

# Effects of Replacement Ratio of Recycled Coarse Aggregate on the Shear Performance of Reinforced Concrete Beams without Shear Reinforcement

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## ABSTRACT

This paper will describe the experimental results on the shear behaviors of reinforced concrete (RC) beam with recycled coarse aggregate (RCA). The primary objective of this research is to evaluate the influences of different RCA replacement percentage (i.e., 0%, 30%, 60%, and 100%) on the shear performance of reinforced concrete beams without shear reinforcement. Eight large-scale RC beams without shear reinforcement were manufactured and tested to shear failure. All had a rectangular cross-section with 400mm width × 600mm depth and 6000mm length, and were tested with a shear span-to-depth of 5.1. The results showed that the deflection and shear strength were little affected by the different RCA replacement percentage. Actual shear strength of each RCA beam was compared with the shear strength predicted using the provisions of ACI 318 code and Zsutty's equation for shear design of RC beams. ACI 318 code predicted the shear strength of RCA reinforced concrete beams well.

**Keywords:** Recycled concrete, Beams, Shear Performance, Recycled coarse aggregates, Shear

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## 1. Introduction

With the increasing desire to improve the quality of life and the concentration of a population in urban areas, many urban development to reconstruct the aged buildings and new town development projects have been actively conducted in Korea during last decades. According to the annual report of 2007 by the Ministry of Environment, the amount of the construction and demolition (C&D) wastes generated in Korea per day has consequently risen from some 47.7 kilotonnes in 1997 to 169 kilotonnes in 2006 shown in Fig. 1(a), with the prediction to increase every year to over 250 kilotonnes in the year 2010. Among all the C&D waste, the occupancy ratio of demolished concrete has also increased from 53.5 percent in 1997 to 78.7 percent in 2006. In the past, almost all the C&D wastes were unlawfully disposed of in landfills. However, the increasing social awareness on environmental preservation and substantial reduction of landfill space have resulted in new disposal, such as the recycling, of C&D waste. The Korean Government strictly prohibits from illegal dumping of C&D waste. In addition to environmental protection and shortage of landfills for the waste

disposal, conservation of the rapidly diminishing natural aggregate resources led to the recycling of C&D waste, especially demolished concrete waste. The reuse of recycled aggregate from demolished concrete is one such an attempt and is one way to solve some of these problems in the construction industries. But almost all the recycled aggregate in Korea was for pavement base or back filling for retaining wall. For effective utilization and increasing recycling of demolished concrete waste, it was necessary to use recycled aggregate for new structural concrete.

In 2005, The Ministry of Construction and Transportation set the quality standard of the recycled aggregate to promote active utilization of the recycled aggregate in the concrete and construction industries by institutionalizing a legislation of bill, where the bill included providing incentives such as easing the building-to-land ratio. In the current standard, it is allowed to use total 60 percent fine or coarse recycled aggregates in proportioning low-grade concrete (specified compressive strength of concrete  $f_{ck} < 21$  MPa) which can be used for non-structural members. In high-grade concrete ( $21 \text{ MPa} \leq f_{ck} \leq 27 \text{ MPa}$ ) which can be used for structural members such as beams and columns, only 30 percent coarse recycled aggregate content is permitted. A standard

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for the quality of recycled aggregate, Korean Industrial Standard (KS) F 2573 “Recycled Aggregate for Concrete”, was enforced in December 2006. As a result of these efforts of authorities, the utilization of recycled aggregate has continuously increased.

Fig. 1(b) shows the trend in the disposal of C&D waste for the period 2000 - 2006. Roughly over 11 percent of the waste is disposed to landfill until 2004, despite its major recycling potential. Fig. 1(b) indicates that after 2005, more than 96 percent of C&D waste is recycled in Korea.

The primary objective of this paper is to investigate the influences of replacement levels of RCA (0%, 30%, 60%, and

100%) on the shear behavior and cracking patterns of reinforced concrete beams without shear reinforcement.

