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SHEAR BEHAVIOR OF STEEL REINFORCED PVA-ECC BEAMS

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SUMMARY

ECC (Engineered Cementitious Composites), which is grouped in one of the fiber reinforced cementitious composites, shows pseudostrain hardening behavior with several percent tensile strain. In this research, bending shear test of steel reinforced PVA-ECC (ECC with Polyvinyl alcohol fiber) beam is conducted to grasp fundamental properties of reinforced PVA-ECC. From the results of beam test, shear strength increases as volume percentage of PVA fiber increases. Average shear strain in shear crack surface at maximum strength is influenced by differences of volume percentage of PVA fiber. Predicting method for shear strength of beams is proposed based on the tensile strength obtained from uniaxial tensile test of PVA-ECC.

INTRODUCTION

ECC (Engineered Cementitious Composites) [1], which is grouped in one of the fiber reinforced cementitious composites, shows pseudostrain hardening behavior with several percent tensile strain. To use fiber reinforced cementitious composites such as ECC as structural elements, steel reinforced ECC members have been experimented by several research institutes. Most of those specimens are flexural yielding type, because of utilizing as energy absorbing elements for structural control, upgrading materials for flexural members, and so on. It is important that shear behavior is comprehended for the purpose of structural performance design as same as flexural behavior. Additionally, it is significantly important that tensile behavior of ECC is appropriately evaluated, and structural performance of ECC members can be predicted and designed from tensile behavior evaluation.

In this research, uniaxial tensile test for PVA-ECC (ECC with Polyvinyl alcohol fiber) and bending shear test of steel reinforced PVA-ECC beam is conducted to obtain fundamental properties of reinforced PVA-ECC. Specimens for reinforced PVA-ECC beam test are designed to show shear failure. Parameters are ratio of lateral reinforcement and volume percentage of PVA fiber. Predicting method for shear strength of beams is considered based on the tensile stress - strain model obtained by uniaxial tensile test of PVA-ECC.

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MATERIAL PROPERTIES

Fiber of ECC is polyvinyl alcohol (PVA) fiber. Volume percentage (V_f) of PVA fiber is set to 1.0, 1.5, and 2.0%. Mechanical properties of PVA fiber are shown in Table 1. These values are given by manufacturer. Table 2 shows the mixture proportion. Results of compression test using 100ϕ - 200mm cylinder test pieces are summarized in Table 3. Normal concrete (NC) beams are designed for comparison to PVA-ECC one. Compressive strength of normal concrete is similar level to compressive strength of PVA-ECC. Mixture proportion and compression test results of normal concrete are shown in same table. Specimens of reinforced beam are made with D13 main bar and D4 stirrup. Tensile test results of reinforcing steel are shown in Table 4.

Table 1 Properties of PVA fiber

Fiber type	Length of fiber (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
PVA	12	0.04	1600	40

Table 2 Mixture proportion

Matrix type	Fiber volume percentage (%)	Water by binder ratio (%)	Sand by binder ratio	Air content (%)
PVA10	1.0	42.7	0.74	10
PVA15	1.5	42.7	0.73	10
PVA20	2.0	42.7	0.71	10
NC	-	48.5	5.11	5.0

Table 3 Compression test results

Matrix type	Compressive strength (MPa)	Compressive strain at maximum (%)	1/3 Secant modulus (GPa)
PVA10	37.3	0.35	17.8
PVA15	35.7	0.35	16.3
PVA20	39.1	0.36	19.5
NC	39.0	0.23	26.2

Table 4 Tensile test results of reinforcing steel

Name	Yield stress (MPa)	Elastic modulus (GPa)	Yield strain (μ)	Elongation after fracture (%)
D13*1	719.7	190.5	3779	9.8
D13*2	719.0	193.2	3721	14.5
D4*3	294.5	192.7	1528	27.4

*1 Main bar of PVA-ECC beams *2 Main bar of NC beams *3 Stirrup

BENDING SHEAR TEST OF PVA-ECC BEAMS

Specimens and Test Methods

The dimensions and bar arrangements of the beam specimens are shown in Fig. 1. Specimens have the 180 x 280mm size rectangular section, and shear span ratio is 1.5. Main bar of yield stress 719MPa is used so that flexural yielding may not occur first. Parameters are ratio of stirrup and volume percentage of PVA fiber. Normal concrete (NC) beams are planned for the comparison. List of specimens are shown in Table 5.

