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UNIAXIAL TENSION TEST METHOD USING SHCC PRISMS MOLDED INTO A DUMBBELL SHAPE

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Abstract: Uniaxial tensile properties of a SHCC can be confirmed by simply fabricating prism specimens at the job site and molding those later into a dumbbell shape for uniaxial tension testing. Level of skill in fabricating dumbbell-shaped specimens and the use of vibratory consolidation led to no significant difference in the uniaxial tension test results. The variances and means of the uniaxial tension test results of specimens molded in this manner showed no significant difference from those of monolithically molded dumbbell-shaped specimens. Also, changes in the fiber content of the molding material from 1.25% to 0.5% in steps of 0.25 percentage points had no significant effect on the test results, leading to test results equivalent to those of monolithically molded dumbbell-shaped specimens.

1 INTRODUCTION

In addition to their use as precast members, strain-hardening cement composites (SHCC) are available as a premix material to be mixed at job sites for spraying or at ready-mixed concrete plants for cast-in-place concreting [1].

The mechanical properties of SHCCs are characterized by their pseudo strain-hardening behavior under uniaxial tensile stress. The Japan Society of Civil Engineers (JSCE) specifies a recommended uniaxial direct tension test method and a method of fabricating specimens for strength testing. These methods require that specimens for this test method be fabricated using dedicated molds having enlarged ends in the shape of a dumbbell to fit to the holding jigs of uniaxial tension testing machines. However, since these molds are made of metal precisely cut to shape, currently they are not readily available. Bending tests are often conducted instead of uniaxial tension tests to confirm cracking behavior, but there are limitations to such substitution, as certain materials that do not show multiple-cracking properties during uniaxial tension testing may show multiple cracks during bending testing [2]. Meanwhile, the authors have been conducting uniaxial tension tests using dumbbell-shaped specimens made by additionally molding enlarged ends for prisms sawed from SHCC block or plate [3].

With this as a background, the authors focused on quality control methods for SHCCs, a promising repair and surface protection material for use on site, for which quality control methods have yet to be established [4]. To solve this problem, the authors [5] investigated a uniaxial tension test method using dumbbell-shaped specimens made of prisms to facilitate material property control by simple preparation of specimens on site, thereby contributing to the stabilization and enhancement of construction qualities.

2 EXPERIMENT OVERVIEW

2.1 Types and mix proportions of SHCC

The SHCC used for the present tests to confirm the uniaxial tensile properties was a type containing 1.25 vol % high-density polyethylene (PE) fibers.

In order to form a dumbbell shape in a mold, so as to make the specimen fit into the holding jigs of a uniaxial tension testing machine, a material was used to enlarge both ends of each prism. This material (hereafter referred to as “molding material”) basically contained 1.25 vol % fibers. Different ratios of 1.0, 0.75, and 0.50% were also adopted to examine the effect of the fiber content of the molding material on the tensile properties of specimens. Note that the case of 0% fibers was excluded from the test program, as it led to localized failure in the enlarged ends during preliminary testing. Also, application of an expansive SHCC to the molding material was investigated to compensate for shrinkage based on the authors’ previous study [6].

Tables 1 and 2 give the component materials and mixture proportions, respectively. An omni mixer with a capacity of 10 liters was used for mixing.

2.2 Molding of specimens and uniaxial tension test procedure

Figure 1 shows the geometry and fabrication steps of the specimen. At an age of 7 days, each prism measuring 29.5 by 30 by 300 mm was set in a mold to form a dumbbell-shape by filling the molding material for enlarging both ends to fit to the holding jigs of a uniaxial tension testing machine shown in Photo 1. These specimens were then subjected to uniaxial tension testing at 14 days. Monolithically molded dumbbell-shaped specimens were also fabricated simultaneously

