論文 Shear Tests on Reinforced Lightweight Aggregate Concrete Beams without Web Reinforcement

Worapatt RITTHICHAUY[*1], Takafumi SUGIYAMA[*2], Tomokazu OKAMOTO[*1] and Yukikazu TSUJI[*3]

ABSTRACT: The results of comparative shear tests are reported on reinforced concrete beams without web reinforcement made with lightweight aggregate of different oven dry densities ranging from 0.85 to 1.87 g/cm^3. It is shown that diagonal cracking loads became lower with equal shear span to depth ratio and tensile steel ratio as the density of aggregates reduced. The shear strength of these beams was calculated by Niwa's equation where a 70% reduction factor was applied constant for every lightweight aggregate concrete beam according to JSCE code. For comparison Walraven's equation was used to take into account the degree of the reduction in dry unit weight of concrete.
KEYWORDS: reinforced concrete beam, lightweight aggregate, shear strength of beam, diagonal cracking load, shear failure mode

1. INTRODUCTION

The problem of shear behavior and shear strength of reinforced concrete beams without web reinforcement has been perplexing researchers for many years. There were many researchers and predicting equations for this complex problem. As the results from many experimental studies on the shear property in reinforced concrete beam without web reinforcement, it has been expected that the shear strength of beam should be related to many factors such as; type of aggregate, compressive strength of concrete, shear span to depth ratio, tensile steel ratio, depth of beam's section, etc. In case of reinforced lightweight aggregate concrete beams without web reinforcement, JSCE code recommends that a constant 70% reduction factor be multiplied to calculate the shear strength of concrete beam regardless of the dry unit weight of concrete [1]. Recently, Walraven [2] has proposed a shear strength equation where a reduction factor for the tensile strength of lightweight concrete (η_1) that is a function of dry unit weight of concrete is used. It also appears rational to change a shear strength reduction factor with different types of lightweight aggregate and/or dry unit weight of concrete [3].

The purpose of present research is to study the shear strength properties of reinforced lightweight aggregate concrete beams without web reinforcement. The effect of using lightweight coarse aggregate of different oven dry densities ranging from 0.85 to 1.87 g/cm^3 is mainly concerned on the shear strength of the beam. Total 18 reinforced concrete beams without web reinforcement of 1.3 m span length were made using 4 types of lightweight coarse aggregate and one normal coarse aggregate type. In this experiment, the shear span to depth ratios (a/d) were 2.12 and 3.03 and the tensile steel ratios (ρ_s) were 1.6% and 3.5% as other concerning variables.

*1 Department of Civil Engineering, Gunma University, Graduate student, Member of JCI
*2 Department of Civil Engineering, Gunma University, Associate professor, Ph.D., Member of JCI
*3 Department of Civil Engineering, Gunma University, Professor, Dr.E., Member of JCI

2. EXPERIMENTAL DETAILS

2.1 MATERIALS

The raw material, density and 24 hours water absorption for each type of coarse aggregate are shown in **Table 1**. Maximum size for all aggregates is 15 mm. Super lightweight aggregates were mixed in dry condition. Meanwhile, other aggregates were mixed in saturated surface-dry condition.

Table 1. Properties of used aggregate

Symbol	Density (g/cm^3)	Water absorption 24 hrs, (%)	Raw material	Type of aggregate
ASL	0.85 (Dry)	4.66	Pearl	Super lightweight aggregate
SML	0.92 (Dry)	10.5	Expanded shale	
ML	1.62 (SSD)	26.9	Expanded shale	Normal lightweight aggregate
TL	1.92 (SSD)	2.93	Fly ash	High strength lightweight aggregate
NA	2.88 (SSD)	0.67	Crushed gravel	Normal gravel aggregate

2.2 MIX PROPORTION

The mix proportion for concrete used in this experiment is shown in **Table 2**. The bulk volume of coarse aggregate for every mix was kept constant at 360 liters per 1 m^3 of concrete. For every mix sand of a normal density of 2.66 g/cm^3 and a water absorption of 1.93% is used as fine aggregate. Superplasticiser with air entraining and high-range water reducing effects is used. The design compressive strength of every mix is 40 N/mm^2.

