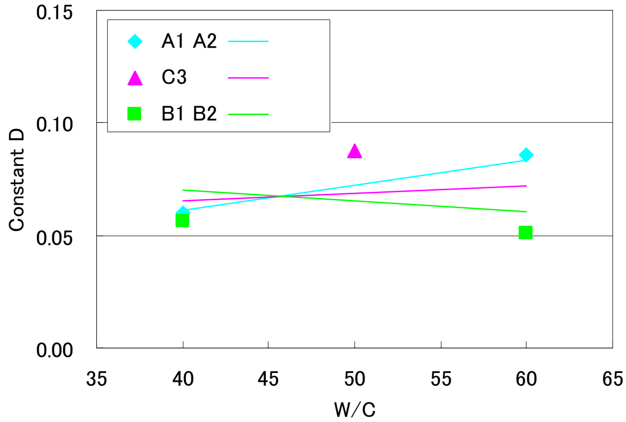

Figure 9. Variation of constant D when s/a=35%.

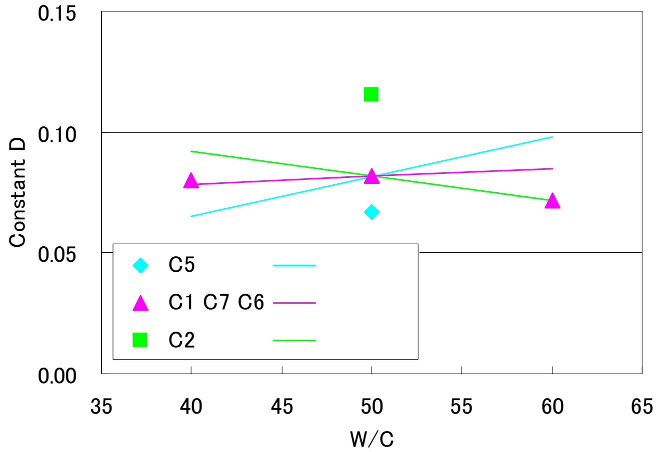

Figure 10. Variation of constant D when s/a=40%.

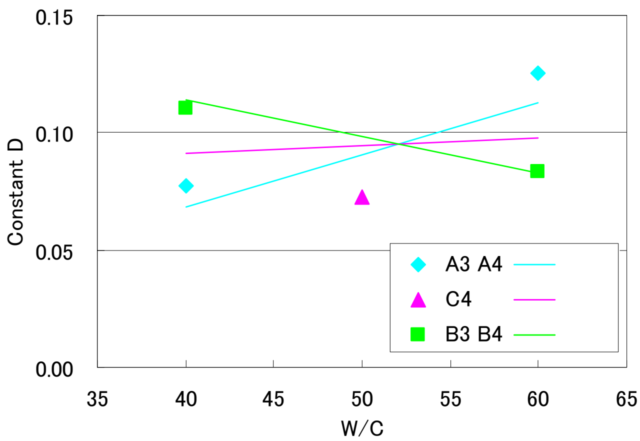

Figure 11. Variation of constant D when s/a=45%.

the lines. Figure 14 shows the variation of w_c. A little deviation is found in comparison with Figure 13. However, such deviation easily occurs, because

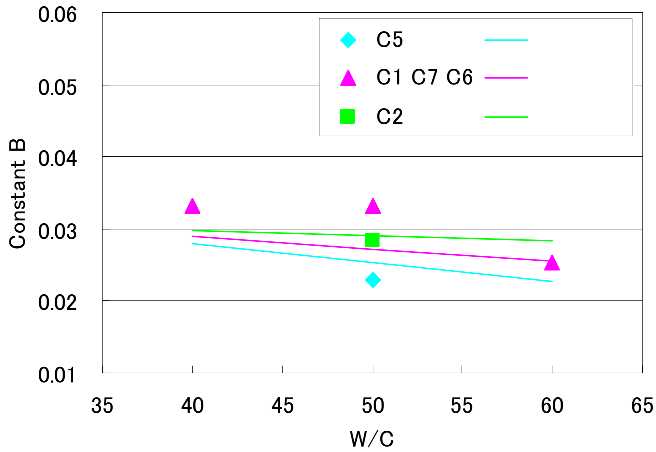

Figure 12. Variation of constant B when s/a=40%.

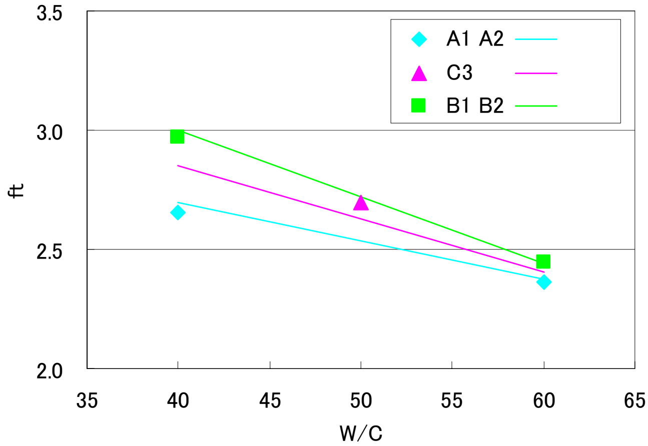

Figure 13. Variation of ft when s/a=35%.