Table 1: Component materials

Materials		Properties
High-strength polyethylene fiber	(PE)	Diameter: 0.012mm, Length: 12mm, Density: 0.97g/cm^3, Tensile strength: 2.6GPa, Young's modulus: 88GPa
Cement	(C)	High-early-strength portland cement, Density: 3.13g/cm^3
Expansive additive	(EX)	Density: 3.05g/cm^3
Limestone powder	(LP)	Density: 2.71g/cm^3, Specific surface area: 3050cm^2/g
Fine aggregate	(S)	Silica sand (size:0.08～0.3mm), Density: 2.63g/cm^3
Super plasticizer	(SP)	Ether polycarboxylic acid
Viscosity enhancer	(MC)	Water-soluble methylcellulose

Table 2: Mix proportions, factor and experimental levels

Series	Point			W/P (%)	W/B (%)	Unit amount (kg/m^3)								Factors	Exp. levels
	Monolithic dumbbell–shaped specimen	Prism	Molding material			W	Powder			S	SP	MC	PE		
							Binder		LP						
							C	EX							
1	○	—	—	30.0	54.5	380	697	0	570	321	19.0	1.0	12.1	skill	2
														fabrication method	2
2	○	○	○	30.0	44.1	380	862	0	405	348	19.0	1.0	12.1	Addition of expansive additive	2
	—	—	Expansion type	30.0	44.1	380	810	52	405	346	19.0	1.0	12.1		
3	○	○	○	30.0	44.1	380	862	0	405	348	19.0	1.0	12.1	Fiber content	5

with pisms to serve as controls. Prior to placing the molding material, the surfaces to come into contact with the molding material were cleaned with a wire brush while rinsing with water. Moist air curing to control moisture evaporation was adopted for these specimens instead of water curing in consideration of the placement control of materials spray-applied at job sites and transportation of prisms to testing institutions.

2.3 Test series and items

(1) Series 1: Effect of skill and method of fabricating specimens on test results

Prior to tests using prisms, uniaxial tension tests were conducted on monolithic dumbbell-shaped specimens, with the factor being the skills in fabricating specimens, in consideration of the fact that various people may fabricate specimens at job sites. Two experienced persons prepared specimens: a researcher with experience of over 5 years and a student with less than 1 year experience. The means and variances of the test results were compared in accordance with JIS Z 9041-2 (Statistical interpretation of data, Part 2: Techniques of estimation and test relating to means and variances). Tension tests were also conducted on monolithic dumbbell-shaped specimens made by two levels of consolidation process: with and without vibration using a table vibrator specified in JIS R 5201 (Physical testing methods for cement). This was done in consideration of the fact that consolidation by tapping with a mallet is general procedure at job sites, while vibratory consolidation is available at laboratories. The means and variances of the test results were similarly compared.

(2) Series 2: Effect of expansive additive added to molding material on test results

According to the authors' previous report [6], SHCCs show large autogenous shrinkage at an early stage of hydration. For this reason, the effect of the volume changes of the molding material on the tension test results of prisms was investigated using an SHCC with and without an expansive additive. 6% of cement mass was replaced by the additive. The variances and means of tension test results were examined in comparison with those of monolithic dumbbell-shaped control specimens.

(3) Series 3: Effect of fiber content of molding material on test results

Increased fluidity of the molding material due to a reduced fiber content can facilitate placing. The fiber content of the molding material was therefore taken as the factor in this tension test series, and four levels were selected: 1.25, 1.0, 0.75, and 0.5 vol %. Their effect on the characteristic values of tension testing was examined by variance analysis including comparison with the control. The confidence interval of the population mean

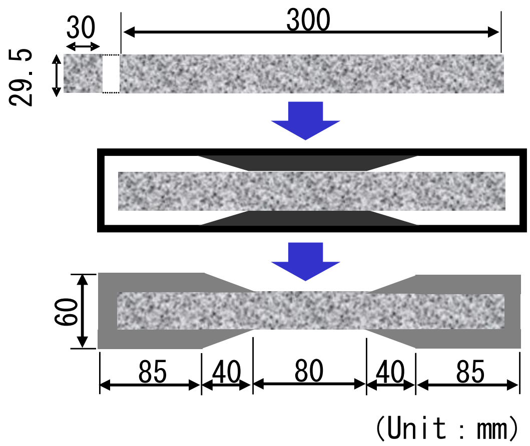


Figure 1: Geometry and fabrication steps

Photo 1: Uniaxial tension testing apparatus

was also estimated to examine the difference from that of the control.