## 2. Research Significance and Objectives

The utilization of recycled aggregate for structural concrete should be essential to promote the recycling of demolished concrete waste and to conserve the non-renewable natural resources. For increasing the reuse of recycled aggregate, the structural behavior of recycled concrete should be investigated by comparing that of conventional concrete. But previous studies on the recycled aggregate concrete were mostly concentrated on the physical and mechanical properties as well as the durability. A few investigations into RAC members such as beams, compressive members, and frames are reported in the literature. Those are not sufficient for making clear behavior of structural members leading to establishing design method and code. These previous studies showed that some mechanical properties of RAC may be generally lower than those of conventional concrete due to higher porosity, lower density, and higher water absorption of recycled aggregate. Especially, the water absorption and density of recycled aggregate have significant effect on the mechanical properties of RAC. But information about the mechanical properties and performance of concrete and members with recycled aggregate fulfilling the standard (KS F 2573) is scarce. The present research aims to explore the shear performance of RCA concrete beams without shear reinforcements. This investigation also provides limited experimental data and examines the applicability of the ACI Building Code shear strength design provision for predicting the strength of reinforced RAC beams.

## 3. Experimental Investigation

Four different concretes were produced with different percentages of recycled coarse aggregates (RCA). The investigation consisted of four point loading tests on eight singly reinforced RAC beams without shear reinforcement. Experimental variable is different RCA replacement percentages (i.e., 0, 30%, 60%, and 100%). A summary of the experimental program is presented in Table 1.

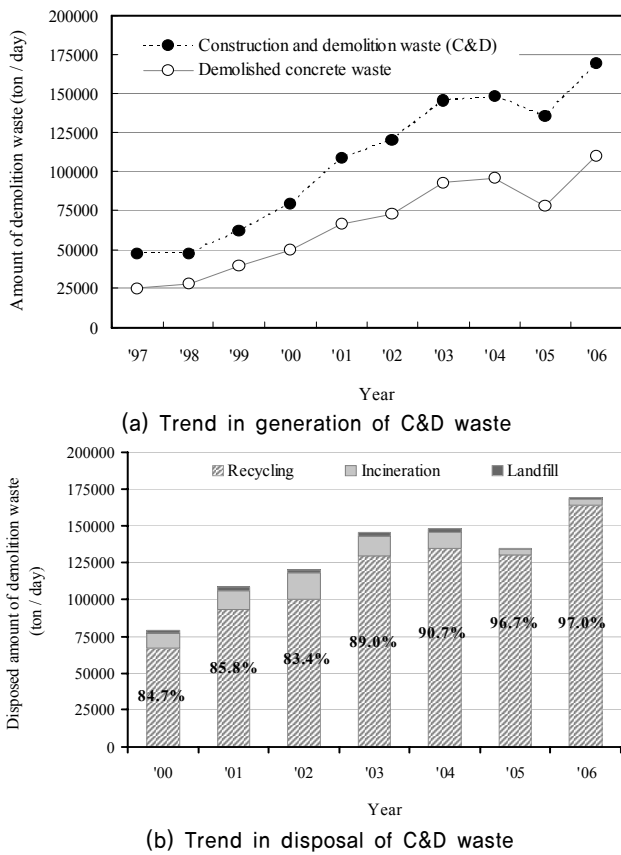


Fig. 1. Trend in generation and disposal of construction and demolition (C&D) waste in Korea

Table 1. Testing program

Beam <sup>a</sup>	<i>B</i> (mm)	<i>D</i> (mm)	<i>l<sub>n</sub></i> (mm)	<i>a/d</i>	<i>f<sub>yt</sub></i> (MPa)	<i>f<sub>cu</sub></i> <sup>b</sup> (MPa)	<i>E<sub>c</sub></i> <sup>c</sup> (MPa)	<i>f<sub>sp</sub></i> <sup>d</sup> (MPa)	Reinforcing bar detail	<i>A<sub>s</sub></i> (mm <sup>2</sup> )	<i>ρ</i>	RCA replacement percentage (%)
S-5-A0	400	525	6,000	5.1	27	37.0	2,416	2.83	8-D25	4,054	0.0193	0
S-5-A30						33.6	2,207	2.52				30
S-5-A60						32.4	2,052	2.67				60
S-5-A100						29.2	2,083	2.65				100

Note: <sup>a</sup> Beam nomenclature: for Beam S-5-A60, “5” indicates shear span-to-depth ratio and “60” indicates the replacement ratio of recycled coarse aggregate.