Table 2. Mix proportion of concrete

Aggregate type	W/C (%)	s/a (%)	Unit weight of materials (kg/m^3)				SP (Cx%)
			W	C	S	G	
ASL	31	40	174	558	639	306	1.5
SML	28	38	173	613	595	331	1.8
ML	49	47	168	342	833	584	1.2
TL	59	48	165	281	894	691	1.2
NA	59	48	165	281	893	1034	1.3

2.3 SPECIMEN'S DETAIL

The detail of beam specimen is shown in **Fig.1**. The shear span length (a) for this experiment was classified in 2 types: a = 350 mm and 500 mm for a/d = 2.12 and 3.03, respectively. The steel ratio (ρ_s) was also classified in 2 types: ρ_s = 3.5% and 1.6%, by using of D19@3 and D16@2, respectively. Therefore, 18 reinforced concrete beams without web reinforcement as classified in **Table 3** were cast. After stripped in 24 hours, every beam was cured in 20°C water for a 28-days. This was done to prevent the lightweight aggregate concrete from drying shrinkage that might reduce the tensile strength of concrete and hence shear experiments were performed on saturated beam conditions.

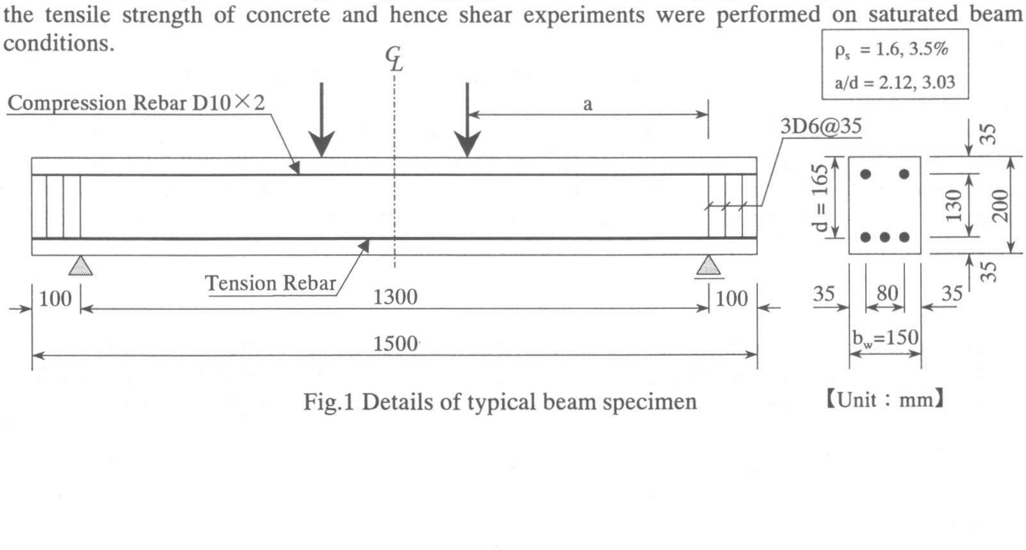


Fig.1 Details of typical beam specimen 【Unit : mm】

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 OUTLINE OF TEST RESUTLS

The classification of beam specimens as well as the experimental results such as; flexural cracking load, diagonal cracking load, maximum load and the mode of failure for each beam are shown in **Table 3**. The compressive strength and dry unit weight of each beam are also shown in this table. However, some beams showed lower compressive strength than 40 N/mm^2.