3 TEST RESULTS AND DISCUSSION

By following the JSCE standard specifications [1], the cracking load, tensile strength, and ultimate tensile strain were determined from the mean of three specimens, excepting the two specimens with the largest and smallest ultimate tensile strains (shaded values in the table expressing the test results). In determining the variance of scatter, all test results were used for calculation.

3.1 Series 1: Effect of skill and method of fabricating specimens on test results

Table 3 gives the results of uniaxial tension tests on monolithic dumbbell-shaped specimens prepared by two persons, A and B, with different levels of experience in fabricating specimens. Figure 2 shows the stress-strain relationship by uniaxial tension test.

(1) Cracking strength

Investigation of the test results began with their variance in regard to specimens prepared using a table vibrator by two persons, A and B, based on Format G of JIS Z 9041-2 (Comparison of two variances or standard deviations).

Null hypothesis and test type: Two-sided tests

H_0: $\sigma_A^2 = \sigma_B^2$

Level of significance: $\alpha = 0.05$,

Degree of freedom: $\nu_A = 5 - 1 = 4$,

$\nu_B = 5 - 1 = 4$

Variance: V_A, V_B

From Table 3, $V_A = 0.0289$ N^2/mm^4,

$V_B = 0.0577$ N^2/mm^4.

F_0 is determined by choosing V_A or V_B, whichever is greater, as the numerator.