Beam specimens are loaded under anti-symmetrical moment monotorically by Ohno Method. LVDTs are set to measure relative displacement between the stubs, partial deformations of each zone (A-C) shown in Fig. 1. Strain guages are set to measure main bar and stirrup strain.

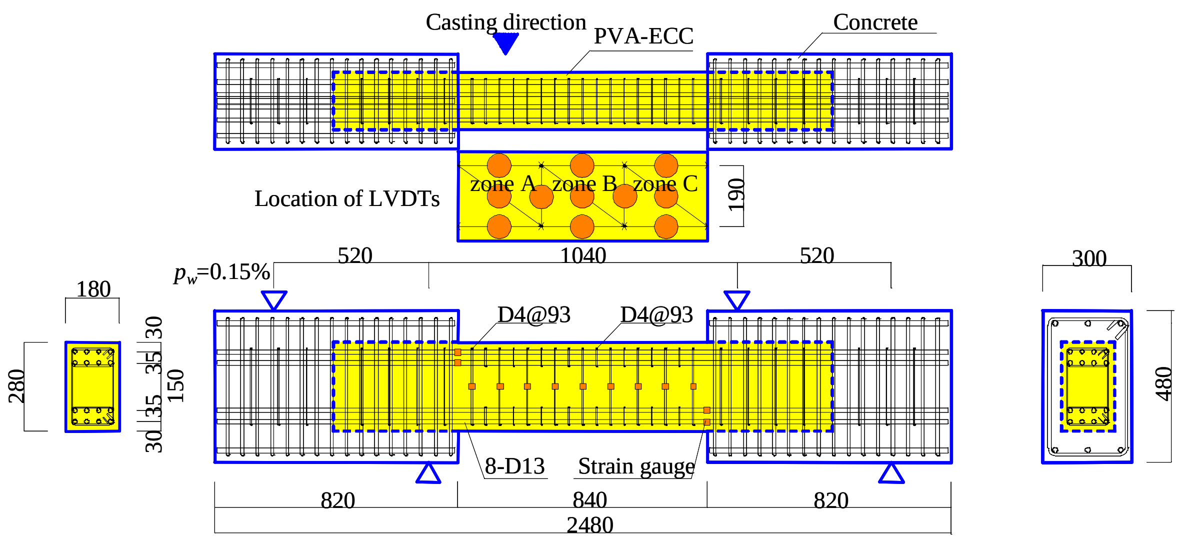

Fig. 1 Dimension and bar arrangement of beam specimen

Table 5 List of beam specimens

Specimen	Fiber	Fiber volume percentage (%)	Section b x D (mm)	Shear span ratio	Main bar	Stirrup	
						Arrangement	Reinforcement ratio (%)
NC-00	(Normal concrete)		180 x 280	1.5	8-D13 SD685 p_t=2.43%	-	0.00
NC-15						2-D4@93	0.15
NC-30						2-D4@47	0.30
PVA10-00	PVA	1.0				-	0.00
PVA10-15						2-D4@93	0.15
PVA10-30						2-D4@47	0.30
PVA15-00		1.5				-	0.00
PVA15-15						2-D4@93	0.15
PVA15-30						2-D4@47	0.30
PVA20-00		2.0				-	0.00
PVA20-15						2-D4@93	0.15
PVA20-30						2-D4@47	0.30

Test Results

The crack patterns at translational angle (R) of 0.01rad. are shown in the Fig. 2. Bending and shear crack are observed at 0.0025rad.. In PVA-ECC beams, multiple cracks and effect of crack opening repression can be observed in comparison with NC beams. When load becomes around the maximum value, deformation is concentrated on a certain one shear crack as for PVA-ECC beams as well. Another crack width is decreased due to localize deformation. Main bar does not show yielding in all specimens.

