EFFECTS OF DRYING SHRINKAGE ON SHEAR TENSION STRENGTH OF REINFORCED CONCRETE BEAMS

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Abstract: The effects of drying shrinkage on shear tension strength as well as size effect of reinforced normal strength-high shrinkage concrete (RC) beams were investigated. Twenty four RC beams with effective depths of 250, 500 and 1000 mm and without web reinforcement were prepared, where half of the beams were sealed and the others were exposed to drying. The loading test results showed that the shear tension strength of drying beams was lower by up to 17% compared with that of sealed beams and the size effect of shear tension strength became more sensitive due to drying shrinkage of concrete. In addition, a new concept based on equivalent tension reinforcement ratio incorporating the effect of compression strain in reinforcement before loading due to drying shrinkage in concrete was effective in evaluating not only the shear tension strength but also size effect independent of shrinkage effect.

1 INTRODUCTION

Drying shrinkage of concrete often induces cracking in reinforced concrete (RC) members. which may result in deterioration of durability in concrete structures. Therefore, the mechanisms of drying shrinkage, risk of cracking, control method of shrinkage, and so on have been studied by many researchers. Moreover, drying shrinkage is one of major factors affecting crack width, deflections, losses in prestress, as well as bending moment and forces in statically-indeterminate structures.

On the other hand, in the case of shrinkage effect on ultimate strength, it was reported that restrained stress and cracks due to drying shrinkage hardly affected the flexural capacity, because flexural failure occurs after yielding of reinforcement, and the strain of steel bars at failure is much larger than shrinkage strain in concrete[1]. On the contrary, shear failure often occurs when the strain of reinforcing steel bars is at an elastic stage. In this respect, it is thought that shear strength could be affected by shrinkage strain in concrete.

Recently, the second author reported that diagonal cracking strength of reinforced high strength concrete beams decreased due to the effect of autogenous shrinkage and proposed a new design equation for estimating shear strength, which was formulated based on a concept of “equivalent tension reinforcement ratio” considering the strain change of tension reinforcing bars before and after loading[2].

Table 1: Materials.

Materials	Symbol	Type / Characteristics
Water	W	Industrial water
Cement	C	Ordinary Portland cement / Density: 3.16g/cm^3
Expansive admixture	EX	Lime based / Density: 3.16g/cm^3
Fine aggregate	S	Crushed sand / Density: 2.65g/cm^3, Absorption: 1.86%
Coarse aggregate	G	Crushed stone / Density: 2.69g/cm^3, Water Absorption: 0.89%, Maximum size: 20mm
Chemical admixture	—	Polycarboxylic AE high-range water reducing agent

Table 2: Mixture proportions.

Curing condition	W/B (%)	Unit content (kg/m^3)				
		W	C	EX	S	G
Seal / Dry	50	170	340	-	832	977
Dry	35	170	486	-	686	1001
Seal	35	170	466	20	686	1001

This study aims at investigating whether drying shrinkage also affects shear tension strength as well as size effect of reinforced normal strength-high shrinkage concrete beams without web reinforcement.

2 EXPERIMENTAL PROGRAM

2.1 Materials and Mixture proportions

Table 1 lists the types of materials used in this study. **Table 2** tabulates the mixture proportions of the concretes prepared in this study. Ordinary Portland cement (N) was used as the cement. Crushed sand and stone were used as fine (S) and coarse aggregates (G) respectively. The maximum particle size of the coarse aggregate was 20mm. The water-to-binder ratio (W/B) was set at 50% and 35%. An expansive additive (EX) of 20kg/m^3 was used in the concrete with W/B of 35% to reduce autogenous shrinkage.

High strength deformed steel bar ($f_y \geq$ 1080N/mm^2) was used to induce shear failure in reinforced concrete before yielding of tension reinforcing bars.

2.2 Specimens

Table 3 outlines dimensions of the RC beams. The size and dimension of RC beams as well as main reinforcing bars used in the present study are shown in **Figure 1**. Three different sizes of RC beams without web reinforcement were prepared in order to investigate the size effect on shear tension strength. The effective depths of RC beams were 250mm, 500mm and 1000mm. The nominal tension reinforcement ratio (A_s/bd) was 1.03%-1.06%. All the specimens were designed to fail in shear.

