Tensile Properties of ECC in Full-Scale Production

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ABSTRACT: ECC is a strain-hardening, highly ductile cementitious composite. The major studies on ECC are limited to a laboratory scale without experiences in the full-scale plants. This may interfere with practical applications of the ECC. Full-scale mixing experiments of total 11 batches were executed, and mechanical and fresh state properties were tested. It was proven that the ECC can provide high fresh and mechanical properties. Mechanical properties including compressive and tensile strength were examined and the standard material properties necessary for structural design were discussed.

Keywords: tensile test, fiber reinforcement, fiber, ductility, full-scale test, structural design

1 INTRODUCTION

Engineered Cementitious Composite - ECC is a strain-hardening and highly ductile cementitious composite (Li, 1993). This new material exhibits a several percent of maximum tensile strain owing to a synergistic effect of high-performance polymer fiber and mortar matrix. Unprecedented high performance structural members can be expected when ECC is applied to seismic components and repair constructions (JCI, 2002).

However, a large amount of worldwide studies of ECC presented thus far are limited to a laboratory scale without experiences in the full-scale plants. Production technology also lacks knowledge of performance standards necessary for designing ECC members: no sufficient discussions have been made how to refer to the design standard tensile strength or how to control the material processing in actual constructions. These problems are the principal obstacle to practical applications and require an early resolution.

This study is thus providing knowledge of full-scale construction of self-compacting ECC with PVA fiber. This shows that the quality assurance of ECC's fresh and mechanical properties from laboratory to plant is possible to a high reliability. A statistical analysis of compressive and tensile performance data and knowledge of performance standards indispensable to the design of ECC structural members are presented. For tensile performance evaluation, two types of tensile test were executed. Their characteristics are discussed in detail.

2 EXPERIMENT

2.1 *Objectives and test parameters*

ECC production has been barely documented except for a report on full-scale mixing test (Kanda et al., 2003), where the possibility of ECC's full-scale production is demonstrated via limited number of mixing trials. Following this result, the current study aims at obtaining knowledge of quality assurance in a full-scale production by a trial production in a pre-cast concrete plant at larger scale than past studies.

The test items and parameters are shown in Table 1 and their combination is shown in Table 2. Types of cement and ambient temperatures at production (in plant) are the variables. Ordinary portland cement- OPC and moderate-heat portland cement-MPC are used. OPC is a major cement type in this study while MPC is added to the experiment due to expectations for better fluidity.

Examination of the ambient temperature is

Table 1. Outline of experiment.

Experimental parameter	Level
Cement type	Ordinary Portland cement Moderate-heat Portland cement
Ambient temperature	Spring (17-20 deg.) Winter (9-16 deg.)

Table 2. Test items and parameters

Exp. Parameter		Batch	Testing item			
Ambient temp.	Cement type		Fresh test	Comp. test	TC test	TP test
Spring	OPC	N1	done	-	done	done
		N2	done	done	done	-
		N3	done	done	done	-
		N4	done	done	done	-
		N5	done	done	done	-
	MPC	M1	done	done	done	-
		M2	done	done	done	-
Winter	OPC	N6	done	done	done	done
		N7	done	done	done	done
	MPC	M3	done	done	done	-
		M4	done	done	done	-

necessary to verify the stability of ECC production quality without regard to seasons. Experiments in spring (in May, temperature of 17 to 20 °C) and in winter (in November, temperature of 9 to 16 °C) are executed. Hot water of 30 °C is used in winter case to keep the mixing temperature as constant as possible for a stable quality of ECC products.

A pre-cast concrete plant equipped with a 1m^3 capability omni mixer is used. A batch of 0.5 m^3 or 0.8 m^3 is mixed 11 times as shown in Table 2, and fresh and mechanical performances are tested. In Table 2, the notations of batch N and M mean the usage of OPC and MPC respectively. The targeted air content is 10 percent and can be controlled with AE agent while this experiments allow a wider range of 6 to 14 percent to study the effects of air content variation on fresh performances and hardened properties.