$F_0 = 0.0577 / 0.0289 = 1.997$

The upper probability of F-distribution

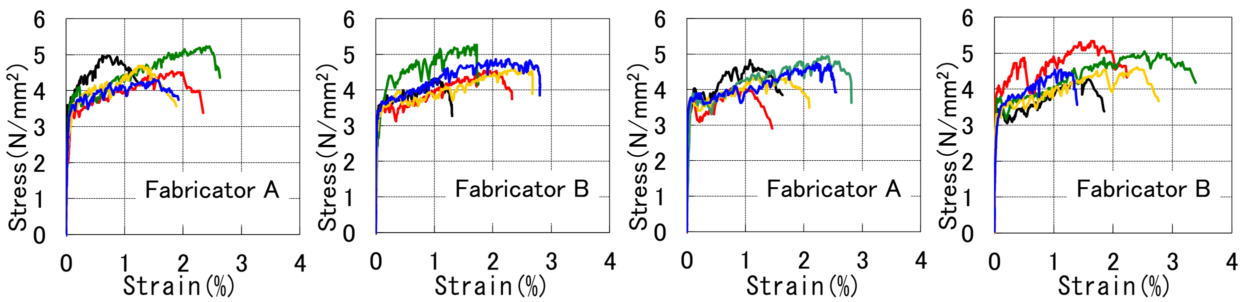
$F_{1-\alpha/2}(\nu_1, \nu_2) = 9.60$

As $F_0 < 9.60$, H_0 is not rejected. As to the

Table 3: Uniaxial tension test results of Series 1

Properties	Factors			1	2	3	4	5	Mean ($\bar{x}_i$)	Variance (V_i)	
First crack strength (N/mm^2)	1	With vibration	A	3.59	3.41	3.88	3.67	3.59	3.56	0.0289	0.0532
			B	3.52	3.52	3.56	2.98	3.41	3.50	0.0577	(N^2/mm^4)
									3.53		
	2	Without vibration	A	4.03	3.70	3.74	3.88	3.77	3.85	0.0176	0.0515
			B	3.34	3.70	3.74	3.30	3.52	3.51	0.0400	(N^2/mm^4)
									3.68		
Tensile strength (N/mm^2)	1	With vibration	A	4.97	4.54	5.23	4.68	4.32	4.51	0.1282	0.1145
			B	4.32	4.54	5.26	4.61	4.86	4.89	0.1289	(N^2/mm^4)
									4.70		
	2	Without vibration	A	4.83	4.07	4.36	4.94	4.75	4.65	0.1335	0.1469
			B	4.28	5.34	5.05	4.61	4.54	4.83	0.1781	(N^2/mm^4)
									4.74		
Ultimate strain (%)	1	With vibration	A	0.74	1.81	2.40	1.32	1.50	1.54	0.3754	0.3436
			B	1.08	1.96	1.69	2.54	2.28	1.98	0.3184	(%^{2})
									1.76		
	2	Without vibration	A	1.08	0.85	1.58	2.42	2.22	1.63	0.4683	0.3783
			B	1.58	1.68	2.53	2.41	1.13	1.74	0.3485	(%^{2})
									1.68		

※Among the data of five test specimens, those having the maximum or minimum ultimate strain are shaded.



(a) Without vibration (b) With vibration

Figure 2: Stress-strain relationship of Series 1 by uniaxial tension testing

variance of the cracking strength of dumbbell-shaped specimens fabricated by A and B using a table vibrator, which was determined by uniaxial tension tests, no significant difference was therefore detected with a significance level of 5%.

Since the variances of both, σ_A^2 and σ_B^2, are thus regarded as being equivalent, investigation was then conducted into means of the cracking strength determined by uniaxial tension tests on dumbbell-shaped specimens fabricated by A and B using a table vibrator. This was in accordance with Format C (Comparison between means of two groups of unpaired measurements with unknown but assumably equivalent variances) of JIS Z 9041-2.

Null hypothesis and test type: Two-sided tests

H_0: $\mu_A = \mu_B$

Level of significance: $\alpha = 0.05$,

Number of measurements: $n_A = 3$, $n_B = 3$,

Degree of freedom: $\nu = 3 + 3 - 2 = 4$

Value of t-distribution table: $t_{1-\alpha/2}(4) = 2.78$

From Table 3, $D = \bar{x}_A - \bar{x}_B = 3.56\text{-}3.50 = 0.06$

Standard deviation: S_A, S_B

Also from Table 3,

Defined as the following equation:

$$Q = (n_A - 1) S_A^2 + (n_B - 1) S_B^2 = 2 \times 0.0289 + 2 \times 0.0577 = 0.1732 \quad (1)$$

$$S_D = \sqrt{\frac{n_A + n_B}{n_A n_B} \frac{Q}{\nu}} = 0.170 \quad (2)$$

$$B = t_{1-\alpha/2}(\nu)\, S_D = 2.78 \times 0.170 = 0.473 \quad (3)$$

While null hypothesis H_0 is abandoned when $|D| > B$, it is not abandoned in this case because $0.06 < 0.473$. Accordingly, no significant difference was found, with a significance level of 5%, between the means of the cracking strength of specimens fabricated by A and B.

Similarly, the variance of cracking strength was examined regarding specimens fabricated by A and B without using a table vibrator.

From Table 3, $F_0 = 0.0400 / 0.0176 = 2.273$. H_0 is therefore not abandoned, since the upper probability of the F-distribution is $F_{1-\alpha/2}(\nu_1, \nu_2) = 9.60$. In regard to investigation into means, $D = \bar{x}_A - \bar{x}_B = 3.85\text{-}3.51 = 0.34$ from Table 3.

Standard deviation: S_A, S_B

Therefore,

$$Q = (n_A - 1) S_A^2 + (n_B - 1) S_B^2 = 2 \times 0.0176 + 2 \times 0.0400 = 0.1152 \quad (4)$$

$$S_D = \sqrt{\frac{n_1 + n_2}{n_1 n_2} \frac{Q}{\nu}} = 0.139 \quad (5)$$

$$B = t_{1-\alpha/2}(\nu)\, S_D = 2.78 \times 0.139 = 0.386 \quad (6)$$

While null hypothesis H_0 is abandoned when $|D| > B$, it is not abandoned in this case because $0.34 < 0.386$. Accordingly, no significant difference was observed, with a significance level of 5%, between the means of the cracking strength of specimens fabricated by A and B.