In order to evaluate the effect of drying shrinkage on shear tension strength, the specimens were cured in sealed and drying conditions. After demolding at the age of 7 days, half of the beams were immediately sealed with aluminum adhesive tape to prevent drying through evaporation, while the others was exposed to drying in the laboratory, until the loading test age. The relative humidity on average during the curing period was between 64.4% and 66.3%. The names of specimens consists of the curing condition (S: seal, D: dry), W/B (50%, 35%), the effective depth (250mm, 500mm, 1000mm), and the use of expansive additive (EX), in that order. Two RC beams of the same size and the same curing condition were prepared for each concrete type.

Cylindrical specimens of dimensions φ100 x 200mm for compressive strength and Young’s modulus, as well as those of dimensions φ150 x 200mm for splitting tensile strength were prepared. In addition, prismatic specimens of dimensions 100 x 100 x 400mm for fracture energy test of concrete were also prepared. All the specimens were cured in the same conditions as the RC beams.

Table 3: Outline of RC beams.

W/B (%)	Curing condition	Name of specimens	*b* (mm)	*h* (mm)	*L* (mm)	*c* (mm)	*a* (mm)	*d* (mm)	*a/d*	p_s (%)
50	Seal	S50-250-A,B	300	305	2300	200	750	250	3.0	1.03 (2D22)
		S50-500-A,B		580	4500	500	1500	500		1.06 (2D32)
		S50-1000-A,B		1130	7500	500	3000	1000		1.06 (4D32)
	Dry	D50-250-A,B		305	2300	200	750	250		1.03 (2D22)
		D50-500-A,B		580	4500	500	1500	500		1.06 (2D32)
		D50-1000-A,B		1130	7500	500	3000	1000		1.06 (4D32)
35	Seal	S35-250EX-A,B		305	2300	200	750	250		1.03 (2D22)
		S35-500EX-A,B		580	4500	500	1500	500		1.06 (2D32)
		S35-1000EX-A,B		1130	7500	500	3000	1000		1.06 (4D32)
	Dry	D35-250-A,B		305	2300	200	750	250		1.03 (2D22)
		D35-500-A,B		580	4500	500	1500	500		1.06 (2D32)
		D35-1000-A,B		1130	7500	500	3000	1000		1.06 (4D32)

b: Width of beam, *h*: Height of beam, *L*: Length of beam, *c*: Distance between two loading point, *a*: Shear span, *d*: Effective depth (distance from the compression fiber to the centroid of the tension reinforcing bars), p_s: Tension reinforcement ratio($=A_s/bd$), A_s: Nominal cross-section area of tension reinforcement