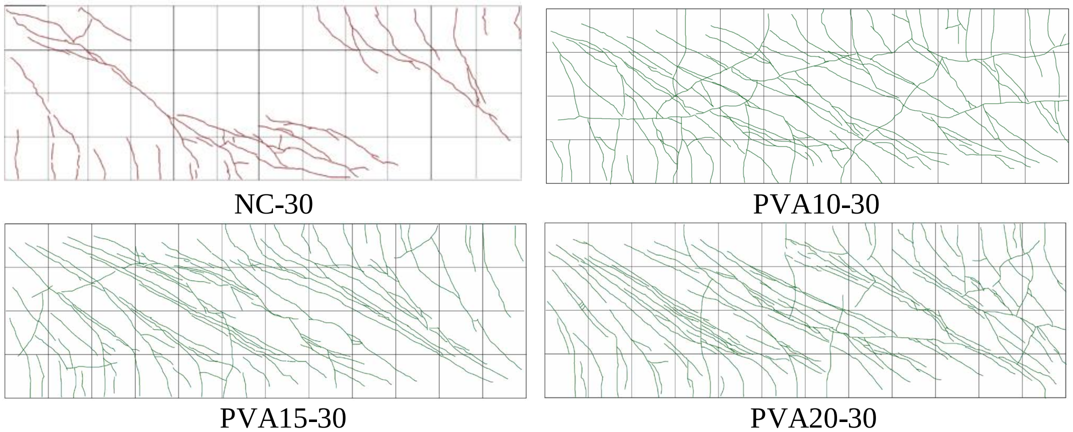

Fig. 2 Crack patterns at 0.01rad.

Results of beam tests are shown in Table 6. Angle of main shear crack is measured values of main shear crack of zone B with a ruler. Maximum stirrup strain is the biggest value in all strain guages at maximum strength. The average angle of main shear crack of PVA-ECC beams is 28.6deg., nearly cotϕ_{cr} = 2.0 (ϕ_{cr} = 26.6deg.). Comparison of maximum strength is shown in the Fig. 3. Maximum strength increases as volume percentage of PVA fiber increases and reinforcement ratio increases. The increase rate of maximum strength due to the increase in fiber volume percentage almost shows constant value. Since stirrup strains show larger strain than yield strain at maximum strength, stirrup is assumed to be yielded. Shear load - translational angle curve is shown in Fig. 4. It is observed in PVA-ECC beams that load decreases at opening shear crack and concentration of deformation.

Table 6 Results of beam tests

Specimen	Load at first crack (kN)		Angle of main shear crack (deg.)	At maximum load		
	Bending crack	Shear crack		Load (kN)	Translational angle ($x10^{-3}$rad)	Maximum stirrup strain (μ)
NC-00	43.6	97.5	26.6	116.4	5.05	-
NC-15	36.9	69.4	21.8	104.8	6.93	2082
NC-30	41.9	74.3	29.7	132.3	12.01	1330
PVA10-00	26.1	66.7	31.0	123.9	6.44	-
PVA10-15	20.4	55.3	23.2	144.8	8.07	3278
PVA10-30	18.8	60.5	29.2	171.5	11.75	981
PVA15-00	31.1	66.6	34.5	142.8	9.11	-
PVA15-15	42.4	63.7	23.2	169.7	11.01	5267
PVA15-30	27.9	123.7	32.4	182.9	11.64	8695
PVA20-00	17.0	36.3	33.4	182.7	10.90	-
PVA20-15	20.8	33.0	26.2	205.8	13.82	985
PVA20-30	19.8	90.6	24.2	208.6	12.62	3825