So, no significant difference was observed between specimen fabricators. Next the effect of vibration from a table vibrator on the test results was investigated by a similar procedure using the test data of both A and B.

Null hypothesis and test type: Two-sided tests

H_0: $\sigma_1^2 = \sigma_2^2$

Level of significance: $\alpha = 0.05$,

Degree of freedom: $\nu_1 = 10 - 1 = 9$,

$\nu_2 = 10 - 1 = 9$

From Table 3, $V_1 = 0.0532$ N^2/mm^4,

$V_2 = 0.0515$ N^2/mm^4.

F_0 is determined by putting V_1 or V_2, whichever is greater, as the numerator.

$F_0 = 0.0532 / 0.0515 = 1.997$

The upper probability of the F-distribution:

$F_{1-\alpha/2}(\nu_1, \nu_2) = 4.02$

As $F_0 < 4.02$, H_0 is not rejected. In regard to the cracking strengths of specimens placed with or without a table vibrator, no significant difference was detected between their variances by uniaxial testing with a significance level of 5%. Their means also led to no significant difference due to the use of vibration.

(2) Maximum tensile strength and ultimate strain

The effects of specimen fabricators A and B and the use of a table vibrator on the maximum tensile strength and ultimate strain were examined by procedures similar to cracking strength testing. As a result, no significant differences were found.

It can therefore be said that the material properties of a SHCC can be confirmed by uniaxial tension testing without being affected by the experience of specimen fabricators or the use of a table vibrator, provided the material is placed carefully without concreting layers or lifts and continuously in one direction to prevent inclusion of air bubbles.

3.2 Series 2: Effect of expansive additive added to molding material on test results

Table 4 gives the results of Series 2 tension tests. Figure 3 shows the stress-strain relationship during the tests. Significant differences in the variance and mean were examined by F- and t-tests similarly to Series 1, using monolithic dumbbell-shaped specimens as the control.

In the F-testing of the cracking strength of specimens made with a molding material containing an expansive SHCC, no significant difference was found between its variance and that of the control. In regard to its mean value, however, Table 4 shows

$D = \bar{x}_0 - \bar{x}_2 = 4.78 - 4.14 = 0.64,$

and $Q = (n_0 - 1) S_0^2 + (n_2 - 1) S_2^2$
$= 2\times 0.0332 + 2\times 0.0990$
$= 0.2644.$ (7)

$$S_D = \sqrt{\frac{n_0 + n_2}{n_0 n_2}\frac{Q}{\nu}} = 0.210 \quad (8)$$

Thus $B = t_{1-\alpha/2}(\nu)\, S_D$
$= 2.78\times 0.210 = 0.583.$ (9)

Since null hypothesis H_0 is abandoned when $|D| > B$, a significant efect of an expansive additive on the cracking strength was detected in this case.

In the tests results of ultimate strain shown

Table 4: Uniaxial tension test results of Series 2

Properties	Factors		1	2	3	4	5	Mean ($\bar{x}_i$)	Variance (S_i^2)
First crack strength (N/mm²)	0	Control	4.68	4.90	4.72	4.60	5.05	4.78	0.0332 (N²/mm⁴)
	1	EX 0%	4.43	4.64	4.61	4.32	4.36	4.54	0.0212 (N²/mm⁴)
	2	EX 6%	4.03	4.10	4.36	4.28	4.83	4.14	0.0990 (N²/mm⁴)
Tensile strength (N/mm²)	0	Control	5.66	5.30	5.77	6.03	5.52	5.74	0.0745 (N²/mm⁴)
	1	EX 0%	6.13	5.48	5.88	5.01	6.32	5.89	0.2764 (N²/mm⁴)
	2	EX 6%	5.59	5.63	5.59	5.26	5.70	5.49	0.0290 (N²/mm⁴)
Ultimate strain (%)	0	Control	<u>1.63</u>	<u>0.93</u>	3.97	1.97	2.20	1.93	1.2764 (%²)
	1	EX 0%	3.00	2.68	2.94	2.12	2.35	2.62	0.1433 (%²)
	2	EX 6%	2.70	2.36	1.70	<u>1.71</u>	3.11	2.26	0.3816 (%²)