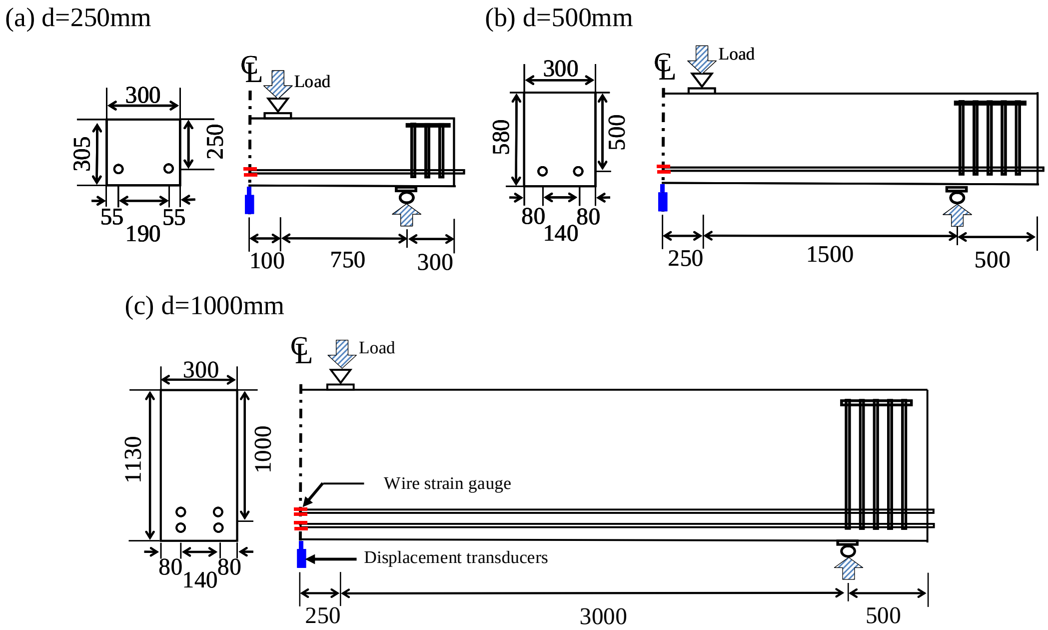


Figure 1: Dimensions and configuration of reinforced concrete beam (Unit: mm).

2.3 Loading and measurement

Loading tests were conducted when reinforcement strain of dried beams reached about 250 x 10^{-6} in compression. All the RC beams were loaded monotonically with two incremental concentrated loads, as shown in **Figure 1**. The shear span length to effective depth ratio was fixed at 3. Deflection at the center section of the RC beam was measured using displacement transducers. Strain in tension reinforcing bar at the center section of span was measured by wire strain gauges just after concrete placement until completion of the loading tests.

The compressive strength, splitting tensile strength, Young's modulus, and fracture energy of concrete were measured at the age of loading test for RC beams. The fracture energy of concrete was determined from the load-crack mouth opening displacement curves of notched beam under three point loading in accordance with JCI standard (JCI-S-001-2003) [3].

Table 4: Mechanical properties of concrete at the age of loading test.

Name of specimens	Loading age (Days)	f_c' (N/mm^2)	f_t (N/mm^2)	E_c (kN/mm^2)	G_f (N/mm)	l_{ch} (mm)
S50-250	92	38.9	3.2	25.0	0.15	367
S50-500	112	39.3	3.2	25.0	0.16	374
S50-1000	112	39.2	3.2	25.0	0.16	380
D50-250	125	40.1	3.2	21.5	0.20	421
D50-500	288	40.8	3.3	21.5	0.20	397
D50-1000	288	40.8	3.3	21.5	0.20	397
S35-250EX	141	53.5	4.0	29.4	0.18	325
S35-500EX	198	53.5	4.0	29.4	0.17	310
S35-1000EX	198	53.5	4.0	29.4	0.17	310
D35-250	210	47.1	3.2	23.3	0.22	493
D35-500	283	47.1	3.2	23.3	0.16	353
D35-1000	283	47.1	3.2	23.3	0.16	353

f_c': Compressive strength, f_t: Splitting tensile strength, E_c: Young's modulus, G_f: Fracture energy, l_{ch}: Characteristic length ($=E_cG_f/f_t^2$)

3 RESULTS AND DISCUSSION

3.1 Mechanical properties of concrete

Table 4 tabulates mechanical properties of concrete at the age of loading test. The compressive strength, splitting tensile strength and fracture energy of concrete were not significantly different, regardless of the curing condition. On the other hand, it was observed that the Young's modulus of the concretes under drying conditions decreased by more than 15% compared with that of the sealed concretes.

3.2 Deformation behavior of concrete and RC beams

Table 5 lists the strain in reinforcing bar and stress in concrete at the bottom of RC beams before loading induced by shrinkage. The stress in concrete at the bottom due to restraint of reinforcing bars was determined using Eq. (1).

$$\sigma_c = -\frac{P_s}{A_c}\left[1+\frac{A_c(d-C_g)(h-C_g)}{I_c}\right] \qquad (1)$$

$$P_s = A_s E_s \varepsilon_s$$

Where:

P_s: Force in the tensile reinforcing bars,

A_c, I_c: Cross-section area and moment of inertia of concrete in section of beam,

A_s: Cross-section area of tension reinforcing bars,

E_s: Young's modulus of tension reinforcing bars,

ε_s: Shrinkage induced strain in tension reinforcing bars,

σ_c: Stress of concrete at bottom,

C_g: Distance from compressive fiber to centroid of concrete section.