<sup>b</sup> On cylinders 100 mm × average 200mm, average compressive strength from five specimens at the ages of 28-day after casting.

<sup>c</sup> Average secant elastic modulus from five specimens at the ages of 28-day after casting.

<sup>d</sup> On cylinders 150 mm × 300mm, ge splitting strength from three specimens at the age of 28-day after casting.

### 3.1 Materials

The cement used in all concrete mixes was normal Portland cement corresponding to KS L 5201 (equivalent to ASTM C150:07 Type I), which is commercially available in Korea. The specific gravity and specific surface area of the cement were  $3.15\text{g/cm}^3$  and  $3,630\text{cm}^2/\text{g}$ , respectively.

The fine aggregate used was natural river sand with a fineness modulus of 2.85. The natural coarse aggregate was crushed granite with maximum size of 25mm. The recycled coarse aggregate with maximum size of 20mm was sourced from the demolished concrete obtained from the reconstruction sites at the urban areas and fulfilled the KS F 2573 that have been defined in Table 2. The grain shapes and the physical properties of the coarse aggregate used are presented in Fig. 2 and Table 2.

The longitudinal steel reinforcement consisted of KS D 3504 SD400 deformed bars of 25mm diameter and had yield strength of 433MPa at 0.23% strain. Transverse steel reinforcement was deformed bars of 10mm diameter with yield strength 375MPa at 0.26% strain.

### 3.2 Mix proportions

Four different mix proportions used by ready-mix producers in Korea for concrete with the target designed compressive strength of 27MPa were used. The main difference among these mixtures is the RCA replacement percentage (i.e., the ratio of the RCAs

mass to the mass of all the coarse aggregate), which is 0, 30%, 60%, and 100%, respectively. Table 3 presents the details of the mix proportions. All the coarse aggregates were surface-dry conditions before mixing. The workability of the mixture was improved by using a high-range water-reducing admixture (superplasticizer).

In Table 1, measured concrete compressive strength was based on an average of five cylindrical specimens, 200mm high and 100mm in diameter. The splitting tensile strength was an

Table 2. Physical properties of recycled coarse aggregate

		KS F 2573(3) for RCA	RCA used
Density ( $\text{g/cm}^3$ )		$\geq 2.5$	2.53
Water absorption (%)		$\leq 3.0$	2.99
Abrasion (%)		$\leq 40$	38.0
Fineness modulus		-	2.44
Content of filler ( $< 0.08\text{mm}$ ) (%)		$\leq 1.0$	0.90
Reactivity to alkali		Non-active	Non-active
Content of pieces of mud (%)		$\leq 0.2$	0.18
External contents (%)	Organic materials	$\leq 1.0$ (Volume)	0.95
	Inorganic materials	$\leq 1.0$ (mass)	0.97



(a) Natural coarse aggregate



(b) Recycled coarse aggregate

Fig. 2. Coarse aggregates used in this study

Table 3. Mix proportions of concrete

Mixes	RCA replacement Percentage (%)	$f_{ck}^a$ (MPa)	W/C (%)	S/a (%)	Unit weight ( $\text{kg/m}^3$ )					
					Water	Cement	Sand	Natural Aggregate	Recycled Aggregate	Super Plasticizer
A0	0	27	43.6	46.0	132	392	823	960	0	2.94
A30	30							672	267	
A60	50							394	533	
A100	100							0	888	