2.2 *Mix proportions and test items*

Mixture proportions used in this study are shown in Table 3 where the Mix-N is based on the literature (Kanda et al., 2003) and the Mix-M is nearly the same as Mix-N except for a substitution of OPC with MPC. An expansive agent and a shrinkage reducing agent are admixed to compensate the large drying shrinkage due to the usage with a large unit water content. A bio-saccharide type viscous agent is also applied to have compatibility between fluidity and fiber dispersibility. The fiber is a PVA with a length of 12 mm, diameter of 0.04 mm, tensile strength of 1690 MPa and elastic modulus of 40600 MPa.

Table 3. Mix proportions

Mix	Water by binder ratio	Unit water (kg/m^3)	Sand by binder ratio	Anti-shrinkage agent (kg/m^3)	Fiber volume fraction (%)	Air content (%)
Mix-N	0.46	364	0.64	15	2	10
Mix-M	0.46	364	0.65	15	2	10

1) Fly ash is added by 0.3 of binder weight
2) Expansive agent replaces sand weight by 10%.

Table 4. Types and test methods.

Test	Property	Testing method
Fresh test	Fresh temparature	-
	Specific gravity	JIS A 1116
	Air content	JIS A 1128
	Slump	JIS A 1101
	Slump flow	JIS A 1150
Compression test	Compressive strength	JIS A 1108
	Elastic modulus	JIS A 1149
Tensile test	Tensile strength and strain capacity	Tensile-coupon (TC)
	Tensile strength and strain capacity	Tensile-prism (TP)

Test items are shown in Table 4. Fresh properties and compressive tests are based on the standard method specified in Japanese Industrial Standard while tensile tests are based on 2 methods tentatively proposed in the past because there is no standard method. Specimens are subjected to the fresh performance tests immediately after mixing. The compressive and tensile tests are conducted at 28 days age after steam-curing of 35 °C for 8 hours and subsequently sealed curing of 20 °C.

Two tensile tests have distinct features. In the tensile-coupon test (hereafter TC test) as described in Table 4, a plate shaped specimen is directly supported by pneumatic chucks and subjected to tensile loads with hinge or fixed boundary conditions as shown in Figure1 (see Kanda et al., 2001). This method is easy to execute, can deal with a number of specimens in a limited time and has a large accumulation of past records. However, it has been pointed out that TC test results often displayed the considerable inconsistency probably caused by the difficulty in precise specimen alignment in loading. Furthermore, the plate shaped thin specimen section is likely to cause a 2-dimensional fiber orientation, resulting in overestimating tensile properties.

Tensile-prism test (hereafter TP test) is an improved version of TC test (Shimizu et al., 2003) as

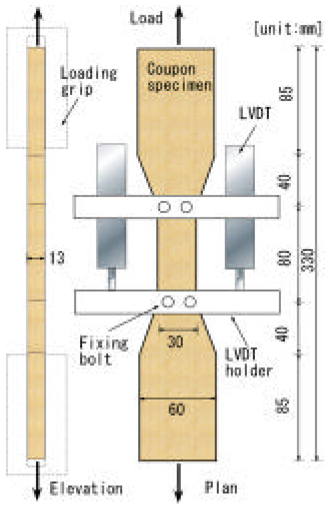

Figure 1. Tensile test of plate shaped specimen (TC test).

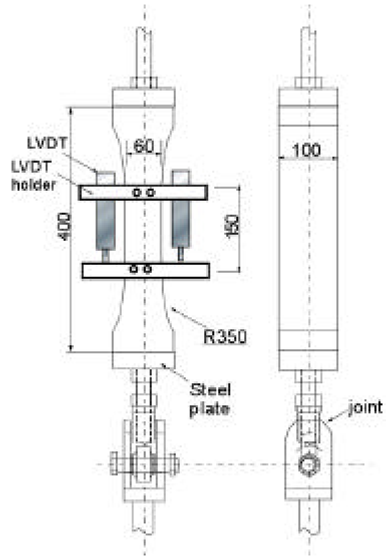

Figure 2. Tensile test of prism specimen (TP test).