The difference of the compression strain in reinforcing bars at the loading test between the drying and sealed beams ranged from approximately 200 x 10^{-6} to 300 x 10^{-6}. Moreover, the tensile stress in the concrete of the drying beams was 1.3N/mm^2 on average, while that of the sealed beams was almost zero.

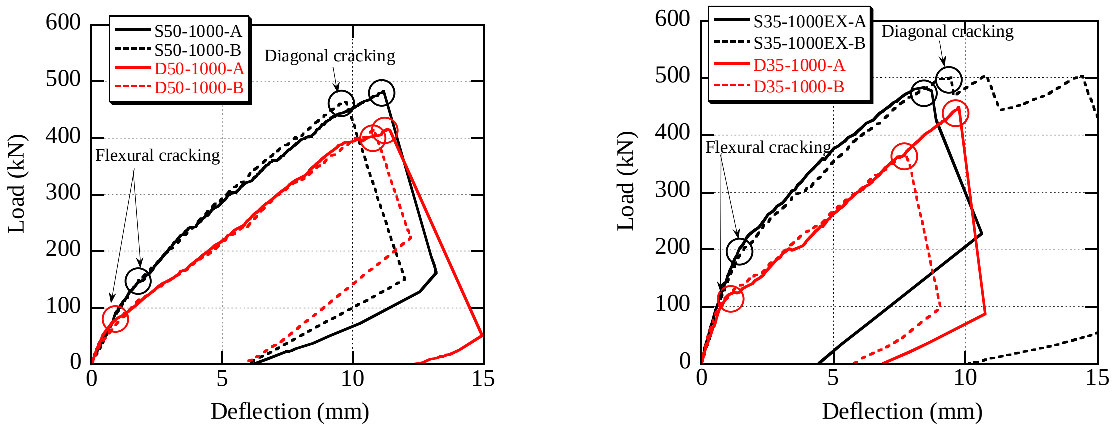
3.3 Effect of drying shrinkage on shear tension strength

As a typical example, the relationship between load and deflection of RC beams with the effective depth 1000mm are shown in **Figure 2**. The flexural cracking load of the drying beams was clearly lower than that of the sealed beams, because of the tensile stress introduced by drying shrinkage of concrete. It was also observed that induced stresses resulting from drying shrinkage reduced not only the stiffness but also the diagonal

Table 5: Outline of loading test results.

W/B (%)	Name of specimen	At the age of loading		Shear tension strength		Failure mode
		$\varepsilon_{s,def}$ ($\times10^{-6}$)	$\sigma_{c,def}$ (N/mm^2)	V_c (kN)	τ_c (N/mm^2)	
50	S50-250-A	-24	0.1	80	1.07	DT
	S50-250-B	-26	0.1	88	1.17	DT
	S50-500-A	-39	0.2	130	0.87	DT
	S50-500-B	-47	0.2	149	0.99	DT
	S50-1000-A	-73	0.4	238	0.79	DT
	S50-1000-B	-57	0.3	232	0.77	DT
	D50-250-A	-291	1.0	79	1.05	DT
	D50-250-B	-288	1.0	78	1.04	DT
	D50-500-A	-302	1.3	140	0.94	DT
	D50-500-B	-307	1.3	131	0.87	DT
	D50-1000-A	-234	1.1	208	0.69	DT
	D50-1000-B	-246	1.2	208	0.69	DT
35	S35-250EX-A	-56	0.2	112	1.49	DT
	S35-250EX-B	-71	0.3	109	1.45	DT
	S35-500EX-A	-4	0.0	152	1.01	DT
	S35-500EX-B	-30	0.1	155	1.05	DT
	S35-1000EX-A	2	0.0	242	0.81	DT
	S35-1000EX-B	-23	0.1	250	0.83	DT
	D35-250-A	-405	1.4	96	1.28	DT
	D35-250-B	-409	1.4	90	1.20	DT
	D35-500-A	-376	1.6	150	1.00	DT
	D35-500-B	-321	1.4	161	1.07	DT
	D35-1000-A	-329	1.6	224	0.75	DT
	D35-1000-B	-318	1.5	182	0.61	DT