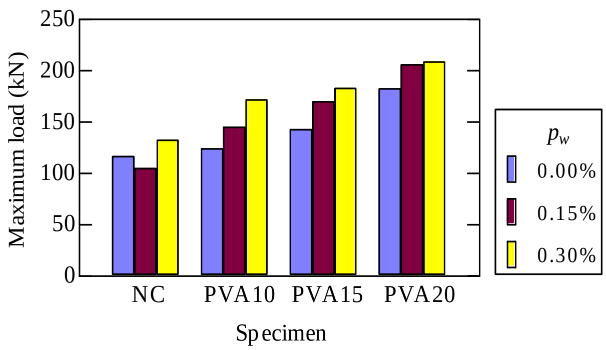

Fig. 3 Comparison of maximum strength

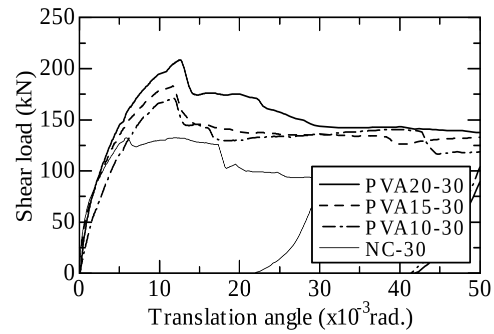

Fig. 4 Relationship between shear load and translational angle

UNIAXIAL TENSILE TESTS OF PVA-ECC

Specimens and Test Methods

Fig. 5 shows the outline of uniaxial tensile test method. This tensile specimen is used to minimize the influence of fiber orientation and was expected to reproduce a more precise tensile performance of ECC in a structure [2]. Sectional dimension in test region of this specimen is 100 x 60mm. The head speed of loading machine is set to 0.5mm/min. Two LVDTs are set to measure axial deformation with gauge length of 160mm. Each number of specimens with PVA10, PVA15, and PVA20 are six.

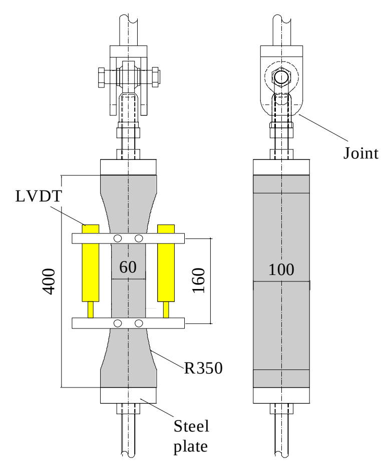

Fig. 5 Uniaxial tensile test

Test Results

Tensile stress - strain curves are shown in Fig. 6. PVA15 and PVA20 test results clearly indicated the pseudostrain hardening characteristics, where stress increased after first crack. Test results are summarized in Table 7. The ultimate strain is defined as the point at whith stress bocomes smaller than half of maximum stress after maximum stress. It can be recognized that difference of fiber volume percentage influences maximum stress and ultimate strain.