Figure 3. Outside view of omni mixer.

Table 5. Results of fresh performance test.

Exp.	Mix	Mixing vol. (m3)	Concrete temp. (deg C)	Specific gravity (kg/m3)	Air cont. (%)	Slump (cm)	Slump flow (cm)
Spring	N1	0.5	28.0	1,870	6.0	23.5	49.5
	N2	0.5	31.7	1,793	10.5	25.5	55.0
	N3	0.8	31.8	1,752	12.0	25.0	55.0
	N4	0.8	30.9	1,789	11.0	24.5	51.5
	N5	0.8	28.0	1,890	6.0	-	54.0
	M1	0.8	31.6	1,868	7.8	25.0	55.0
	M2	0..8	32.0	1,772	12.0	-	45.5
Winter	N6	0.8	28.0	1,788	13.5	25.0	45.5
	N7	0.8	32.0	1.866	8.8	26.5	53.0
	M3	0.8	30.0	1,808	14.0	27.0	57.0
	M4	0.8	31.0	1,824	10.5	27.5	56.0

described in Table 4. As seen in Figure 2, a larger specimen with a cross section of 60 x 100 mm is used to minimize the influence of fiber orientation on test results (refer to Shimizu et al., 2003 for more detail) and was expected to reproduce a more precise tensile performance of ECC in a structure. TP tester can also use hinge or fixed boundary conditions but the chucking mechanism is different from the TC test: a steel rod fixed to a plate that is bonded to a specimen is directly chucked by the compression tester to eliminate the error in alignment. However, TP test requires larger specimen and hence longer preparation time than TC test, making it difficult to adopt to a quality control routine test in ECC component production in industry. This study aims to obtain ECC's consistently achieving tensile performances in the full-scale production by a statistical analysis of the test results attained from two different test methods. As a result, the tensile performances are expressed in terms of two parameters: tensile strength and ultimate tensile strain. A tensile strength is the maximum stress in a test and the ultimate tensile strain is a point where stress begins to decrease continuously with an increase in strain.

Minimum of 5 specimens are tested per batch, and the specimens with the highest and lowest values are excluded from the analysis.

3 EXPERIMENTAL RESULTS

3.1 *Mixing and fresh properties*

Table 6. Test results of mechanical performance.

Exp.	Mix	Comp. Test		TC test		TP test	
		Comp. strength (MPa)	Elastic modulus (GPa)	Ultimate tensile strain (%)	Tensile strength (MPa)	Ultimate tensile strain (%)	Tensile strength (MPa)
Spring	N1	-	-	2.90	5.14	1.18	2.76
	N2	31.5	14.2	3.00	4.57	-	-
	N3	27.5	12.7	3.08	4.06	-	-
	N4	33.4	15.2	2.49	4.89	-	-
	N5	37.4	16.7	2.45	5.19	-	-
	M1	31.5	15.0	1.96	4.00	-	-
	M2	27.9	13.9	3.29	3.93	-	-
Winter	N6	31.6	14.3	3.17	3.95	1.65	3.63
	N7	36.6	17.2	2.55	4.51	1.60	3.56
	M3	30.4	14.4	2.51	3.40	-	-
	M4	32.0	15.2	3.80	4.01	2.10	3.60

Mixing was made by an omni mixer as shown in Figure 3 and the resulting fresh properties are shown in Table 5. Air contents of the fresh mortar ranged from 6 to 14 percent as expected. Flow values were generally more than 500 mm and demonstrated excellent fluidity. Visual confirmation of fiber dispersion was conducted and no significant problems were detected. Since no distinct change in fluidity was observed with variations in air content, the effects of air content variation on fluidity and fiber dispersion may be considered small enough.

It should be noted that ECC in this study has excellent workability. Over 500 mm of flow value satisfies one of the requirements for self-compacting nature established by Japan Society of Civil Engineers (JSCE 1998). While the other fresh tests required for self-compacting definition were not conducted in this study, the workability was very similar to that of self-compacting ECC in the literature (Kanda et al. 2003).