$\varepsilon_{s,def}$: Tension reinforcement strain induced by shrinkage of concrete(+: tension, -: compression), $\sigma_{c,def}$: Stress in concrete at the bottom of RC beams induce by shrinkage, V_c: Shear force at diagonal cracking, τ_c: Shear strength at diagonal cracking (V_c/bd), DT: Diagonal tension

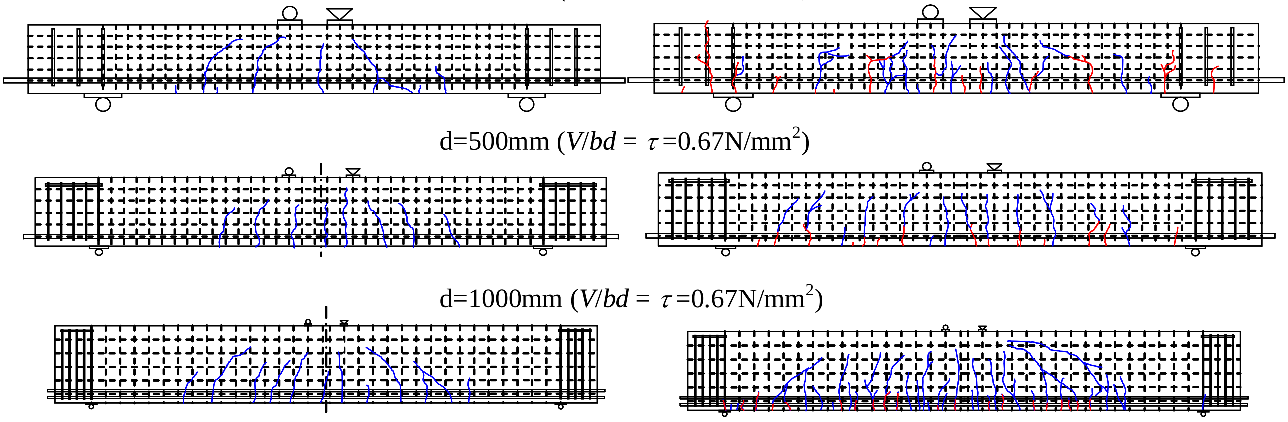


(a) W/B50% (b) W/B35%

Figure 2: Load and deflection relation (d=1000mm).

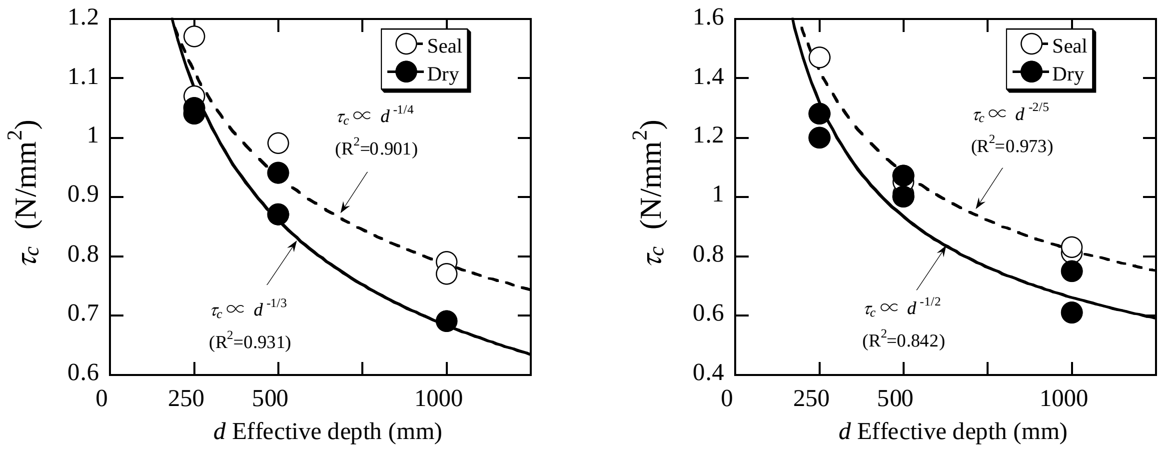
cracking load of RC beams.

