

# Full Scale Processing Investigation for ECC Pre-cast Structural Element

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## Abstract

ECC is a pseudo-strain-hardening, highly ductile cementitious composite. However, the major studies on this material have been limited to laboratory scale without experience in full-scale plants. Thus, practical applications of ECC have not been previously investigated. In the current study, full-scale processing experiments were executed, and mechanical and fresh properties were tested, where emphasis was placed on two types of tensile test. It was thus proven that ECC can provide excellent fresh and mechanical properties in full scale production, and a statistical basis for determining tensile property specifications was provided. Furthermore, it was found that flexural tests can be utilized for inspecting tensile properties in daily production. These experimental data were reflected in an actual building construction project that was designed to utilize ECC structural elements. As a result, ECC element production was successfully achieved with the required quality in this project.

**Keywords:** fiber; cement composite; tensile property; full scale production; structural application

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## 1. Introduction

Engineered Cementitious Composite, ECC, is a pseudo-strain-hardening ductile cementitious composite<sup>1</sup>. Pseudo-strain-hardening behavior is characterized in tensile stress-strain relation where stress increases gradually under large strain development. This new material exhibits a maximum tensile strain of several percent owing to the synergetic effect of high-performance polymer fiber and specifically designed mortar matrix. Unprecedented high-performance structural members can be expected when ECC is applied to seismic components<sup>2</sup>.

However, the large number of worldwide studies on ECC presented so far have been limited to laboratory scale without experiences in full-scale plants. Production technology also lacks knowledge of performance standards necessary for designing ECC members; there have been insufficient discussions on how to refer to the design standard on tensile properties or how to control the material processing in actual construction. These problems have been the principal

obstacle to practical applications and needed to be quickly resolved.

This paper describes the full-scale production of self-compacting ECC with PVA fiber<sup>3,4</sup>, and shows that quality assurance of fresh and mechanical properties of ECC in the plant is highly reliable, and that its tensile properties can be verified by a simple test. A statistical evaluation of tensile properties and knowledge of performance standards indispensable to the design of ECC structural members are presented. Two types of tensile test were executed, and the characteristics and mechanical performance under tension are discussed. The applicability of the tensile property control by a flexural test in production is proposed in comparison with the tensile tests. These experimental data are reflected in an actual building construction project that is designed to utilize ECC structural elements. ECC element production is shown to be successfully achieved with the required quality in this project.

## 2. Experiment

### 2.1 Objectives and test parameters

ECC production has been poorly documented except for a few reports on a full-scale mixing test<sup>4</sup>. This study aims to obtain knowledge on quality assurance in full-scale production by a trial production in pre-cast concrete plants on a large scale.

The test items and parameters are shown in Table 1. and their combination is shown in Table 2. These

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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.)
Manufacture	Plant#1(P1) Plant#2(P2)

Table 2. Test Items and Parameters

Exp. Parameter			Testing item					
Plant	Ambient temp.	Cement type	Mix	Fresh test	Comp. test	TC test	TP test	Flexural test
P1	Spring	OPC	P1N1	done	-	done	done	-
			P1N2	done	done	done	-	-
			P1N3	done	done	done	-	-
			P1N4	done	done	done	-	-
			P1N5	done	done	done	-	-
	Winter	MPC	P1M1	done	done	done	-	-
			P1M2	done	done	done	-	-
			P1M3	done	done	done	done	done
			P1M4	done	done	done	done	done
			P1M5	done	done	done	done	done
P2	Spring	OPC	P2N1	done	done	done	-	-
			P2M1	done	done	done	-	-
			P2M2	done	done	done	done	done
	Winter	MPC	P2M3	done	done	done	done	done
			P2M4	done	done	done	done	done
			P2M5	done	done	done	done	done

Table 3. Mix Proportions

Mix	Water by binder ratio	Unit water (kg/m <sup>3</sup> )	Sand by binder ratio	Anti-shrinkage agent (kg/m <sup>3</sup> )	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. Testing Method

Test	Property	Testing method
Fresh test	Fresh temperature	-
	Unit weight per volume	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-prism (TP)
Flexural test	Tensile strength and ultimate tensile strain	JCI-SC3-2005

experiments were executed in two pre-cast concrete plants equipped with Omni mixers with a capacity of 1 m<sup>3</sup> and 0.5 m<sup>3</sup>. Batches of 0.8 m<sup>3</sup> and 0.4 m<sup>3</sup> were mixed, and the total of 15 mixes were subjected to fresh and mechanical property tests as shown in Table 2. Types of cement, ambient temperatures (in plant) at production and pre-cast concrete plants were varied. Ordinary portland cement (OPC) and moderate-heat portland cement (MPC) were used. OPC was a major cement type in this experiment while MPC was also examined for its better fluidity.