Effects of ambient temperature and type of cement were small in this experiment, which may be attributed mainly to the use of a hot water of 30 °C for the mixing in winter. Consequently, the slurry temperatures immediately after mixing were not so different by seasons that the fluidity and the fiber dispersion exhibited no differences. It was confirmed that a special care for the temperature of mixing water and hence controlling of mixing temperatures may lead to stable fresh and hardened properties. When ambient temperatures exceed 30 °C, which is a case excluded in this experiment, a decrease of fluidity of N-mix is expected and M-mix may be recommended.

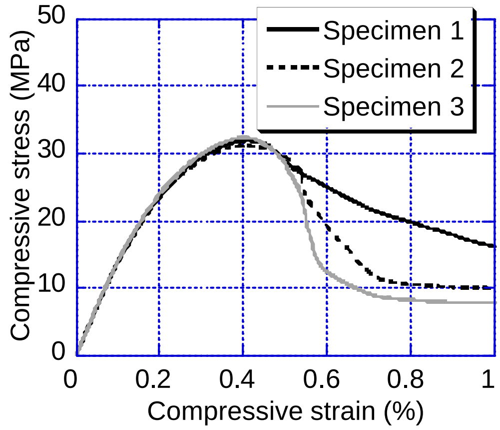

Figure 4. Stress-strain curves under compression.

3.2 *Mechanical properties*

A series of test results of mechanical performance including mean values of compressive strength and elastic modulus are shown in Table 6. All the recorded values are the means of the measured value of three specimens. Examples of stress-strain curves are shown in Figure. 4. As shown in Table 6, compressive strength and elastic modulus, ranged from 27.5 to 37.4 MPa and 12.7 to 17.2 GPa respectively, demonstrated considerable variation by batch. This appears due to air content variation as discussed in later sections. The stress-strain curves in Figure 4 show that the decrease in post-peak compressive stress was slower than that of normal concrete and reflected a highly ductile nature of ECC.

Results of tensile stress-strain curves in TC and TP test are shown in Figure 5 and Figure 6 respectively. It is shown that both TC and TP test result clearly indicated the pseudo strain hardening characteristics, where stress increased gradually under a large strain development. Mean values of the tensile performance per batch are also shown in Table 6. The results of TC test found generally greater than that of TP test.

4 DISCUSSION

4.1 *Effects of ambient temperatures and type of cement*

The effects of ambient temperature and of cement type on mechanical properties are shown in Table 7 and 8 respectively, where a mechanical property is represented by the mean of all specimens. Table

Table 7. Effect of ambient temperature on mechanical performance.

Property		Ambient temparature	
		Spring	Winter
Compressive strength	(MPa)	32.4	34.1
Elastic modulus	(GPa)	14.7	15.8
Ultimate tensile strain (TC test)	(%)	2.88	2.86
Tensile strength (TC test)	(MPa)	4.57	4.23

Table 8. Effect of cement type on mechanical performance.

Property		Cement type	
		Mix-N (OPC)	Mix-M (MPC)
Compressive strength	(MPa)	33.0	30.4
Elastic modulus	(GPa)	15.1	14.6
Ultimate tensile strain (TC test)	(%)	2.88	2.93
Tensile strength (TC test)	(MPa)	4.49	3.81

7 suggests that the effect of ambient temperature was small, and a stable mechanical performance can be achieved under a controlled mixing temperatures within the range of this experiment.

Table 8 shows that compressive and tensile strength of N-mix with OPC are both 10 to 15 percent greater than those of M-mix. This is reasonable because the hydration rate of MPC is less than that of OPC at 28 days age, while the effect of cement type on the ultimate tensile strain is generally small in this experiment.