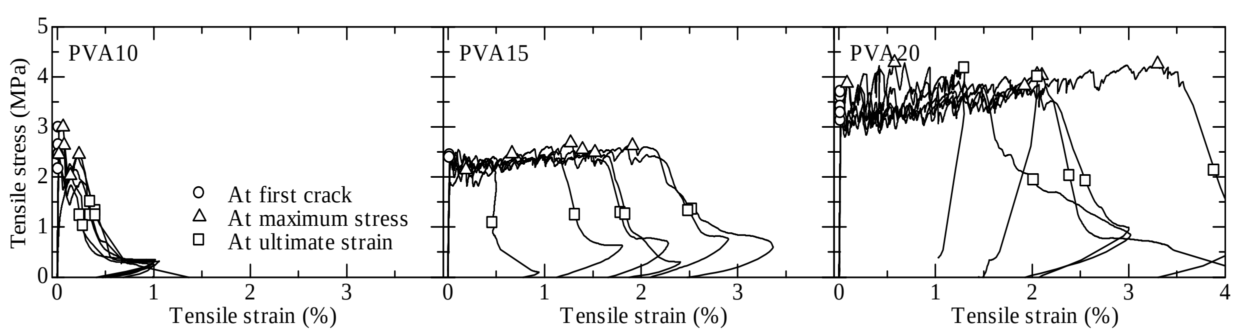

Fig. 6 Tensile stress - tensile strain relationship

Table 7 Uniaxial tensile test results

Specimen	At first crack		At maximum stress		Ultimate strain (%)
	Tensile stress (MPa)	Tensile strain (%)	Tensile stress (MPa)	Tensile strain (%)	
PVA10	2.54	0.017	2.52	0.10	0.33
PVA15	2.41	0.018	2.50	1.16	1.74
PVA20	3.41	0.018	4.06	1.67	2.37

EVALUATION OF SHEAR STRENGTH PVA-ECC BEAM

Strain Behavior of Beam

Principal strain (ε_1, ε_2) and principal shear strain (γ_{12}) are calculated by using Mohr's strain circle from average strain (ε_x, ε_y, and ε_{xy}) which is calculated from partial deformation shown in the Fig. 1. Normal strain (ε_{cr}) and shear strain (γ_{cr}) on the shear crack (ϕ_{cr} = 26.6deg.) is calculated, too. Method of calculating these strains is shown in Fig. 7.

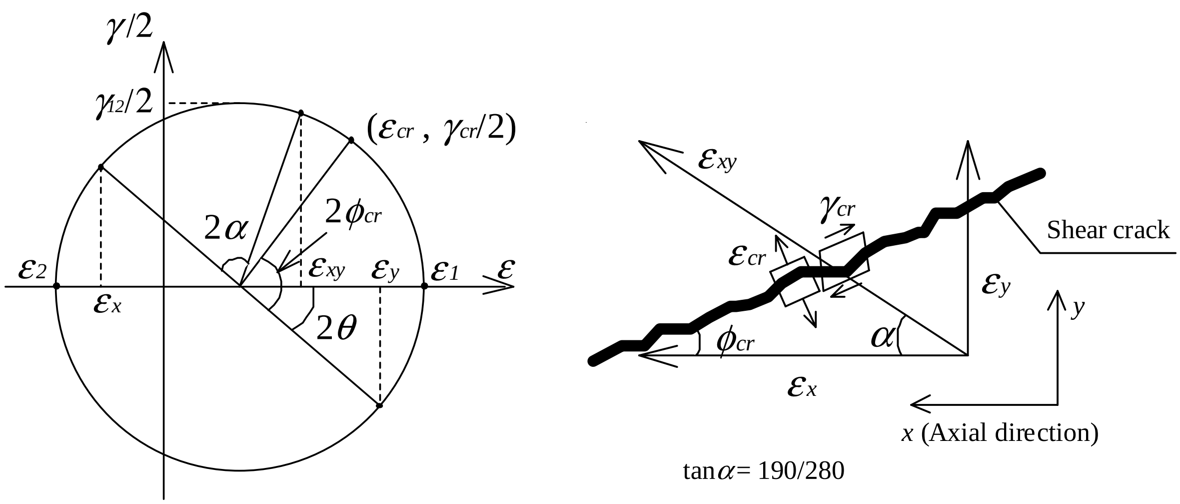

Fig. 7 Method of calculating principal strain

Transitions of principal strain in zone B is shown in Fig. 8. *X* axis shows load step. Compressive principal strain remained almost zero. On the other hand, tensile principal strain of PVA10, PVA15, and PVA20 beams at maximum strength are 0.5 to 0.9%, around 0.9%, and 1.0 to 1.3%, respectively. It is considered that fiber volume percentage influences tensile performance of PVA-ECC in beam test. In uniaxial tensile test results of PVA-ECC, however, tensile stress of PVA10 is zero when tensile strain is 0.5 to 0.9%, and tensile stress of PVA15 and PVA20 does not reach the limit value of tensile performance when tensile strain is around 1.0%. Therefore, it is considered that principal strain is not the cause to occur shear failure of PVA-ECC beams.