Examination of the ambient temperature is necessary for stable ECC production without regard to season. Experiments were executed in spring (May, temperature 17 to 20°C) and in winter (November, temperature 9 to 16°C). The pre-cast concrete plants were located in the Kanto area (near Tokyo) and the

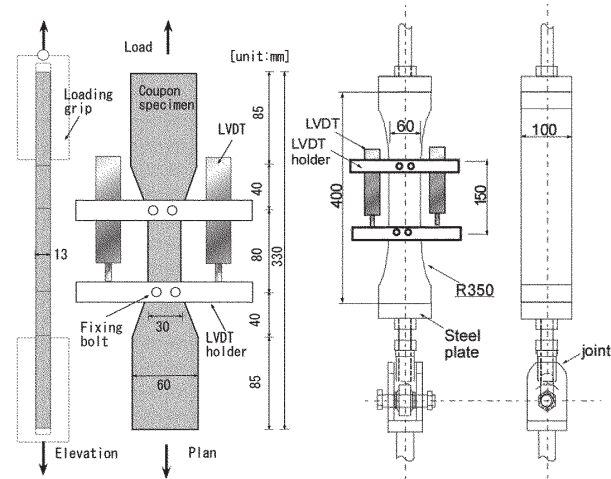


Fig. 1. Tensile Test of Plate Specimen (TC Test)

Fig. 2. Tensile Test of Prism Specimen (TP Test)

Tokai area (near Nagoya), and are hereafter denoted as Plant 1 and Plant 2, respectively. The material suppliers and manufacturers, and a lot of the major raw materials such as cement, aggregate and fly-ash for the two plants differed. The cement manufacturer was the same but the cement lots used in each plant were uncontrolled. Fly-ash products used were type II, as specified in the Japanese Industrial Standard (JIS) A 6202 and they were stored in each plant. However, their original power plants were different and hence their properties were subjected to change. The aggregates used in each plant came from different areas. The air content varied from 6 to 14 percent, a controllable manufacturing range, with an air-entraining agent. This was done to determine the effects of air content variation on the fresh state and the mechanical properties, although the designed air content was 10 percent.

## 2.2 Mix proportions

The mix proportions used in this study are shown in Table 3., where Mix-N is based on the literature<sup>4)</sup> and the Mix-M is nearly the same as Mix-N except for the substitution of OPC with MPC. These two mixes showed self-compacting fresh properties in laboratory mixing<sup>3)</sup>, and slump flow values of over 500mm. A CSA-type expansive agent and an alcohol-type shrinkage reducing agent were admixed with each mix assuming a large unit water content.

A bio-saccharide-type viscous agent was also applied to provide compatibility between fluidity and fiber dispersibility. In addition, a polycarboxylic-acid-based superplasticizer was simultaneously used. The fiber was PVA with a length of 12 mm, a diameter of 0.04 mm, tensile strength of 1690 MPa and an elastic modulus of 40,600 MPa.

## 2.3 Test items

The test items and methods are listed in Table 4. Fresh properties and compressive tests were based on the standard method specified in JIS while uniaxial tensile tests were based on two methods tentatively

proposed in the past because there is no standard method. The flexural test follows a newly proposed standard, JCI-S-003-2005. Specimens were subjected to the fresh performance test immediately after mixing and to the compressive and tensile tests after steam curing of 35°C-8 hours and subsequent sealed curing of 20°C-28 days.

The two tensile tests have distinct features. In the TC tensile test<sup>5)</sup>, a plate shaped specimen is directly supported by pneumatic chucks and subjected to tensile loads with hinge or fixed boundary conditions as shown in Fig.1. This method is easy to execute, can deal with a number of specimens in a limited time and has large accumulation of past records. However, it has been pointed out that test results have often shown considerable scatter probably because of the difficulty to precisely align the loading axis with the specimen center axis. It is also pointed out that the thin plate-shaped specimen section is likely to cause 2-dimensional fiber orientation, resulting in overestimate of tensile properties.

The TP tensile tester in Table 4. is an improved version of the TC tester<sup>4),6)</sup>. As seen in Fig.2., a larger specimen with a cross section of 60 x 100 mm was used to eliminate the 2-dimensional fiber orientation (refer to literature vi for more detail) and was expected to provide a more precise tensile performance of ECC in a structure. The TP tester can also use hinge or fixed boundary conditions, but its chucking mechanism is different from that of the TC tester. A steel rod fixed to a plate bonded to a specimen is directly chucked by the compression tester to ensure precise matching of the two axes. However, the TP test requires a larger specimen and hence longer preparation time than the TC test, making it difficult to adapt to a quality control routine test in the production of ECC components. This study aimed to obtain a tensile performance of ECC necessary for full-scale production by statistical analysis of the test results obtained from two different test methods. The tensile performance results were expressed in terms of two parameters: tensile strength and ultimate tensile strain. The tensile strength is the maximum stress obtained in a test and the ultimate tensile strain is the point where stress begins to decrease continuously with increase in strain. More than five specimens were tested in each batch and data of a minimum of three specimens, excluding the highest and lowest values, were subjected to analysis.

The flexural test is a modified version of the normal bending test, newly published in JCI-S-003-2005<sup>7)</sup>. The test method is outlined in Fig.3. Specimens with dimensions of 100 x 100 x 400 mm were subjected to 3-point equivalent loading. Strains at two points in the central flexural zone of 100 mm were measured, and the flexural curvatures calculated with the strains were recorded with the corresponding loads.