4.2 *Effects of air content variations*

(1) Effects of air content on compressive performance

Effects of air content variation on the compressive performance of N-mix and M-mix are shown in Figure 7 and 8 respectively. It is seen in both mixes that compressive strength decreased with an increase in air content while the decrease rate per 1 percent air content increase was 1 MPa in N-mix and 0.3 MPa in M-mix. When air content is 10 percent, an air content variation of 1 percent results in a 1 to 3 percent variation of compressive strength. This variation is almost a half of that of 5 percent known in the ordinary concrete. In ensuring the design standard compressive strength for quality control, it may be possible to allow ECC to

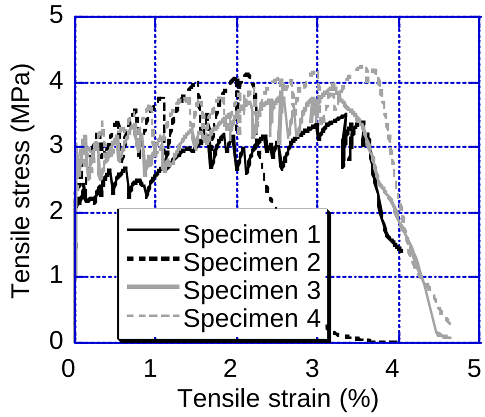

Figure 5 Stress-strain curves under tension – TC test (N6)

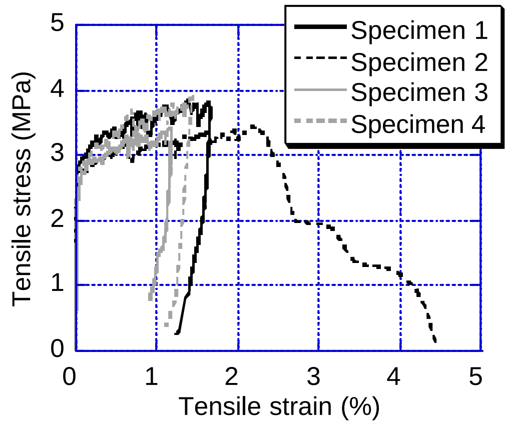

Figure 6. Stress-strain curves under tension – TP test (N6)

have a broader range of air content than that of concrete. This is because in ECC the volume fraction of cement paste, where air exclusively exists, is twice as large as that of concrete, which is hence more sensitive to a variation of air content.

When air content is controlled with a range of 10±4 percent as in this experiment, the lower limit of 96 % confidence is 27 MPa in N-mix and 27.5 MPa in M-mix. This lower limit is determined by following Japanese Architectural Standard Specification 5 (AIJ 2003), which permits 4 percent defectives. These values may be reflected to the ECC structural design as a standard compressive strength.

Variation of elastic modulus per 1 percent variation of air content was 1 to 2 percent in N-mix that is much smaller than that of compressive strength as seen in Figures 7 and 8.

(2) Effects of air content on tensile performance

The effects of air content on the ultimate tensile

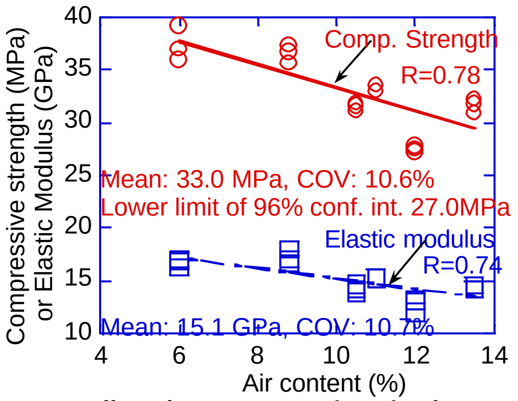

Figure 7. Effects of air content on mechanical performance (N-mix)

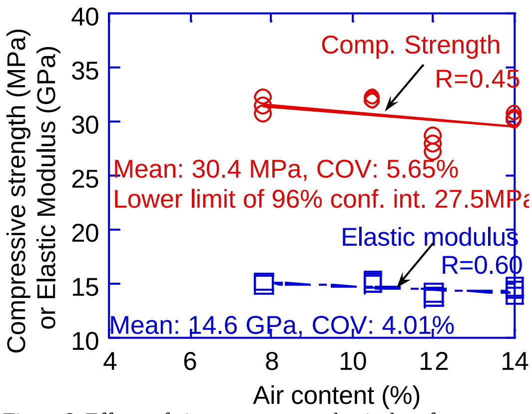

Figure 8. Effects of air content on mechanical performance (M-mix)