Table 3. Outline of beams and test results

Specimen	Dry unit weight (kg/m^3)	f'_c (N/mm^2)	a/d	Steel ratio (%)	Flexural cracking load (kN)	Diagonal cracking load (kN)	Maximum load (kN)	Mode of failure
ASL1	1673	40.5	2.12	3.5	55.0	96.0	232.0	Compression shear
ASL2	1661	40.3	3.03		28.9	58.6	93.4	Compression shear
ASL3	1597	32.6	2.12	1.6	8.3	58.3	100.7	Compression shear
ASL4	1563	37.5	3.03		5.6	49.8	57.1	Diagonal tension
SML1	1742	44.8	2.12	3.5	45.6	87.7	151.5	Compression shear
SML2	1682	41.9	2.12	1.6	8.0	51.0	140.3	Compression shear
ML1	1821	40.4	2.12	3.5	42.6	99.4	207.2	Compression shear
ML2	1865	41.0	3.03		28.4	65.5	111.5	Compression shear
ML3	1823	39.3	2.12	1.6	23.5	63.2	71.2	Diagonal tension
ML4	1859	42.7	3.03		12.2	66.1	82.0	Diagonal tension
TL1	1968	42.7	2.12	3.5	28.6	103.0	244.1	Compression shear
TL2	1968	43.9	3.03		18.6	78.4	82.6	Compression shear
TL3	1997	50.3	2.12	1.6	21.4	84.0	169.2	Flexure + shear※
TL4	1993	51.0	3.03		13.7	70.0	74.0	Diagonal tension
NA1	2431	51.5	2.12	3.5	28.2	120.0	250.2	Compression shear
NA2	2457	52.2	3.03		24.0	110.0	127.0	Compression shear
NA3	2424	52.2	2.12	1.6	23.5	104.0	179.6	Flexure + shear※
NA4	2414	52.8	3.03		17.8	83.3	87.0	Diagonal tension

※Load at tensile steels yield are 164.3 kN and 166.4 kN for TL3 and NA3, respectively.

Table 4. Results of flexural cracking load

Specimen	f_t (N/mm^2)	Flexural cracking load (kN) Exp	Flexural cracking load (kN) Cal	Exp/Cal	Average
ASL1	2.38	55.0	15.8	3.48	2.94
ASL2	2.55	28.9	12.0	2.41	
ASL3	1.65	8.3	10.9	0.76	0.71
ASL4	1.83	5.6	8.4	0.67	
SML1	2.82	45.6	18.5	2.47	2.47
SML2	2.23	8.0	14.6	0.55	0.55
ML1	2.64	42.6	17.6	2.42	2.38
ML2	2.61	28.4	12.1	2.35	
ML3	2.67	23.5	17.3	1.36	1.16
ML4	2.77	12.2	12.5	0.97	
TL1	2.53	28.6	16.3	1.76	1.60
TL2	2.88	18.6	13.0	1.43	
TL3	3.28	21.4	20.5	1.04	1.04
TL4	3.01	13.7	13.1	1.04	
NA1	3.42	28.2	21.3	1.32	1.39
NA2	3.76	24.0	16.4	1.46	
NA3	3.56	23.5	21.8	1.08	1.07
NA4	3.88	17.8	16.6	1.07	

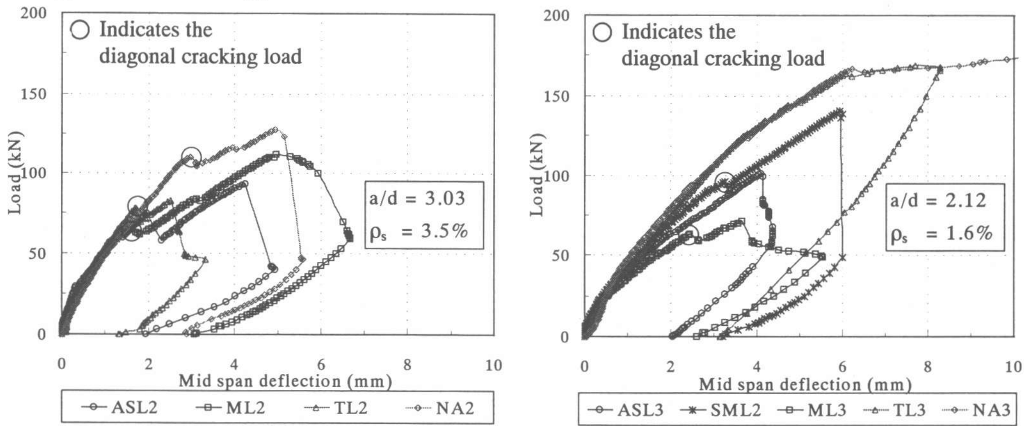
3.2 FLEXURAL CRACKING LOAD

In this experiment, flexural cracking load was determined graphically from the curves of load-concrete's tensile strain on the tension fiber. At this load, we can see clearly that the tensile strain of concrete suddenly changed exceeding about 200μ. The test results for all beams were shown in **Table 4** where the concrete tensile strength that was determined by the splitting tensile test is also shown. The flexural cracking loads were also calculated by the theory of elasticity of beam including the effect of the tensile steel and the concrete tensile strength. The results showed that, for the same a/d, flexural cracking load of beams with 3.5% steel ratio were higher than beams with 1.6%, because of high moment of inertia in higher steel ratio's section.