※Among the data of five test specimens, those having the maximum or minimum ultimate strain are shaded. The Underlines in the table indicate they are unreliable because the localized crack occurred at the end of the measuring area.

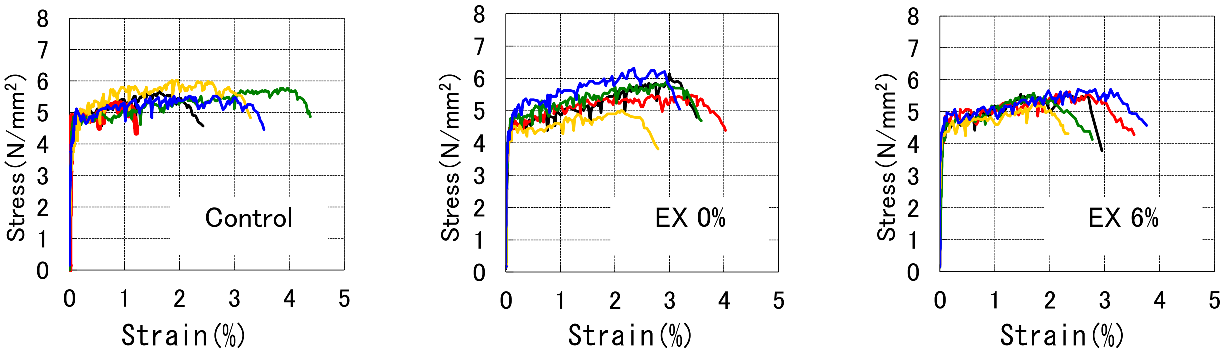


Figure 3: Stress-strain relationship of Series 2 by uniaxial tension testing

in Table 4, the values of a specimen in which cracking was localized near the clamping jig at the end of the test zone are underlined and boldfaced. Localized cracks at the end of the test zone reduce the test values of ultimate strain. This is presumably the reason for the large variance and small mean of the ultimate strain of control specimens.

In contrast, no significant difference was found between the test values of specimens made with a molding material containing no expansive additive and control specimens, demonstrating that the absence of shrinkage-preventing measures does not affect the test results. It was therefore decided to use a molding material containing no expansive additive for subsequent tests.

3.3 Series 3: Effect of fiber content of molding material on test results

Table 5 gives the results of uniaxial tension tests to clarify the effect of fiber content in the molding material. Figure 4 shows the stress-strain relationship during these tests including the results of control specimens. The fluidity of the molding material in terms of flow value with jigging (15 drops) ,which was determined by the base diameter of the mortar mass, increased from 155 to 167, 185 , and to 224 mm as the fiber content decreased.

The effect of the adopted factors on the characteristics determined by tension tests was examined by variance analysis including comparison with the control. Table 6 gives the variance analysis tables of cracking strength, tensile strength, and ultimate strain. The limit values represent the upper quantile of the F-distribution with a risk factor of 5%. The variance ratio in each table is lower than the limit value. No significant difference is