### 3. Tensile Performance Prediction

This study aims at applying the flexural test to the quality control of tensile performance of ECC components at the manufacturing process and at establishing a method for predicting tensile performance from flexural test results. The prediction method originally proposed by Kanakubo *et al.*<sup>8),9)</sup> is to predict ultimate tensile strain  $\epsilon_u$  and tensile strength  $\sigma_{max}$  from the maximum moment point in the moment-curvature relation obtained from a flexural test. This study introduces conversion factors to calibrate flexural test results with those in TP tests as follows.

$$\sigma_{max} = \alpha_s \cdot \frac{E \cdot \phi_u \cdot D \cdot x_{nl}^2}{2(1-x_{nl})} \quad (1)$$

$$\epsilon_u = \alpha_e \cdot \phi_u \cdot D(1-x_{nl}) \quad (2)$$

where  $D$  is the height (mm),  $E$  is the elastic modulus of ECC (N/mm<sup>2</sup>),  $\phi_u$  is the curvature at the maximum moment determined by flexural test, and  $\alpha_s$  and  $\alpha_e$  are the conversion factors of strength and ultimate strain respectively, which are newly introduced in this study.  $x_{nl}$  can be obtained from the relation between measured load and curvature and is a solution to the following equations (3) and (4).  $M_{max}$  in equation (3) is the maximum moment by experiments, and  $B$  is the width of a specimen.

$$m^* \equiv \frac{M_{max}}{E \cdot \phi_u \cdot B \cdot D^3} = \frac{x_{nl}^3}{3} + \frac{x_{nl}^2(1-x_{nl})}{4} \quad (3)$$

$$x_{nl}^3 + 3x_{nl}^2 - 12m^* = 0 \quad (4)$$

Equations (1)-(4) are derived on the assumption that the stress and strain distributions shown in Fig.4. form within the cross section of a specimen under flexure<sup>6)</sup>, i.e., modeled in triangular distribution for compressive stress and uniform distribution for tensile stress ( $x_{nl}=x_n/D$ ). To ensure this tensile stress distribution, the ECC stress-strain relation was assumed to behave as perfect elasto-plastic type.

It is important to note that the  $\alpha_s$  and  $\alpha_e$  values may vary according to the material properties, size of the flexural test specimen and loading conditions. This dependency originates from the fact that flexural performance is a structural performance strongly sensitive to specimen size and loading conditions while tensile performance by nature can be regarded as a material property<sup>10)</sup>. Thus, the prediction of tensile performance by means of a flexural test should be executed with special care of the targeted materials, and the values of  $\alpha_s$  and  $\alpha_e$  may vary depending on the flexural test conditions. At the present technical levels, the conversion factors  $\alpha_s$  and  $\alpha_e$  may not be derived theoretically and may be reasonably treated as experimental parameters. This study aims at obtaining

these conversion factors by comparing the flexural and tensile test results.

## 4. Experimental Results

### 4.1 Mixing and fresh properties

Mixing was executed with an Omni mixer as shown in Fig.5., and the resulting fresh properties are shown in Table 5. The air contents of the fresh mortar ranged from 6 to 14 percent as expected. Flow values were generally more than 500 mm, thus demonstrating excellent fluidity. The casting process necessitated no vibrators in the form. No distinct changes in fluidity were observed with different air contents, showing that the effects on fiber dispersion were small.

The effects of ambient temperatures and cement type were found to be small in this experiment, which may be attributed mainly to the use of hot water of 30°C for the mixing in winter at Plant 1. Consequently, the fresh temperatures immediately after mixing varied little with the season, so that the fluidity and the fiber dispersion exhibited no differences. It was confirmed that special care with the mixing water temperature and hence control of the mixed temperatures led to stable fresh and hardened properties. When the ambient temperatures exceed 30°C, which did not occur in this experiment, the fluidity of the N-mix is expected to decrease. For this case, M-mix may be recommended.

Fresh properties obtained from the two manufacturing plants varied. Significantly poor fresh properties were observed in the N-mix of Plant 2 (P2N1), where the slump flow was lower than 400 mm, showing much lower fluidity than those of the other mixes. The fresh properties of M-mixes from the two plants were similar. Thus, the reason for the poor

Table 5. Test Results of Fresh Properties

Mix	Mixing vol. (m <sup>3</sup> )	Fresh temp. (deg C)	Specific gravity (kg/m <sup>3</sup> )	Air cont. (%)	Slump (cm)	Slump flow (mm)
P1N1	0.5	28.0	1,870	6.0	23.5	495
P1N2	0.5	31.7	1,793	10.5	25.5	550
P1N3	0.8	31.8	1,752	12.0	25.0	550
P1N4	0.8	30.9	1,789	11.0	24.5	515
P1N5	0.8	28.0	1,890	6.0	-	540
P1M1	0.8	31.6	1,868	7.8	25.0	550
P1M2	0.8	32.0	1,772	12.0	-	455
P1N6	0.8	28.0	1,788	13.5	25.0	455
P1N7	0.8	32.0	1,866	8.8	26.5	530
P1M3	0.8	30.0	1,808	14.0	27.0	570
P1M4	0.8	31.0	1,824	10.5	27.5	560
P2N1	0.4	23.9	1,845	9.1	22.0	390
P2M1	0.4	23.5	1,783	10.5	25.0	495
P2M2	0.4	25.1	1,757	12.9	25.0	510
P2M3	0.4	25.9	1,767	12.5	25.0	510