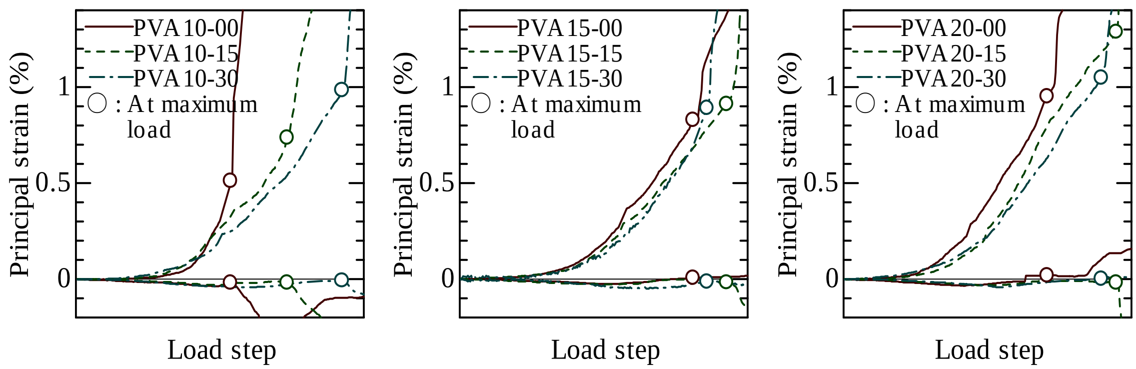

Fig. 8 Transitions of principal strain in zone B

Transitions of nomal strain and shear strain on the shear crack in zone B is shown in Fig. 9. Influences of fiber volume percentage and reinforcement ratio are not clear about normal strain, which is around 0.3% at maximum strength. On the other hand, the differences are comparatively clear about shear strain. Shear strain at maximum strength of PVA10, PVA15, and PVA20 are 0.4 to 0.7%, around 0.6%, and 0.7 to 0.8%, respectively. The possibility is recognized that shear failure of PVA-ECC beams is influenced by shear transmittance capacity of PVA-ECC.

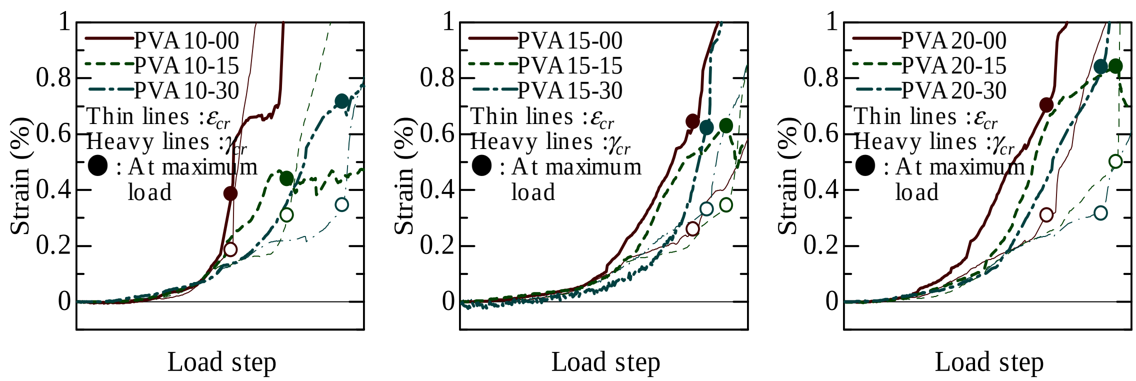

Fig. 9 Trasitional normal and shear strain

Proposal of Shear Strength Evaluation

At present, the research of shear transmittance capacity of ECC on cracks has been conducted [3]. There have been many unclear points in relationship between stress and strain at ultimate state (i.e., failure completing curve concerning stress and strain under multi-axial stress). In literature [3], for example, it was reported that shear strength is almost equal to uniaxial tensile strength, even this depends on stress path of normal and shear stress.