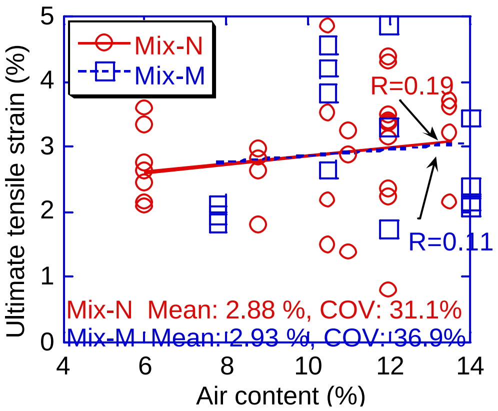

Figure 9. Effects of air content on the ultimate tensile strain (TC test).

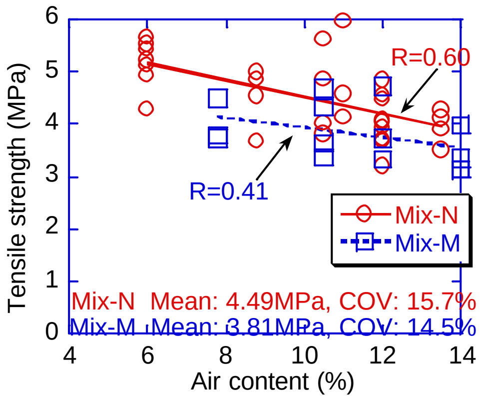

Figure 10. Effects of air content on tensile strength (TC test).

strain and tensile strength in TC test are shown in Figures 9 and 10 respectively. When an air content increased, the ultimate tensile strain increased as shown in Figure 9 and tensile strength decreased as shown in Figure 10. In spite of the large coefficient of variation of more than 30 percent, the correlation coefficient, R, of ultimate tensile strain with air content is as low as 0.2. Hence it can be concluded that the effect of air content is negligible. On the other hand in tensile strength, the coefficient of variation is as low as 15 percent compared to the ultimate tensile strain and a slight correlation with air content is found as the correlation coefficient ranges from 0.4 to 0.6.

Results of the TP test are summarized in Figures 11 and 12. It is seen in Figure 11 that the ultimate tensile strain shows no correlation with air content as in TC test, while in Figure 12, tensile strength shows a positive correlation with an increase in air content by unknown reasons. Because the correlation is so low, it can be said that the effect of air content on tensile strength may be negligible.

(3) Reliability limit of tensile strength

Statistical data of tensile performance in TC and TP test are shown in Figure 13. This figure indicates TC test exhibits ultimate tensile strain and tensile strength 1.5 and 1.3 times greater than those of TP test. This may be attributed to a size effect of the specimen and to the fiber orientation in the specimen since the specimen size was smaller in TC test. It is also shown in Figure 13 that the standard deviation of tensile performance in TC test was greater than that of TP test. This may be a result of the precision of specimen alignment: a precise chucking is possible in TP test but not in TC test where direct pneumatic chucking often causes errors in alignment. As a result, no big differences between two tests were observed in the lower limits of the 96 percent confidence: ultimate tensile strain 1 percent and tensile

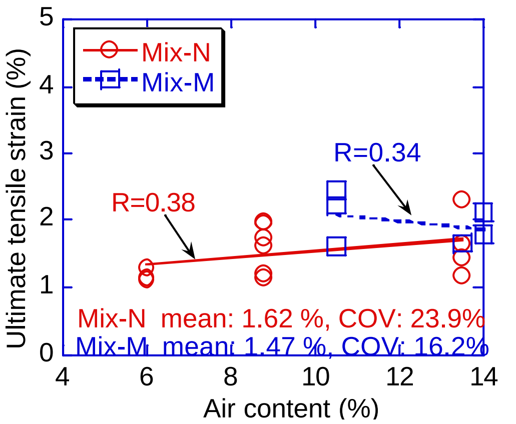

Figure 11. Effects of air content on the ultimate tensile strain (TP test).