Table 6. Test Results of Mechanical Properties

Mix	Comp. Test		TC test		TP test		Flexural test	
	Comp. strength (MPa)	Elastic modulus (GPa)	Ultimate tensile strain (%)	Tensile strength (MPa)	Ultimate tensile strain (%)	Tensile strength (MPa)	Ultimate curvature (10 <sup>-6</sup> *1/mm)	Modulus of rupture (MPa)
P1N1	-	-	2.90	5.14	1.18	2.76	-	-
P1N2	31.5	14.2	3.00	4.57	-	-	-	-
P1N3	27.5	12.7	3.08	4.06	-	-	-	-
P1N4	33.4	15.2	2.49	4.89	-	-	-	-
P1N5	37.4	16.7	2.45	5.19	-	-	-	-
P1M1	31.5	15.0	1.96	4.00	-	-	-	-
P1M2	27.9	13.9	3.29	3.93	-	-	-	-
P1N6	31.6	14.3	3.17	3.95	1.65	3.63	319	13.6
P1N7	36.6	17.2	2.55	4.51	1.60	3.56	249	14.1
P1M3	30.4	14.4	2.51	3.40	1.98	3.69	297	13.0
P1M4	32.0	15.2	3.80	4.01	2.10	3.60	344	13.8
P2N1	28.1	14.3	2.05	4.34	-	-	-	-
P2M1	24.7	12.3	3.68	3.93	-	-	-	-
P2M2	24.0	12.3	3.96	4.00	2.22	3.94	370	12.0
P2M3	24.6	12.6	4.34	3.96	2.59	3.27	382	13.5

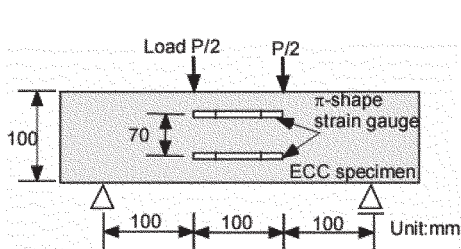


Fig.3. Flexural Test

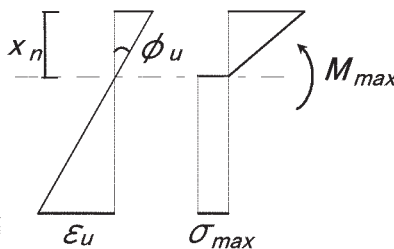


Fig.4. Assumed Stress and Strain Distribution



Fig.5. Omni Mixer Outside View

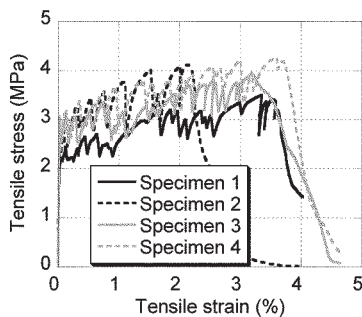


Fig.6. Tensile Test Result (TC Test)

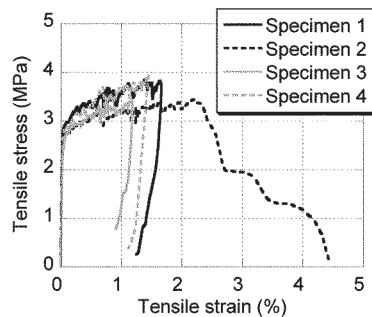


Fig.7. Tensile Test Result (TP Test)

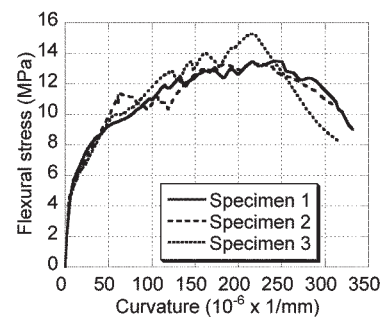


Fig.8. Flexural Test Result

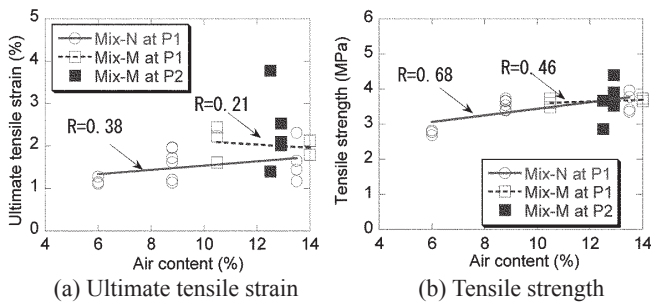


Fig.9. Effect of Air Content (TP Test)

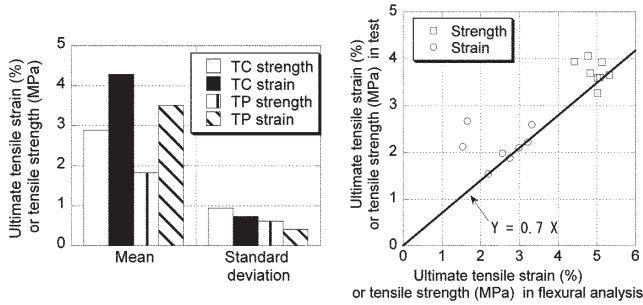


Fig.10. Comparison of Tensile Tests Fig.11. Flexural Analysis Application

fluidity in P2N1 has not been identified. However, it may be due to an inappropriate combination of constitutive material products, e.g., cement, fly ash, viscous agent, and superplasticizer. This result implies the importance of initial checking of constitutive material combination by trial mixing. As a result, it is still indispensable for ECC to execute test mixings prior to manufacture because variations in properties are sure to occur in different plants.