Note:  $f_{ck}^a$  : specified compressive strength of concrete

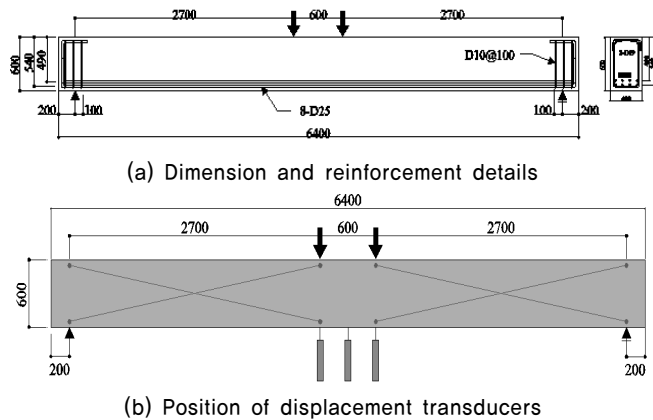


Fig. 3. Configuration and details of beam specimens



Fig. 4. Testing set-up

average of three cylindrical specimens, 300mm high and 150mm in diameter.

### 3.3 Fabrication and curing of specimens

All beams had the same cross section, with 158in. (400mm) width and 207in. (525) effective depth. The shear span was selected as 9ft, which provides a shear span-to-effective depth ratio ( $a/d$ ) of approximately 5.1 as shown in Fig. 3.

The longitudinal steel reinforcements were supported from the bottom form on steel chairs at a height to give an effective depth of 525mm. All the beams were singly reinforced beams with only bottom longitudinal reinforcing bars which consisted of eight D25 (25mm diameter deformed bar). The reinforcement ratio was 1.88%. In order to prevent local shear failure in the supports of the beam, a sufficient amount of stirrups were provided only in the end portions, which were outside the zone of interest.

Eight 6.4m beams were cast in plywood forms. For each mix, two beams were manufactured. After placement in the forms, the concrete was vibrated internally and externally. Test cylinders also were cast from each batch of concrete. When casting was complete, the beams and cylinders were completely wrapped in the polyethylene sheets to prevent moisture loss. The beams and cylinders were stripped of all forms and molds after 24hr and all exposed surface of the beams were covered with saturated towels and again completely wrapped in polyethylene to prevent rapid moisture loss. The average room temperature during curing was approximately 70 °F (21 °C) and a relatively humidity of 95 to 100 percent. All beams were cured as described until a week prior to testing.

### 3.4 Testing procedure

Fig. 4 show the actual test configuration. In order to determine the load-deflection curve, vertical deflection were measured in all beams by means of three linear variable displacement transducers below two loading points and the mid point of beam. To measure the web shear strain, two diagonal dial gauges were mounted on the surface within the shear span of beam.

The beams were simply supported and subjected to a four-point load applied by 1,000kN actuator. The distance between the two-point loads was kept constant at 600mm. The beam vertical deflection and the strains at the top and bottom faces of the beam at its midspan were measured. All beams specimens were supported by very low friction material, i.e., Teflon which was placed between the pin bearing and beam.

Initially, the beam was loaded in increments of 10kN until the load reached 150kN. After the load of 150kN, the loading processes were ruled by the midpoint deflection which increased at a constant rate of approximately 0.2mm per minute without interruption. Also, all macrocracks observed during testing were marked and recorded. After failure, each beam was photographed to show the crack pattern and the mode of failure.

## 4. Results and Discussion

A summary of the test results, including the loads at initial crack, shear crack and ultimate, is presented in Table 4. Discussion of the test results is divided into three sections: (1) cracking pattern and failure mode; (2) load-deflection behavior, and (3) shear strength.

### 4.1 Cracking pattern and failure mode

The typical cracking patterns of the beam specimens at failure are shown in Fig. 5. Similar characteristics are seen in the cracking patterns of beams with different RCA replacement ratios. At loads close to approximately bending moments predicted based on the measured modulus of rupture, flexural cracking originated in the region of pure bending. As the applied load was increased, existing flexural cracks propagated toward compression zone and additional flexural cracks formed between two loading points. Initial crack propagation outside pure bending region is similar to flexural cracking. Inclined cracking then begins due to the present of increasing shear stresses within shear span as the load is increased. As the flexural cracks in the shear span widened, they expanded into flexural-shear cracks. As shown in Fig. 5, the