We can also see that the flexural cracking load in ASL, SML and ML for ρ_s=3.5% tends to be higher than those of beams with TL and NA although the tensile strengths of these lightweight concretes give lower values. However, for a lower steel ratio of 1.6%, super lightweight concretes provide poor flexural cracking behavior. At present, there is no apparent reason regarding the different characteristics observed on the super lightweight concrete beams between the steel ratios of 3.5% and 1.6%.

3.3 DIAGONAL CRACKING LOAD

After flexural cracks occurred in the central portion of the beam the other flexural cracks were originated vertically from the bottom surface in shear span as the applied load was increased. Then these cracks gradually inclined to the applied load point. Initial diagonal crack eventually developed suddenly and became wider than other cracks. The diagonal cracking load was determined from load-mid span deflection curves at the first point that load was suddenly decreased, as shown by circle mark in **Fig.2 (a)** and **(b)**. However, this point cannot be seen obviously in some beams such as in TL3 and NA3. Therefore, eye-observation for diagonal cracking load was also practically used during the test was being performed.



(a) (b)

Fig.2 Load – mid span deflection of beams

As given in **Table 3**, the diagonal cracking load of beam specimen with ASL is higher than that with SML with equal shear span to depth ratio and steel ratio although the dry unit weight and tensile strength of ASL are lower than those of SML. In the point of view in aggregate itself, ASL aggregate surface is seemed to be harder and neatly manufactured than SML's that may result in higher diagonal cracking load. However, the diagonal cracking load of beam specimens with ASL, ML and TL became larger with the increased dry unit weight for equal a/d and steel ratio. This is because of slightly higher compressive strength and hence higher tensile strength in these lightweight aggregate concretes. In comparison of normal concrete with TL concrete the diagonal cracking load is always higher for NA concrete than that of TL concrete regardless of similar compressive strength but slightly higher tensile strength. In addition, better aggregate interlocking in NA concrete has a beneficial effect on the shear behavior.

In **Fig.3**, the ratio of experimental value of diagonal cracking load to calculated one by Niwa's [1,4] Eq.1 and Walraven's [2] Eq.2 ($V_{exp\ dia}/V_{cal}$) is shown with the dry unit weight of concrete. The diagonal cracking load and dry unit weight of concrete is an average value among 4 beams for each type of concrete with ASL, ML, TL and NA but 2 beams with SML in **Table 3**. The ratio using Eq.1 without the 70% reduction factor is lower than 1.0 for ASL, SML, ML and TL where the lower dry unit weight the lower ratio. Beam specimen of NA concrete exhibits good correlation $V_{exp\ dia}/V_{cal}$ ratio being higher than and close to 1.0. However when the 70% reduction factor was multiplied to Eq.1 for beams with ASL, SML, ML and TL these $V_{exp\ dia}/V_{cal}$ ratios increased although beam with TL resulted in underestimating the diagonal cracking load.

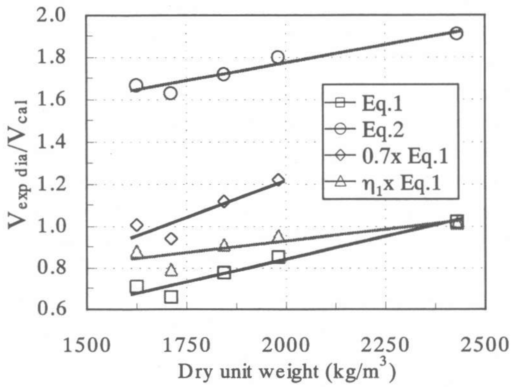


Fig.3 $V_{exp\ dia}/V_{cal}$ of diagonal cracking load-Dry unit weight of concrete