#### 4.2 Mechanical properties

A series of test results of mechanical performance are shown in Table 6., including mean values of compressive strength and elastic modulus. All the recorded values are the means of the measured values of three specimens. As shown in Table 6., compressive strength and elastic modulus ranged from 24.0 to 37.4 MPa and 12.3 to 17.2 GPa, respectively, thus demonstrating considerable variation by batch.

Tensile stress-strain curves obtained from TC and TP tests (P1N6) are shown in Fig.6. and Fig.7., respectively. Both TC and TP test results clearly indicate pseudo-strain-hardening characteristics, where stress increases gradually under large strain development. Mean values of tensile performance by batch are also shown in Table 6. It is shown that the results of the TC tests were generally greater than those of TP tests.

Results of flexural tests are shown as a relationship between flexural stresses and curvatures in Fig.8. The deflection-hardening characteristics are clearly exhibited; early-stage elastic behavior is followed by stiffness reduction due to cracks, and in the later stages, resistance to applied loads is maintained at large flexural curvatures.

Table 7. Summary of Experimental Parameter Effects

Property	Ambient temp.		Cement type		Manufacture	
	Spring	Winter	Mix-N	Mix-M	P1	P2
Compressive strength (MPa)	32.4	34.1	33.0	30.4	33.0	24.4
Elastic modulus (GPa)	14.7	15.8	15.1	14.6	15.1	12.4
Ultimate tensile strain (TC test) (%)	2.88	2.86	2.88	2.93	2.88	3.99
Tensile strength (TC test) (MPa)	4.57	4.23	4.49	3.81	4.49	3.96

Table 8. Statistical Data of Tensile Properties

		Mean	Standard dev.	COV	Lower lim. of 96% conf. int.
Ultimate tensile strain (%)	Mix-N at P1	1.52	0.39	0.26	0.85
	Mix-M at P1	2.05	0.33	0.16	1.47
	Mix-M at P2	2.37	0.88	0.37	0.84
Tensile strength (MPa)	Mix-N at P1	3.40	0.40	0.12	2.70
	Mix-M at P1	3.64	0.10	0.03	3.46
	Mix-M at P2	3.67	0.56	0.15	2.70

## 5. Discussion of Experimental Results

### 5.1 Effects of experimental parameters

Effects of ambient temperature, cement type and difference in plant on mechanical properties of ECC are shown in Table 7., where the mechanical properties are represented by the mean of all specimens. It is seen in Table 7. that the effects of ambient temperature were small and that stable mechanical performance can be achieved with control of mixing temperatures within the temperature range of this experiment.

As seen in Table 7., 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, while the effect of cement type on the ultimate tensile strain is generally small in this experiment.

The different mechanical properties obtained from the two manufacturing plants are shown in Table 7. The ECC produced in plant 2 shows 20 to 30 percent lower compressive strength, tensile strength, and elastic modulus than that in plant 1. This leads to lower fracture toughness of the mortar matrix in plant 2 than that produced in plant 1 and agrees closely with the larger ultimate strain observed in the experiments. The different mechanical responses of ECC from the two plants are still unclear from the experiment, but the reactivity of the fly-ash is a possible cause.

### 5.2 Effects of air content variations

Effects of air content on tensile properties obtained in the TP tests are shown in Fig.9. Fig.9.(a) demonstrates rather weak correlation between ultimate tensile strain and air content, showing a correlation coefficient of less than 0.4. Furthermore, variation in air content appears to show negligible effects on ultimate tensile strain. Similar trends are found in tensile strength, as shown in Fig.9.(b), while the correlation coefficient is larger than for tensile strain capacity. The results in TC

test show similar weak correlation and influence with different air content levels. As a result, the effect of air content on ultimate tensile strain and tensile strength appears to be negligible.

### 5.3 Statistical evaluation and specified design material properties

Statistical data of tensile performance in the TP test are shown in Table 8. This test is regarded to represent the behavior of the ECC component, where specified material properties applied in design can be obtained. The ultimate tensile strain and its lower limit allowed a 4-percent defective for 3 mixes, N and M mix in plant 1 and M mix in plant 2, are listed in this table. As shown in this table, the lower limit of ultimate tensile strain for each mix is approximately one percent. Furthermore, the lower limit of tensile strength for each mix is approximately 3 MPa. Because the lower limit represents a material performance that can be assured, specified material properties of ECC manufactured in this study can be set as one percent for the ultimate tensile strain and 3 MPa for the tensile strength.