Table 4. Summary of test results

Beam	$f_{cu}^a$ (MPa)	Equivalent $f_{cu}^b$ (MPa)	Measured shear stress <sup>c</sup> (MPa)				Predicted shear stress (MPa)		
			Initial crack	Inclined crack	Shear strength		ACI 11-3 Eq. (1)	ACI 11-5 Eq. (2)	Zsutty Eq. (3)
					(MPa)	$(1/\sqrt{f_{cu}^b})$			
S-5-A0-1	37.0	35.9	0.14	0.47	1.09	0.18	1.00	1.02	1.11
S-5-A0-2	37.0	35.9	0.16	0.49	1.04	0.17	1.00	1.02	1.11
S-5-A30-1	33.6	32.6	0.12	0.45	1.12	0.20	0.95	0.98	1.08
S-5-A30-2	33.6	32.6	0.14	0.43	1.14	0.20	0.95	0.98	1.08
S-5-A60-1	32.4	31.4	0.16	0.67	0.98	0.17	0.93	0.96	1.07
S-5-A60-2	32.4	31.4	0.10	0.69	0.98	0.17	0.93	0.96	1.07
S-5-A100-1	29.2	28.3	0.15	0.61	0.98	0.18	0.88	0.90	1.03
S-5-A100-2	29.2	28.3	0.14	0.63	1.04	0.20	0.88	0.90	1.03

Note: <sup>a</sup> From  $100 \times 200$ mm cylinders

<sup>b</sup> Using equivalent  $150 \times 300$ mm cylinder strength, assumed to be 97 percent of  $100 \times 200$ mm strength.

<sup>c</sup> A half of the load measured by the load cell of actuator because all beam were subjected to a two point loads.

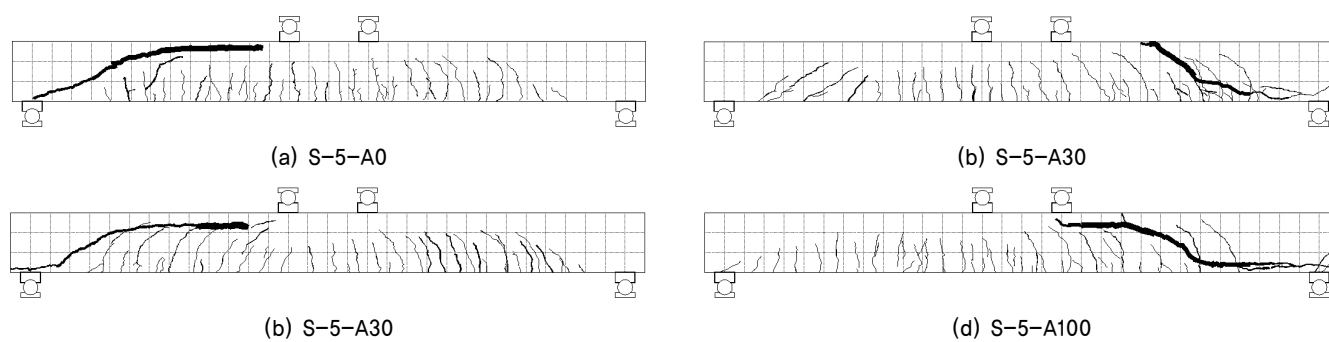


Fig. 5. Typical crack pattern of beams

formation of shear cracks is evident in the load deflection curves, as seen by the jump in deflection at these load points. This phenomenon was pointed out by Frosch. The crack widths of the shear cracks increased with further increases in load. All beam specimens failed suddenly in shear with a primary shear crack that propagated immediately in two directions (i.e., toward the loading point in the compression zone and toward the support along the longitudinal reinforcement) and crushing of the compression zone at the location of the loading point. Following failure, splitting cracks were evident along the bottom longitudinal reinforcement, especially in RCA concrete beams as reported by Belén and Fernando. Failures become more sudden and explosive as the RCA replacement percentage increases.

#### 4.2 Load–deflection behavior

The midspan deflection curves for the beam specimens with beams with different RCA replacement percentages (0, 30%, 60%, and 100%) are shown in Fig. 6(a) through (d), respectively. For each mix, twin beams present the shear behavior similar to each other.