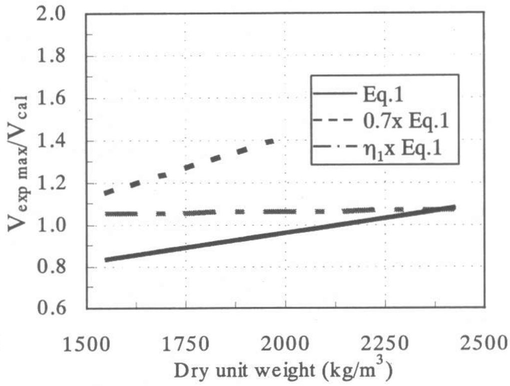


Fig.4 $V_{exp\ max}/V_{cal}$ of maximum load-Dry unit weight of concrete

The $V_{exp\ dia}/V_{cal}$ ratio with Eq.2 resulted in much higher than 1.0 for every beam specimen. In Eq.2 the reduction factor of tensile strength (η_1) expressed in Eq.3 is included and therefore the decreased tensile strength and/or the dry unit weight of concrete was taken into account in the shear strength calculation. Since V_{cal} with Eq.2 appeared to underestimate the diagonal cracking load for these beams, η_1 was multiplied to Eq.1 to replace the 70% reduction factor. The result of the calculation in **Fig.3** shows lower $V_{exp\ dia}/V_{cal}$ ratio than by using Eq.1 with the 70% reduction factor. In addition, the $V_{exp\ dia}/V_{cal}$ ratios calculated by η_1 x Eq.1 of ML and TL beam specimens seem to become closer to 1.0 than those calculated by 0.7 x Eq.1. We can see that the diagonal cracking load should also depend on the dry unit weight of concrete. In other words, the application of a reduction factor of 70% regardless of the dry unit weight of concrete may not provide rational result for some reinforced lightweight aggregate concrete beams without web reinforcement.

$$V_c = [0.2f'_c{}^{1/3}(1/d)^{1/4}(100\rho_s)^{1/3}(0.75+1.4/(a/d))]b_wd \quad \text{: Niwa's [1,4]} \quad (1)$$

$$V_c = [0.12\eta_1k(100\rho_sf'_c)^{1/3}-0.15\sigma_{cd}]b_wd \quad \text{: Walraven's [2]} \quad (2)$$

$$\eta_1 = 0.4 + 0.6\rho/2400 \quad \text{: Walraven's [2]} \quad (3)$$

where, f'_c: compressive strength of concrete (N/mm^2), ρ_s: tensile steel ratio (%), d: effective depth of the section (mm), b_w: breadth of the web section (mm), a: shear span length of beam (mm), ρ: oven dry unit weight of concrete (kg/m^3), k: the size factor = $1 + (200/d)^{1/3} \leqq 2.0$ and σ_{cd}: average longitudinal prestress in the section (N/mm^2).

3.4 FAILURE OF BEAMS

Failure loads and failure modes are also given in **Table 3**. A beam specimen was judged to fail in **diagonal tension failure** when the maximum load reached as soon as a large diagonal crack occurred although the maximum load was higher than the diagonal cracking load by 5 to 20%. As a whole the diagonal tension failure was observed in beams of an a/d of 3.03 and a ρ_s of 1.6%. In these beams, the ratios of the experimental maximum load to the calculated shear strength for the diagonal tension failure using Eq.1 and Eq.3 ($V_{exp\ max}/V_{cal}$) is shown in **Fig.4** with the dry unit weight of concrete. Each line is a regression line representing the ratio $V_{exp\ max}/V_{cal}$ for beam specimen with ASL, ML, TL and NA. The beam specimen with ML behaved erroneously after the formation of diagonal crack resulting in somewhat higher maximum load.