It should be noted that ECC tensile mechanical properties tend to exhibit rather strong size effects, as demonstrated in Fig.10. and explained in the next section. However, research results in the literature show that tensile mechanical properties obtained from TP tests can be utilized to predict shear and flexural performance of structural beam elements<sup>11)</sup> while results of TC tests lead to overestimating of structural performance<sup>12)</sup>. Hence, the specified material properties in the above are considered for the structural design of ECC elements.

### 5.4 Quality control of tensile performance

There are two ways to check whether the above specific material properties are achieved in the production of ECC members. One is the TC test. In this study, 6 specimens per hour could be tested in the TC test, while the maximum for the TP test was 6 specimens per day. Thus, the TC test, which is easy to execute, is preferable for quality control to the TP test, which requires considerable time and care, provided that the mean value for the test is not less than the control value. The applicable range of this quality control method, however, should be specified taking account of the difference in the mean and the standard deviation with respect to the TP test. This difference is demonstrated in Fig.10., where the TC test exhibits ultimate tensile strain and tensile strength 1.5 and 1.3 times greater than those of the TP test on average. This may be attributed to the size effect of the specimen and to the fiber orientation in the specimen because the specimen size was smaller in the TC test. It is also shown in Fig.10. that the standard deviation of tensile performance in the TC test was greater than that in the TP test. This may be attributed to the precision in aligning the loading axis with the specimen center axis; precise chucking is possible in the TP test but not

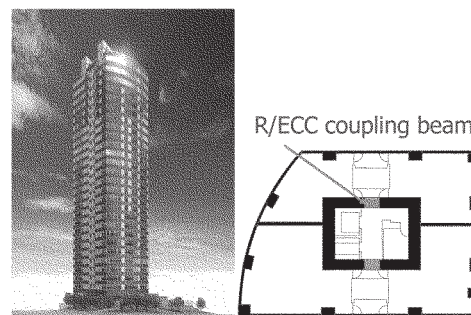


Fig.12. Application of ECC Coupling Beam

Table 9. Inspection Outline in Processing

Property	Inspection	Testing specification	Frequency	Judgement for Approval
Fresh	Slump flow	JIS A 1150	Once a day or once for each 150m3 placing	530±100 (mm)
	Air content	JIS A 1128		9±4 (%)
	Fresh temperature	-		Over 5, Less than 40 deg.
Mechanical	Compressive strength	JIS A 1108		Over 36 MPa at 56 day age
	Tensile strength	JCI-S-003-2005		Over 2 MPa at 56 day age
	Ultimate tensile strain			Over 0.5% at 56 day age

in the TC test, where direct pneumatic chucking often fails to center.

The other possible quality control method is the flexural test, which is more realistic than the TC test. For the ultimate tensile strain and tensile strength, flexural test data analyzed using Eqs. (1) to (4) are compared with those of the TP test in Fig.11. In this analysis of flexural test data,  $\alpha_s$  and  $\alpha_e$  were set to unity for the initial values. It is shown that both ultimate tensile strain and tensile strength of ECC can be evaluated on the safe side by multiplying by a conversion factor of 0.7 on the basis of flexural test and associated analysis. This means that the conversion factors  $\alpha_e$  and  $\alpha_s$  in Eqs. (1) and (2) can be set to 0.7. Taking into account the ease of execution and simplicity of the apparatus, the flexural test may be the most realistic solution for quality control.

As explained in the previous chapter, theoretical derivation of the conversion factors is rather difficult at this moment. A brief remark based on mechanics is presented as follows. A conversion factor  $\alpha_e$  for ultimate tensile strain reflects easier multiple crack formation under flexure than under tension. When the ultimate flexural load exceeds the initial cracking load during flexure, an increase in flexural deflection is accompanied by multiple fine cracking between the loads. This phenomenon is known as deflection hardening, which is demonstrated in Fig.8. Deflection hardening, although it looks similar to strain hardening under tension as shown in Fig.6. and Fig.7., occurs under milder mechanical conditions than strain hardening. A straightforward example is the analytical consequence by Naaman<sup>13)</sup> that, when compressive strength is high enough, the tensile strength of a composite necessary to show deflection hardening is