A summary of loading test results for each beam is given in **Table 5**, which shows the shear tension strength and the failure mode of all the RC beams. The shear tension strength was determined from the load-deflection relationship. All beams failed in diagonal tension before yielding of tension reinforcing bars. Almost all the drying beams showed a decrease in shear tension strength by up to 17% compared with the sealed beams. This is similar to what was observed in the case of



(a) Sealed beam (b) Drying beam

Figure 3: Crack patterns (W/B=50%).



(a) W/B50% (b) W/B35%

Figure 4: Relationship between effective depth and shear tension strength.

high strength concrete beams in the previous study[2]. The decrease was explained by increase of reinforcement strain change before and after loading, because the reinforcement was compressed by autogenous shrinkage of concrete, which resulted in the increase of flexural and shear crack widths.

Figure 3 shows typical examples of crack patterns in sealed and drying beams at the same nominal shear stress, in which the beams are represented as equally large, in spite of their different dimension. As is shown in this figure, cracks of the drying beam propagates deeper toward compression fiber probably resulting in the reduction of thickness of compression concrete which is one of major shear resisting components.

3.4 Size effect on shear tension strength

Figure 4 shows that the relationship between the shear tension strength and the effective depth of the sealed and drying beams, in which the regression curves for both beams obtained by the method of least squares are also shown. According to this figure (see **Figure 4(a)**), the size dependency of the shear tension strength became more sensitive due to the drying shrinkage of concrete, and the power of the effective depth(d) for the sealed and the drying beams were -1/4 and -1/3, respectively. The same tendency was also observed in RC beams of W/B of 35% (see **Figure 4(b)**), in which the shear strength depends on $d^{-2/5}$ for sealed beams and $d^{-1/2}$ for drying beams.

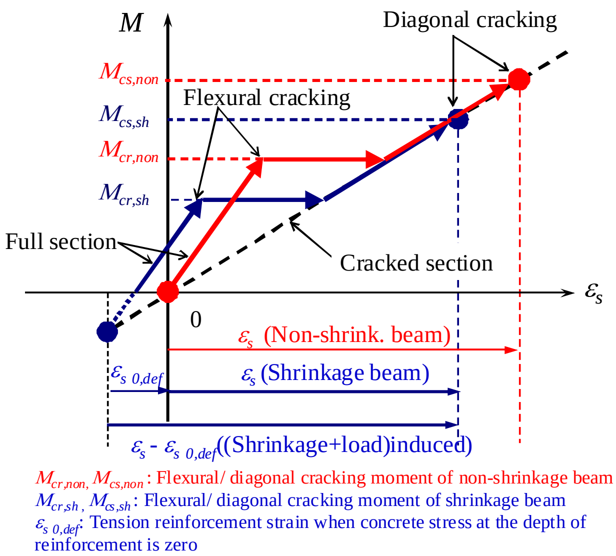


Figure 5: Concept of strain change in tension reinforcement due to drying shrinkage.