The combination of using Eq.1 multiplied by η_1 in Eq.3 demonstrates better approximation for the maximum load where the ratio ($V_{exp\ max}/V_{cal}$) is closer to 1.0 irrespective of the dry unit weight of concrete. On the contrary, the Eq.1 with the 70% reduction factor applied constant for lightweight concrete beams underestimates the maximum load and its effect becomes more acknowledged for increased concrete's dry unit weight as shown in **Fig.4**. Therefore for the maximum load for beam specimens failed in diagonal tension failure, the use of the Eq.3 that is a function of the dry unit weight of concrete is more rational than a constant reduction factor of 70%.

Most of beam specimens were judged to fail in **compression shear failure** where the steel bar never yielded. The maximum load was twice as high as the diagonal cracking load. The reason for this might be related to the arch action for a smaller a/d of 2.12 and large dowel action for a larger steel ratio of 3.5%. With these effects it seems to be difficult to evaluate the shear behavior of beam specimen with lightweight aggregate concrete after the formation of diagonal crack. Beam specimens with normal weight aggregate always exhibited the largest maximum load with equal a/d and steel ratio. This may be explained due partially to the larger compressive strength and hence larger tensile strength and bond strength with reinforcing bar for the normal weight aggregate concrete.

Typical crack pattern for beam specimens are shown in **Fig.5**. The numbers of flexural cracks on beam specimens were also observed. We found that the distribution of flexural cracks in all of lightweight aggregate concrete beams were almost similar to that of NA beams. However, the width of diagonal crack appeared in beam specimen with ASL, SML and ML became wider than beam with TL and NA. The reason for this might be related to the strength of aggregate that should be higher for TL and NA. Therefore, diagonal crack did not occurred through aggregate particle but passed along the interface between aggregate and mortar that made the diagonal crack became narrow.

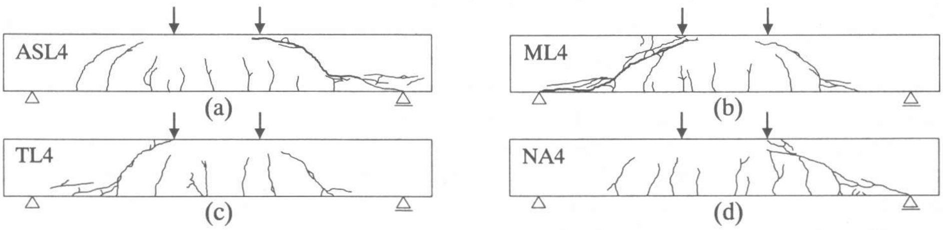


Fig.5 Typical crack pattern of beam specimens (a/d=3.03 and ρ_s=1.6%) after failure

4. CONCLUSIONS

1) Shear strength of reinforced lightweight aggregate concrete beam without web reinforcement increased when the dry unit weight of concrete increased. In other words, the shear strength depended on the dry unit weight of concrete. Therefore current JSCE code with the 70% reduction factor for the shear strength of lightweight concrete beam should be changed according to the dry unit weight of lightweight aggregate concrete.
2) Within the range of the present research, the diagonal cracking load for lightweight concrete beam with TL was well-predicted by using Eq.1 and η_1, tensile strength reduction factor instead of a 70% constant reduction factor. In addition, in the prediction of the maximum load for beams that failed by diagonal tension failure, the combination of using Eq.1 and η_1 provided better results.

REFERENCES

1. S.MAEHORI, S.TAMURA, J.NIWA and T.OKAMOTO, "Shear Resistance of Large Scale PC Beams Using Super Lightweight Aggregates", Proceedings of JCI Symposium on High Performance Structural Lightweight Concrete, Aug.2000, pp.95-100.
2. Joost Walraven, "Design of Structures With Lightweight Concrete: Present Status of Revision of EC-2" Delft University of Technology Convenor of Project Team for EC-2, pp.57-70.
3. J.NIWA, T.OKAMOTO and S.MAEHORI, "Application of Super Lightweight Aggregates to Concrete Structures" JCI Concrete Journal, Vol.38, No.12, Dec.2000, pp.3-9.
4. J.NIWA, K.YAMADA, K.YOKOZAWA and H.OKAMURA, "Revaluation of The Equation for Shear Strength of Reinforced Concrete Beams Without Web Reinforcement" Concrete Library of JSCE No.9, June 1987, pp.65-84.