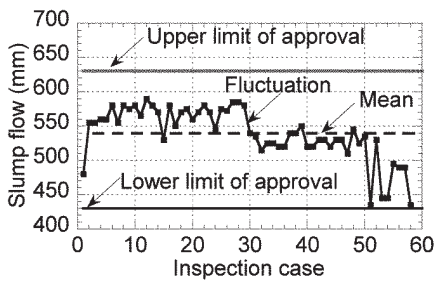


Fig. 13. Slump Flow Inspection Results

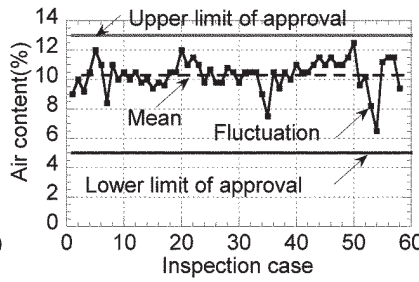


Fig. 14. Air Content Inspection Results

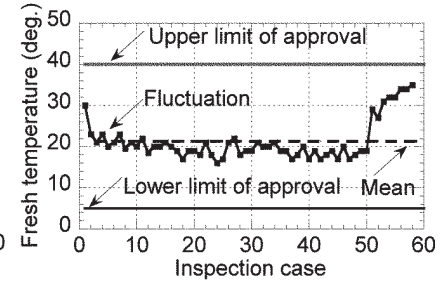


Fig. 15. Fresh Temperature Inspection Results

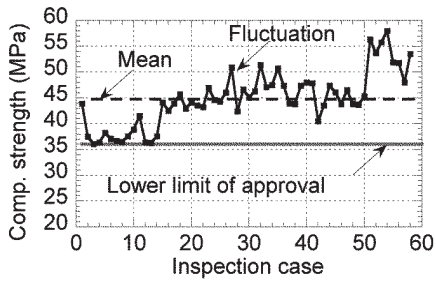


Fig. 16. Comprehensive Strength Inspection Results

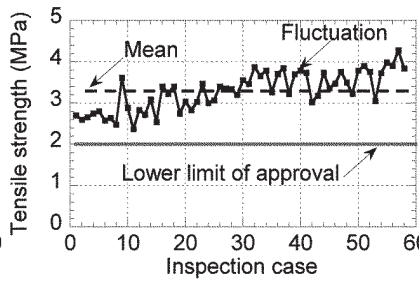


Fig. 17. Tensile Strength Inspection Results

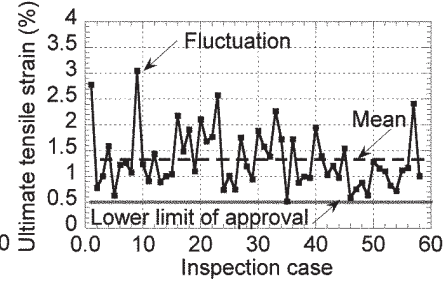


Fig. 18. Ultimate Tensile Strain Inspection Results

one third of the strength of matrix cracking. When strain hardening occurs under tensile loading, the tensile strength of the composite material should be greater than the matrix cracking strength. It is important to note the difference between deflection and strain hardening since multiple cracking occurs more easily under flexural than under tensile loading. The conversion factor  $\alpha_c$  representing the difference in conditions of multiple crack formation in flexure or in tension has a meaning that reduces the ultimate strain predicted from a flexural test.

The other conversion factor  $\alpha_s$  represents the difference between tensile stress-strain relations assuming perfect elasto-plasticity in the derivation of Eqs. (1)-(4) and reality. As can be seen from Fig.6. and Fig.7., the stress-strain relation of ECC can in general be approximated as bi-linear where stress increases gradually after initial cracking. The predicted tensile strength presented in this study was based on the perfect elasto-plastic model and is likely to be greater than that obtained in the TP test<sup>14)</sup>, and an error that may be involved in the assumptions of the stress-strain relation forms a part of  $\alpha_s$ .

## 6. Application in Structural Element

### 6.1 Outline of application and inspection

Based on the prescribed experimental results, reinforced ECC structural elements (R/ECC elements, hereafter) were first applied in building structure as shown in Fig.12. This application utilized R/ECC in a coupling beam connecting two structural walls in a 27-story high-rise reinforced concrete building 93m high. The coupling beam was 500mm wide by 900mm high in cross section, and 1650mm long.

Structural features in this application are referred to the literature<sup>15)</sup>.

These elements were produced one piece per day, for which ECC was mixed with an Omni-mixer in plant 2 as shown in Fig.5. The adopted mix proportions followed Mix-M shown in Table 3. Production started in November 2004 and was completed in June 2005. Element products and specimens for inspection were steam cured as for the full scale production experiments, and then cured in a stock field for at least 56 days.

The quality inspection process was determined as shown in Table 9., where lower bounds of tensile properties were adopted at 2 N/mm<sup>2</sup> for strength and 0.5% for ultimate strain, which were identical to the specific values adopted in the structural design of the elements. For safety, these lower bounds were set for larger variation than that in the results of Table 8. Tensile properties were inspected by flexural test and the results in Fig.11. are reflected in this inspection process. For compressive strength, lower bound of 36 MPa, which is required from necessity in structural design, is higher than the results in Table 6. This discrepancy was allowed for by adopting two operations, a) extending the testing age to 56 days, and b) decreasing the fly-ash weight ratio in the binder to 0.15.

### 6.2 Results of inspection

In the actual processing, all inspection items were satisfied. The results of fresh property inspection are depicted in Fig.13., Fig.14., and Fig.15., where all fresh inspection data are within the specified range. Mechanical property inspection results are shown in Fig.16., Fig.17., and Fig.18. All mechanical data

satisfied the specification in Table 9. In the 58 days of production, the lowest magnitudes were: 36.3 MPa in compressive strength, 2.37 MPa in tensile strength, and 0.59% in ultimate tensile strain.

The lowest compressive strength data were found close to the approval limit, as shown in Table 9., despite of the prescribed two operations. To decrease risk, it appears appropriate for future project to further extend the test age or to decrease the specific compressive strength.