Table 5: Uniaxial tension test results of Series 3

Properties	Factors	1	2	3	4	5	Mean ($\bar{x}_i$)	Variance (s_i^2)
First crack strength (N/mm^2)	Control	4.36	4.28	4.50	4.50	4.21	4.40	0.0169 (N^2/mm^4)
	1.25%	4.43	4.39	4.68	4.36	4.46	4.39	0.0160 (N^2/mm^4)
	1.0%	4.25	4.21	4.36	4.07	4.32	4.30	0.0127 (N^2/mm^4)
	0.75%	4.25	4.84	4.43	4.14	4.10	4.27	0.0908 (N^2/mm^4)
	0.5%	4.54	4.28	4.32	4.57	4.61	4.48	0.0232 (N^2/mm^4)
Tensile strength (N/mm^2)	Control	5.59	5.99	6.61	6.21	6.35	6.39	0.1486 (N^2/mm^4)
	1.25%	6.17	6.13	6.13	6.13	4.90	6.14	0.3078 (N^2/mm^4)
	1.0%	5.63	6.28	5.81	4.46	5.84	5.98	0.4661 (N^2/mm^4)
	0.75%	5.66	6.61	6.10	6.42	5.05	6.07	0.3929 (N^2/mm^4)
	0.5%	6.17	5.26	5.26	6.39	5.99	5.81	0.2758 (N^2/mm^4)
Ultimate strain (%)	Control	1.84	3.57	3.39	3.11	2.66	3.05	0.4783 (%^{2})
	1.25%	2.85	3.38	4.13	3.98	1.74	3.40	0.9396 (%^{2})
	1.0%	3.30	3.27	2.93	0.73	2.77	2.99	1.1434 (%^{2})
	0.75%	2.31	3.79	3.14	3.73	2.12	3.06	0.6064 (%^{2})
	0.5%	2.78	2.79	2.65	3.45	2.66	2.74	0.1108 (%^{2})

※Among the data of five test specimens, those having the maximum or minimum ultimate strain are shaded.

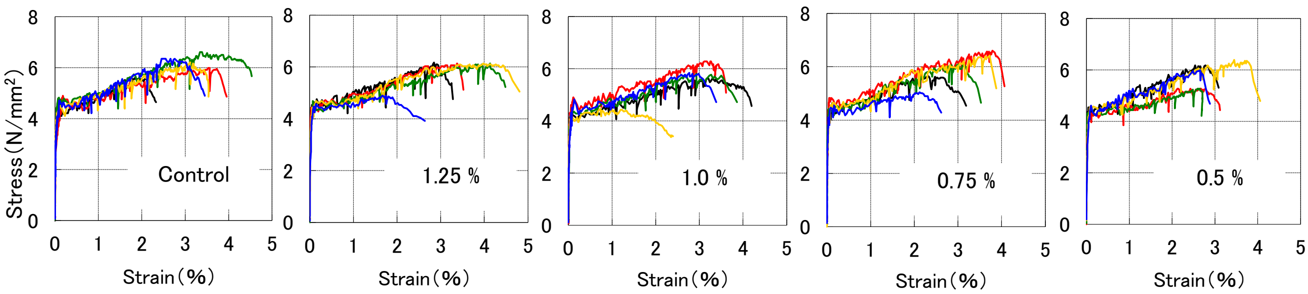


Figure 4: Stress-strain relationship of Series 3 by uniaxial tension testing

therefore found between the test levels of cracking strength, tensile strength, and ultimate strain, including control specimens, with a risk factor of 5%.

The confidence interval of the population mean was then estimated using Eq. (10) regarding the characteristic values at each level with a confidence coefficient of 95%.

$$\bar{x}_i \pm t(\phi_e, \alpha)\sqrt{\frac{V_e}{n_i}} = \bar{x}_i \pm t(20, 0.05)\sqrt{\frac{V_e}{n_i}} = \bar{x}_i \pm 2.086\sqrt{\frac{V_e}{5}} \qquad (10)$$

where $\bar{x}_i$ and V_e denote the mean at each level given in Table 5 and the variance of experimental error given in Table 6, respectively.

Figure 5 shows the results of estimation. The horizontal bold lines in the figure represent the mean of control specimens. The value of control specimens is included in the estimation interval of each level of each characteristic value. No trend due to fiber said that, when fabricating dumbbell-shaped specimens from prisms with a fiber content of 1.25 vol %, test results equivalent to those of monolithic dumbbell-shaped specimens can be obtained regardless of the fiber content in the molding material within the range of this study.