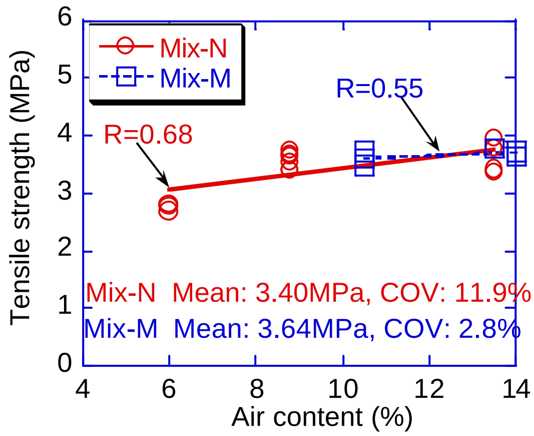

Figure 12. Effects of air content on tensile strength (TP test).

strength is 3 MPa.

(4) Design standard of tensile performance and quality control

Since TP test is supposed to reflect the actual behavior of ECC component, it may be possible to propose a design standard of tensile strength necessary for the structural design, as 3 MPa and standard ultimate tensile strain as 1 percent within the scope of this study. There are two options to check the above design standards of tensile performances in the production of ECC members. Execution of TC test is one solution. In this study, testing of 6 specimens per hour was possible in TC test while it was the maximum efficiency in TP test per day. That implies TP test is more difficult to execute and requires longer time than TC test. Thus for the quality control purpose, use of TC test that is easy to execute is more reasonable than the use of TP test, provided that the mean value of the test is not less than the control value. The applicable range of this quality control method, however, should be specified to take the difference in the mean and the standard deviation with respect to TP test into account.

The other possible quality control method is bending test since a high correlation has been found between tensile properties obtained with TP test and that with bending test. A simple estimation method of tensile performance obtained by TP test has been proposed using the post-processed bending test data (Shimizu et al. 2003 and Kanakubo et al. 2003). While this option seems more realistic, it is still necessary to study the relationship between TP test and bending test further in depth to ensure the reliability of this test.

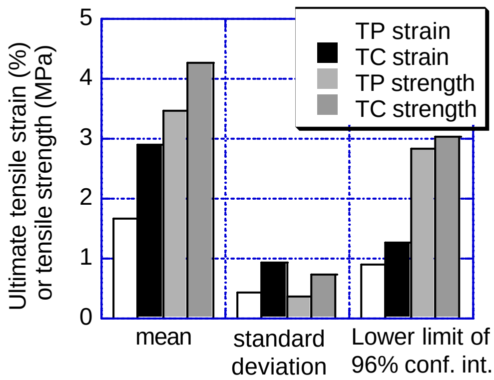

Figure 13. Reliability limit of tensile strength

5. CONCLUSIONS

A full-scale mixing experiment and tests of associated properties were dealt with in this study. The major findings are as follows.

(1) ECC in full-scale production can achieve a high mechanical performance and an excellent fluidity as same as that in laboratory.

(2) Effects of ambient temperature and type of cement on the fresh and mechanical performance were small in this experiment.

(3) Effects of variation of air content on compressive strength were smaller than that of normal concrete, and a control of air content at a range of 10±4 percent can ensure the standard design compressive strength of approximately 27 MPa with the mix design used in this experiment.

(4) Effects of air content variation on tensile mechanical performances were not significant.

(5) The result of tensile performance test with a prism specimen showed smaller value but less inconsistency than that with a plate shaped specimen, but the discrepancy became smaller at the lower limit of confidence.

(6) In a full-scale ECC production, a performance of the ultimate tensile strain of approximately 1 percent can be ensured in a high confidence based on the tensile test of prism specimen that is believed to reflect the actual behavior of ECC component.

(7) As a quality control of ECC component production, the plate shaped specimen may be used by taking the difference in statistical values obtained with the prism specimen into account.

Based on the above findings, ECC has been proven to be ready for commercial production while further investigation is needed to establish consistent and economic testing methods for tensile performance quality control.

Acknowledgment

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