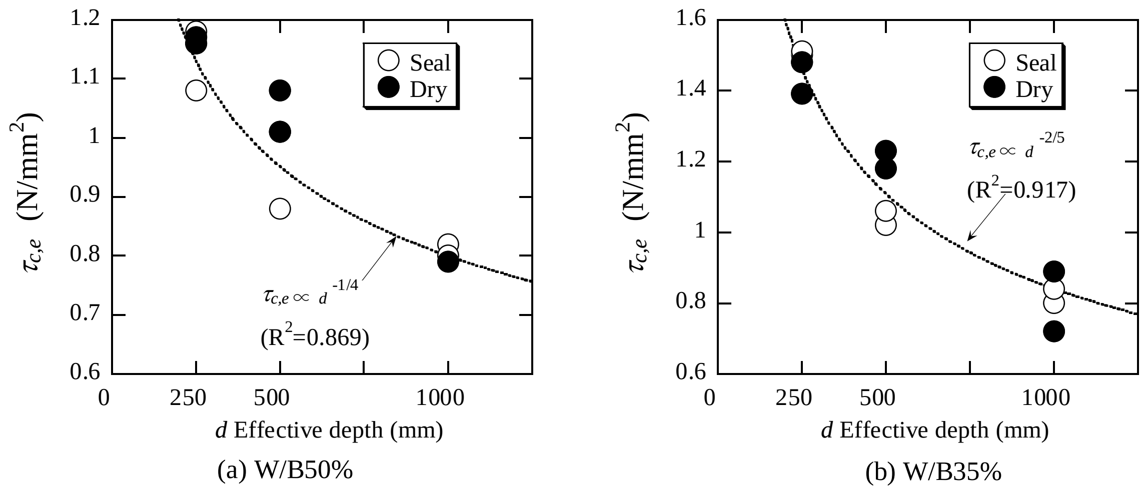


Figure 6: Shear tension strength based on equivalent tension reinforcement ratio.

3.5 A new concept for evaluating shear tension strength

The compression strain in tension reinforcing bars is produced by drying shrinkage before loading, for this reason the magnitude of strain change in drying beam is larger than that of sealed beam, as shown in **Figure 5**, which is a conceptual diagram of strain change of reinforcement before and after loading for both beams. The increase of strain change should be functionally equivalent to the decrease of reinforcement ratio. Based on this hypothesis, a new concept of the equivalent tension reinforcement ratio given by the following Eq.(2) was proposed for estimating the effect of autogenous shrinkage on the shear strength in high-strength concrete beams[2]. This concept is applicable to evaluate shear tension strength of RC beams before yielding of reinforcement. Additionally, a similar concept for predicting flexural crack width and curvature of RC beams considering the concrete shrinkage before loading was already proposed. It was verified that the proposed concept improved the prediction accuracy compared with the conventional equation [4].

$$p_{s,e} = \frac{\varepsilon_s}{\varepsilon_s - \varepsilon_{s0,def}} p_s \tag{2}$$

Where:
$p_{s,e}$: Equivalent tension reinforcement ratio
p_s : Nominal tension reinforcement ratio,
ε_s : Tension reinforcement strain at the section 1.5d (d: effective depth) distant from loading section in shear span at the diagonal cracking,
$\varepsilon_{s0,def}$: Tension reinforcement strain when concrete stress at the depth of reinforcement is zero, which is positive in tension and negative in compression.

Figure 6 shows the relationship between the effective depth and the shear tension strength obtained by Eq.(3) based on the equivalent tension reinforcement, in which the shear strength is assumed to be proportional to 1/3 power of reinforcement ratio in accordance with JSCE design code[5].

$$\tau_{c,e} = \tau_c \times \left(\frac{p_s}{p_{se}} \right)^{1/3} \tag{3}$$

According to this figure, it is found that the concept of the equivalent tension reinforcement ratio is effective in evaluating not only the shear tension strength but also the size dependence independent of the shrinkage effect. The shear strength of RC beams of W/B50% and W/B35% followed to approximately -1/4 and -2/5 power of the effective depth, respectively.

4 CONCLUSIONS

The effects of drying shrinkage on shear tension strength as well as its size effect of reinforced normal strength-high shrinkage concrete beams without web reinforcement were experimentally investigated. The following conclusion can be drawn within the limit of the present study.

(1) The shear tension strength of reinforced concrete beams exposed to drying condition decreased by 17% in case of effective depth(d) of 1000mm compared with that of companion sealed beams.

(2) The size effect of shear tension strength of drying beams became more sensitive than that of sealed beams due to the shrinkage effect, which depended on $d^{-1/4}$ and $d^{-1/3}$ for sealed and drying beams with W/B50%, and $d^{-2/5}$ and $d^{-1/2}$ for those with W/B35%, respectively.

(3) A concept based on equivalent tension reinforcement ratio incorporating the effect of strain change in reinforcement before loading due to shrinkage in concrete was effective in evaluating not only the shear tension strength but also the size dependence independent of the shrinkage effect.

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