In order to design simply, predicting method for shear strength of beams is proposed using truss - arch method. Assuming that stress of PVA-ECC is influenced by shear stress on crack, shear strength which is same value as uniaxial tensile strength is added to truss mechanism. From Method A of AIJ [4], Eq.(1) can be obtained.

$$V_u = b \cdot j_t \left(p_w \cdot \sigma_{wy} \cdot \cot\phi + \sigma_{max}^{ECC} \right) + \tan\theta (1-\beta) b \cdot D \cdot \nu \cdot \sigma_B / 2 \qquad (1)$$

$$\tan\theta = \sqrt{(L/D)^2 + 1} - L/D \qquad (2)$$

$$\beta = \frac{\left(1+\cot^2\phi\right)\left(p_w\cdot\sigma_{wy} + \sigma_{max}^{ECC}/\cot\phi\right)}{\nu\cdot\sigma_B} \le 1 \tag{3}$$

$$\cot\phi = \min\{2,\ j_t/(D\tan\theta)\} \tag{4}$$

where,

b : width of member
D : depth of member
L : clear span length
j_t : distance between tensile and compressive main bars
p_w : reinforcement ratio
σ_{wy} : yield strength of stirrup
σ_{max}^{ECC} : tensile strength of PVA-ECC
σ_B : compressive strength
ν : effective coefficient of concrete compressive strength

It is necessary that stirrups are yielded at maximum load of PVA-ECC beams, because stress of PVA-ECC is superposition to stirrup strength in truss mechanism. Fig. 10 shows comparison between calculated results and beam test results. Since average strain at tensile strength is 0.10% not more than yield strain of stirrup in PVA10, 2.23MPa is used for calculation as tensile stress at yeild strain of stirrup. Following Eq.(5) is used for calculating effective coefficient of concrete compressive strength. Average ratio of test results to calculus is 1.03. Shear strength of PVA-ECC beans can be evaluated well by this calculation method.

$$\nu = 3.68\sigma_B^{-0.333} \quad \text{(unit of } \sigma_B \text{ is kgf/cm}^2\text{)} \tag{5}$$

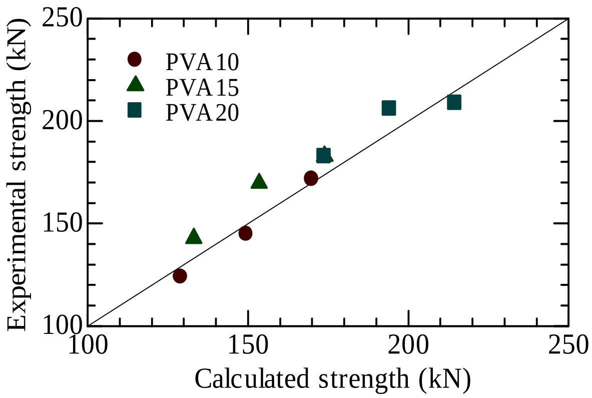

Fig. 10 Comparison between calculated strength and experimental strength

CONCLUSIONS

1. In the beam test, maximum strength increases as volume percentage of PVA fiber increases and reinforcement ratio increases.
2. In the uniaxial tensile test of PVA-ECC, it can be recognized that difference of fiber volume percentage influences maximum stress and ultimate strain.

3. Influences by fiber volume percentage and reinforcement ratio are not clear about normal strain at maximum strength. On the other hand, the differences are comparatively clear about shear strain.
4. Predicting method for shear strength of beams is proposed based on the tensile strength obtained from uniaxial tensile test of PVA-ECC. Shear strength of PVA-ECC beans can be evaluated well by this calculation method.

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