Table 6: Variance of experimental errors

(a) First crack strength

Source	Sum of squares	Degrees of freedom	Variance	Variance ratio	Limit value
Fiber content	0.170	4	0.0425	1.33	2.87
Error	0.638	20	0.0319		
Total	0.808	24			

(b) Tensile strength

Source	Sum of squares	Degrees of freedom	Variance	Variance ratio	Limit value
Fiber content	0.806	4	0.201	0.633	2.87
Error	6.365	20	0.318		
Total	7.171	24			

(c) Ultimate strain

Source	Sum of squares	Degrees of freedom	Variance	Variance ratio	Limit value
Fiber content	1.012	4	0.253	0.386	2.87
Error	13.114	20	0.656		
Total	14.126	24			

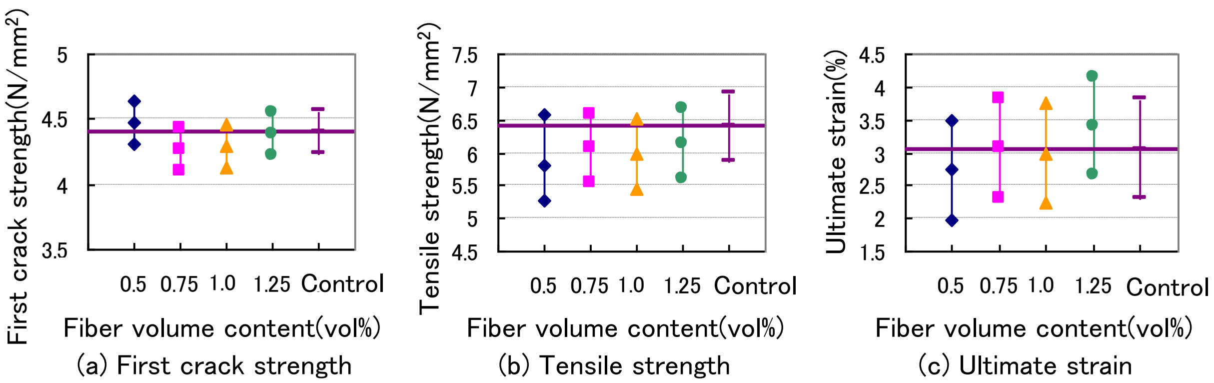


Figure 5: Comparison of interval estimation of population mean

4 CONCLUSIONS

A method of uniaxial tension testing was investigated using a SHCC, with which dumbbell-shaped specimens were fabricated from prisms by molding the enlarged ends. Findings from this study include the following:

(1) Experience in fabricating specimens or the use of a table vibrator for consolidation led to no significant difference in the uniaxial tension test results of dumbbell-shaped specimens.

(2) As to the uniaxial tension test results of dumbbell-shaped specimens fabricated in two steps using a SHCC containing no expansive additive as the molding material, their variance and mean showed no significant difference from those of monolithic dumbbell-shaped specimens. It was therefore confirmed that the absence of shrinkage-preventing measures has no effect on the test results.

(3) For prisms with a fiber content of 1.25 vol %, reductions in the fiber content of the molding material for enlarging the ends of prisms from 1.25 to 0.5 vol % had no effect related to the fiber content on the test results, leading to results equivalent to those of monolithic dumbbell-shaped specimens.

Accordingly, it was confirmed that the uniaxial tensile properties of SHCCs can be examined by simply preparing prisms at the job site and subsequently enlarging their ends into dumbbell shapes for uniaxial tension testing.

In this study, statistical investigation has been conducted based on a limited amount of data. The authors therefore intend to continue to accumulate test data to increase the reliability of test results, as well as to examine the allowable difference between the SHCC materials for core prisms and enlarged ends, including the search for molding materials that allow rapid testing.

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