Table 10. summarizes the tensile property inspection results. It shows that the statistical trend of tensile strength inspection data is similar to that in the full scale processing experiment shown in Table 8. However, the mean ultimate tensile strain in Table 10. is lower than the corresponding value in the full scale experiment shown in Table 8. This leads to higher risk of failure to meet the specification than expected from the full scale experiment. Major sources of this lower mean value have not been clarified at this stage. However, possible instability may result from wider variation in fresh temperature, as shown in Fig.15. (17-35 deg.), than that described in Table 5. (23.5-32 deg.). Including fresh temperature control, any further improvement in processing procedure for increasing material reliability is appropriate for future projects. This improvement operation remains for future study.

## 7. Conclusion

This study focused on full-scale production of ECC. First, an extensive full-scale processing experiment was conducted using actual facilities of pre-cast element manufacturers, where associated ECC properties were clarified in tests. As a result of the full-scale experiment, it was found that ECC with high mechanical performance and excellent fluidity can be produced in full scale along with that produced in the laboratory. The results of this experiment indicated that 1 percent ultimate tensile strain and 3 MPa tensile strength can be achieved with high statistical confidence based on tensile tests on prism specimens (TP test) that are believed to reflect the actual behavior of ECC components.

Furthermore, tensile performances obtained in these TP tests were indicated to be reasonably reproduced using standardized flexural tests. This reproduction was successfully achieved by introducing a conversion factor of 0.7 for both tensile strength and ultimate tensile strain. This conversion factor was identified from comparison between tensile tests and flexural

tests. As a result, it was shown that flexural tests can be utilized for ECC's tensile quality inspection in industrial production.

The above experimental results were fully reflected in determining specifications in applying ECC to a high-rise building construction project. This project facilitated R/ECC coupling beams and is the first application example of R/ECC structural elements in building structures. Daily fresh test results confirmed with confidence that inspection data satisfied the specification. Furthermore, standardized flexural test data showed that tensile properties in daily production attained the level required by the specification. However, tensile property margins for this were lower than expected and operations to increase confidence appear necessary for future projects. Discussion on this improving operation remains for further study.

## References

- 1) Li, V.C. (1993): From Micromechanics to Structural Engineering- The Design of Cementitious Composites for Civil Engineering Applications, JSCE J. of Struc. mechanics and Earthquake Engineering, 10(2), pp.37-48.
- 2) Japan Concrete Institute (2002): Committee Report on the Performance Evaluation and Structural Application of Ductile Fiber Reinforced Cementitious Composites (in Japanese).
- 3) Kanda, T. *et al.* (2003): Experimental Study on Workability and Durability of Engineered Cementitious Composite, Proceedings of Japan Concrete Institute, 25(1), pp.1859-1864 (in Japanese).
- 4) Kanda, T. *et al.* (2004): Tensile Properties of ECC in Full-Scale Production, Proceedings of FRAMCOS-5, pp.1013-1020.
- 5) Kanda, T. and Li, V.C.(1999): A New Micromechanics Design Theory for Pseudo Strain Hardening Cementitious Composite, Journal of Engineering Mechanics, ASCE, 125(4), pp.373-381.
- 6) Shimizu, K. *et al.* (2003): Effects of placing direction on the uniaxial tensile and flexural strength of HPFRCC, Proceeding of the annual meeting of JCI, 25(1), pp.280-286 (in Japanese).
- 7) JCI Technical Committee (2006): Method of Test for Bending Moment-Curvature Curve of Fiber-Reinforced Cementitious Composites, Journal of Advanced Concrete Technology, 4(1), pp.73-78.
- 8) Kanakubo, T. (2006): Tensile Characteristics Evaluation Method for Ductile Fiber-Reinforced Cementitious Composites, Journal of Advanced Concrete Technology, 4(1) pp.3-17.
- 9) Kanakubo, T. *et al.* (2003): Evaluation of Tensile Performance of DFRCC-Results of Round-Robin Test in JCI-TC, Symposium on Highly Ductile Cementitious Composites, pp.101-112 (in Japanese).
- 10) Li, V.C.(2003): On High Performance Fiber Reinforced Cementitious Composite", JCI Symposium on DFRCC, pp.13-23.
- 11) Shimizu, K. *et al.*(2005): Evaluation of Shear Characteristics of PVA-ECC Beams, Proceedings of Japan Concrete Institute, 27(2), pp.1333-1338 (in Japanese).
- 12) Nagai, S. *et al.*(2004): Structural Capacity of Dampers with ECC, Proceedings of Japan Concrete Institute, 26(2), pp.1513-1518 (in Japanese).
- 13) Naaman, A.E. (2002): Toughness, ductility, surface energy and deflection-hardening FRC composites, Proc. JCI Int. Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC), pp.33-57.
- 14) Japan Concrete Institute (2004): Technical Committee Report on the Structural Applications of Highly Ductile Cementitious Composites, Chap. 3 (in Japanese).
- 15) Maruta, M. *et al.* (2005): New High-Rise RC Structure Using Pre-Cast ECC Coupling Beam, Concrete Journal, 43 (11), pp.18-26 (in Japanese).

Table 10. Tensile Property Inspection Summary

Property		Mean	Stand. dev.	COV
Ultimate tensile strain (%)	Mix-M at P2	1.33	0.57	0.43
Tensile strength (MPa)	Mix-M at P2	3.30	0.46	0.14