#### 4.3 Shear strength

The test results were used to verify the applicability of RCA

concrete beams to the ACI Building Code and Zsutty's proposed equation pertaining to shear strength design. Fig. 7 presents the measured test results and four predicted values of shear capacity expressed in terms of shear stress  $V/bd$ . The shear stress and concrete strength are in units of MPa.

The ACI Building Code contains two equations for the shear strength of beams without stirrups under only shear and flexure, ACI code Eq. (11-3).

$$V_c = \frac{1}{6} \lambda \sqrt{f'_c} b_w d \quad (1)$$

and Eq. (11-5)

$$V_c = \left( 0.16 \lambda \sqrt{f'_c} + 17.6 \rho \frac{V_u d}{M_u} \right) b_w d \quad (2)$$

Zsutty equation

$$V_c = 2.1746 \left( f'_c \rho \frac{d}{a} \right)^{\frac{1}{3}} b_w d \quad (3)$$

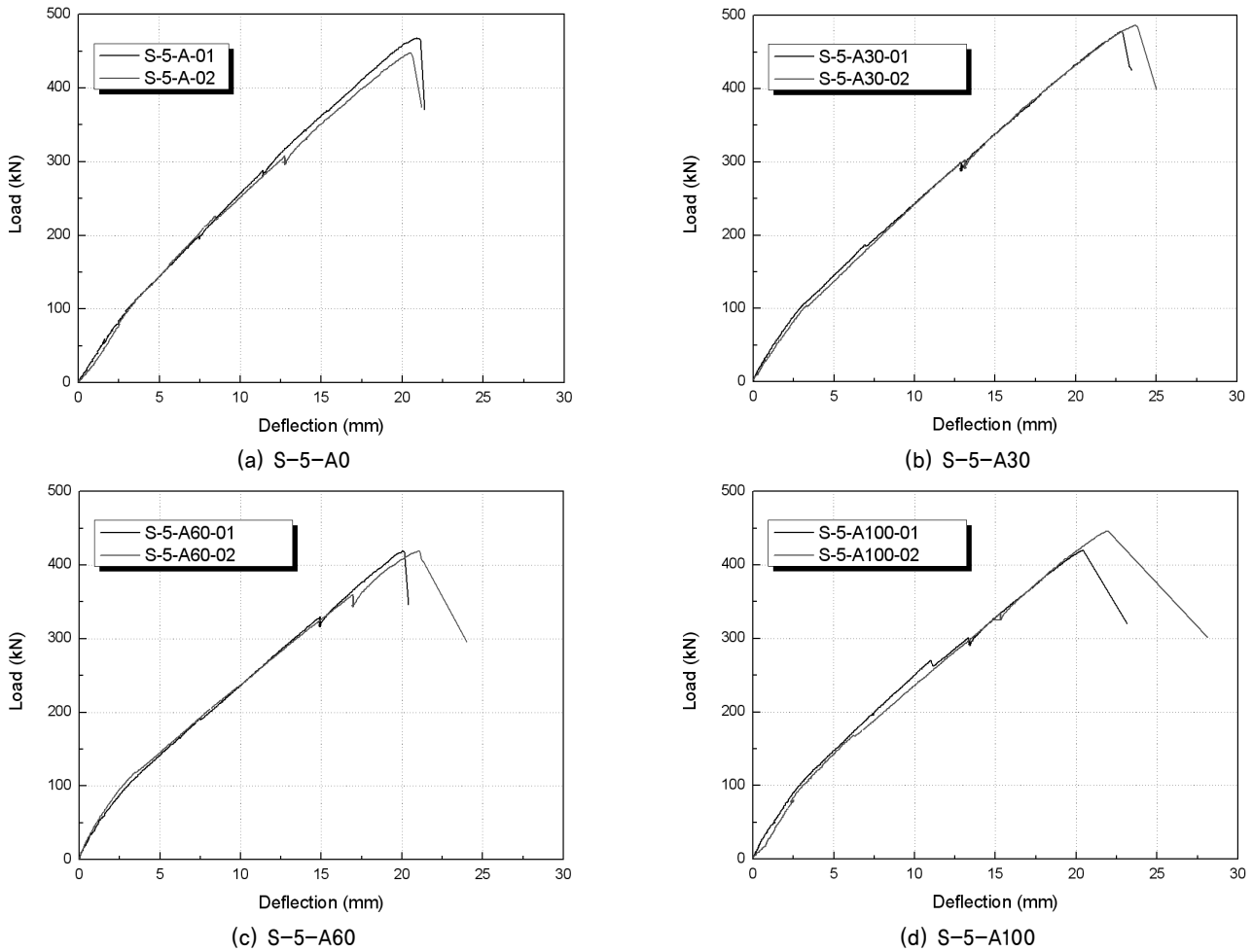


Fig. 6. Load-midspan deflection for all beam specimens

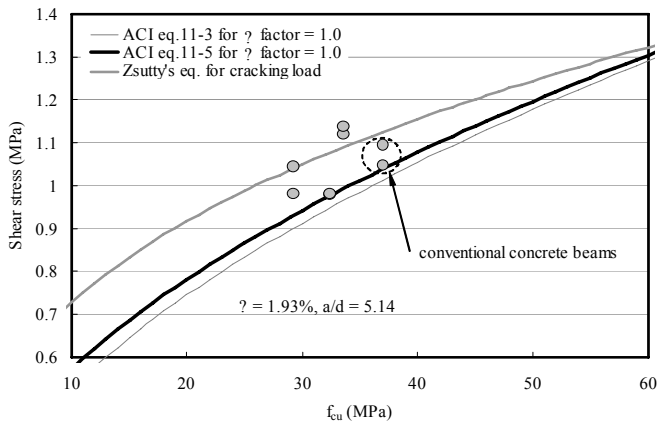


Fig. 7. Test results compared to ACI code and Zsutty's Equation

These equations are based on beam tests with relatively low strength concrete. Although the ACI code states that Eq. (11-3) and (11-5) define nominal, i.e., ultimate, concrete shear strength, the equations are based on the shear causing a primary inclined crack. In equations (1) and (2), factor  $\lambda$  reflects the lower tensile strength of lightweight concrete. Two alternative procedures are

provided to determine  $\lambda$ . The first alternative is to apply 0.85 and 0.75 for sand-lightweight concrete and all-lightweight concrete as  $\lambda$  factor, respectively. The second alternative is based on the laboratory tests. If average splitting tensile strength of lightweight concrete,  $f_{sp}$ , is specified  $\lambda = f_{sp}/(6.7\sqrt{f_{ck}}) \leq 1.0$ . For above two cases, factor  $\lambda$  of normal weight concrete is 1.0.  $f'_c$  is the concrete compressive strength in MPa.  $\rho$  is tensile reinforcement ratio.  $a$  and  $d$  are shear span and effective depth, respectively.