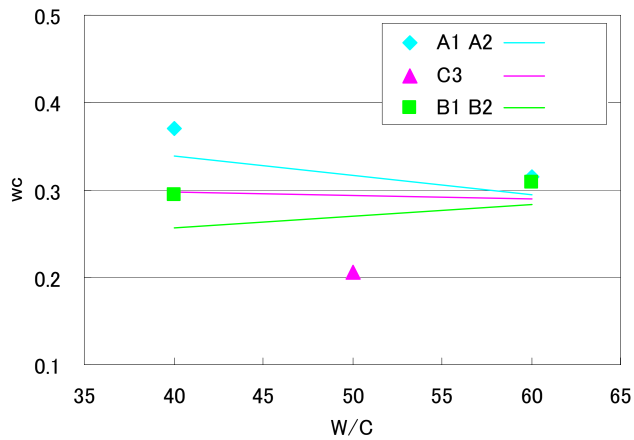

Figure 14. Variation of wc when s/a=35%.

small vertical variation in tension softening curve results in large variation in w_c, as w_c means the point where the almost flat curve intersects the horizontal w axis.

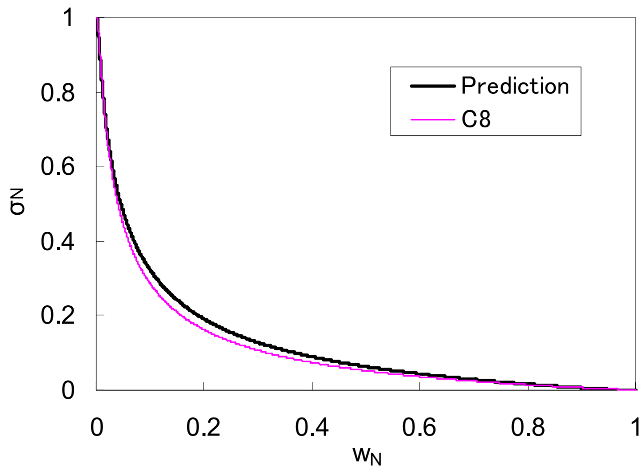

Figure 15. Two curves in normalized form.

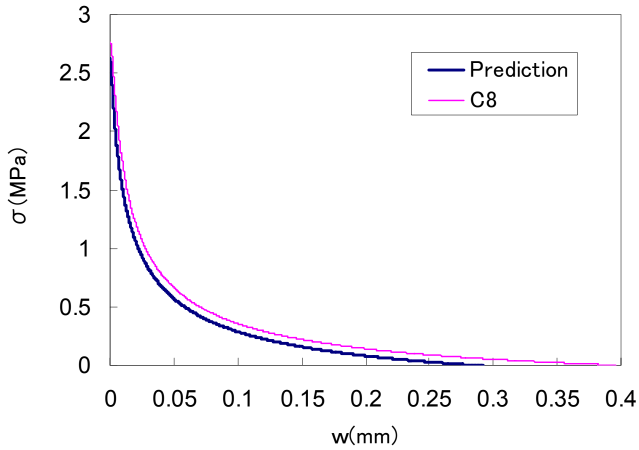

Figure 16. Two curves without normalization.

7 APPLICATION

In order to evaluate the applicability of this database, an example of a given concrete (mix C8 in Table 1) was examined. From the mixture in Table 1, x (W/C), y (s/a) and z (G_{max}) were determined and the constants A to E were predicted by Equation 2. Then the normalized tension softening curve is obtained as shown in Figure 15. The predicted curve is well correlated to the average curve obtained by the experiment in mixture C8.

Predicting f_t and w_c by the same way, tension softening curve without normalization is obtained for mixture C8. Figure 16 shows the curve comparing with the experimental one. In predicted curve, f_t is a little smaller than the experimental one and w_c is tolerably smaller than that. In spite of the fact, the two curves correlate well each other. It means that the present database is applicable to the prediction of tension softening curve made from crushed andesite without performing such tension test.

8 CONCLUSIONS

A database to predict tension softening curve without performing an uniaxial tension test was developed. An examination against one mixture gave a satisfactory result. It is concluded that this database is applicable for ordinary concrete made from crushed andesite.

REFERENCES

Akita, H. et al. 2002. Three Misunderstandings in Uniaxial Tension Test of Concrete, Proc. ACI SP-209, pp.405-414.

Li, Q. et al. 2002. Behaviour of Large Concrete Specimens in Uniaxial Tension, Mag. of Concrete Research, Vol.54, No.5, pp.385-391.

Reinhardt, H. W. et al. 1986. Tensile Test and Failure Analysis of Concrete, J. of Structural Engrg, ASCE, Vol.112, No.11, pp.2462-2477.