Measuring the inclined cracking load in beam tests is not easy and not simple because the load is affected by observer's judgment and its definition and is also sensitive to the actual location of the initiating flexural crack. For beams without stirrups with higher  $a/d$ , the ultimate shear capacity slightly exceeded or is approximately equal to the inclined cracking load as expected due to beam action. In this study, inclined cracking load was defined as the ultimate shear capacity.

As shown in Fig. 7, the shear strength developed in these beams with different RCA replacement percentages was higher than that computed according to the ACI code while Zsutty's proposed equation underestimated for a half of specimens.

## 5. Conclusions

This paper presented the test results on the shear performance of large-scale reinforced concrete beams without stirrups and with different replacement levels of RCA satisfied with Korea Standard on the recycled aggregate for concrete. Within the scope of this study, the following conclusions may be summarized as follows,

1. RCA concrete beams shows the same cracking patterns and failure mode as those of conventional concrete beams. Shear failure was more abrupt and explosive for RCA concrete beams.
2. The shear strength developed in RCA concrete beams ranged from  $0.17\sqrt{f_{cu}}$  to  $0.20\sqrt{f_{cu}}$ , while the average shear strength of conventional concrete beams was  $0.17\sqrt{f_{cu}}$ .
3. The ACI code approach to shear design was conservative for all beams without stirrups, regardless of RCA replacement percentages.

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