Size Effect in Shear Failure of Reinforced Concrete Beams with Recycled Aggregate

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Abstract

This study evaluates the size effect of shear strength in reinforced concrete (RC) beams with various replacement ratios of recycled coarse aggregate. A total of 15 simply supported specimens with recycled aggregates were cast and tested in shear. The test variables were designed to be the width and effective depth of the beam and the replacement ratio of recycled coarse aggregate. The width of the specimens was varied from 200 mm to 400 mm, and the effective depth was changed from 300 mm to 600 mm. To estimate the size effect of shear strength in recycled aggregate concrete beams, the specimens had no shear reinforcement. The experimental results showed that the shear strength of the specimens made of recycled aggregate decreased with a higher effective depth irrespective of the replacement ratio, whereas the beam width exhibited no size effect. Furthermore, the strength reduction and crack patterns of the specimens with recycled aggregates were similar to those of the specimens with natural aggregates.

Keywords: recycled aggregate; shear strength; size effect; RC beams

1. Introduction

Because of indiscriminate development worldwide today, there are many deteriorated reinforced concrete (RC) structures that are waiting to be demolished. The demolition of such structures produces a large quantity of construction waste, which accounts for approximately 50% of total industrial waste, leading to serious environmental problems. Therefore, research on the recycling of construction wastes is necessary to solve these problems.

Recently, some research (Katz 2004; Morohashi et al. 2007; Fathifazl et al. 2009) has been conducted on the recycled aggregate obtained from waste concrete, which accounts for a large proportion of construction waste. In particular, countries with a lack of aggregates have been conducting studies in this field with the goal of using these recycled aggregates in structural concrete. However, most of these studies have been conducted from a material point of view or with the member size reduced to a lab-scale level.

The recent trend has been to increase the height and size of buildings, which has resulted in an increase in the size of structural members. Generally, an increase in the size of the concrete leads to reduced strength.

The size effect in shear strength of RC beams was first confirmed in an experiment performed by Kani (1967). Since then, some researchers (Bazant and Kim 1984; Collins and Kuchma 1999; Sneed and Ramirez 2010) have reported that a higher effective depth of the beam produces a lower shear strength and that the ACI shear equation could overestimate the shear strength of RC beams as their effective depths increased.

In this study, the size effect in the shear strength of RC beams with recycled aggregates was evaluated experimentally to estimate the applicability of the recycled aggregates in structural members. The results obtained from this study, that verifies the size effect in shear strength according to the replacement ratio of the recycled aggregate, will be important basic data for the application of recycled aggregate to actual RC members.

2. Experimental Program

2.1 Materials

A maximum aggregate size of 25 mm was used for both the natural and recycled coarse aggregates used in this study. The natural and recycled coarse aggregates had water absorption values of 0.68% and 1.67%, respectively, and their specific gravities under an absolute dry condition were 2.64 and 2.57, respectively. Washed sand was used as a fine aggregate, with a specific gravity of 0.64 under an absolute dry condition.

The design strength of the concrete used in this study was 30 MPa, as listed in Table 1. All of the specimens
and their concrete cylinders were moist cured for 7 days and, after formwork removal, were stored in the laboratory.

The test for compressive strength of concrete was conducted at the time of the parent specimen test. The results showed that the natural aggregate concrete had a compressive strength of 31.8 MPa, whereas the compressive strengths of the recycled aggregate concrete with replacement ratios of 50% and 100% were 32.4 MPa and 34.9 MPa, respectively. The stress versus strain relationships of the concrete are shown in Fig.1.(a).

Three types of reinforcements, D10 (71.3 mm²), D19 (286.5 mm²), and D22 (387.1 mm²), were used in this test. The mechanical properties of the tension, compression, and shear steel bars are summarized in Table 2. The D10 steel bar, which had a yield strength of 346.9 MPa, was used for shear reinforcement. D19 and D22 had yield strengths of 529.0 MPa and 651.2 MPa for tension reinforcement, respectively, and 489.9 MPa and 464.2 MPa for compression reinforcement, respectively. The stress versus strain relationships of the reinforcements are shown in Fig.1.(b).

2.2 Specimen Details and Test Setup

To evaluate the size effect of reinforced recycled aggregate concrete beams in shear, a total of 15 specimens with various aggregate types, beam widths, and effective depths were designed in this study, as shown in Fig.2. and Table 3. The test specimens can be classified into three types according to the aggregate used: NA-series (natural coarse aggregates only), RH-series (50% recycled coarse aggregates), and RF-series (100% recycled coarse aggregates) specimens. The width of the specimens varied from 200 mm to 400 mm.

Table 1. Mixture Proportions of Concrete

| Mix types | Design strength (MPa) | W/C (%) | Water | Cement | Aggregate | Air Entraining agent |
|-----------|-----------------------|---------|-------|--------|-----------|---------------------|
| NA        | 30                    | 45.8    | 181   | 209    | 802       | 905                 |
| RH        | 45.8                  | 177     | 209   | 778    | 905       | 2.73                |
| RF        | 44.8                  | 177     | 209   | 783    | 911       | 2.73                |

Table 2. Mechanical Properties of Reinforcing Bars

| Reinforcements | $f_y$ (MPa) | $f_u$ (MPa) | $E_s$ (GPa) | $\varepsilon_y$ |
|----------------|-------------|-------------|-------------|-----------------|
| Tension        |             |             |             |                 |
| D19            | 529.0       | 604.3       | 190         | 0.0026          |
| D22            | 651.2       | 777.8       | 193         | 0.0035          |
| Compression    |             |             |             |                 |
| D19            | 489.9       | 588.0       | 189         | 0.0026          |
| D22            | 464.2       | 567.2       | 187         | 0.0025          |
| Shear          |             |             |             |                 |
| D10            | 346.9       | 465.6       | 167         | 0.0020          |

Fig. 2. Dimensions and Reinforcement Details of Specimens

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mm, and their effective depths were 300 mm (S-series), 450 mm (M-series), and 600 mm (L-series).

As shown in Fig.2., the specimens had a shear span-to-depth ratio of 2.5 to obtain the dominant influence of shear. To induce shear failure on one side, the test region of each specimen was designed to have no shear reinforcement, whereas the other regions were reinforced in shear using the D10 steel bars. A tension reinforcement ratio of 1.9% was utilized in all the specimens to prevent flexural yielding prior to shear failure. The compression reinforcement was designed to have a value that was approximately 50% of the tension reinforcement.

Strain gauges were attached to the tension, compression, and shear reinforcements to measure the deformation of the specimens, as seen in Fig.2. To estimate the change of the neutral axis and concrete crushing at the section with maximum bending moment, strain gauges were attached to the concrete subjected to compression at the mid-span of the specimen, as shown in Fig.3.

The test setup of the specimens is shown in Fig.3. The specimens were designed to be simply supported beams subjected to four-point loading. As shown in Fig.3., load cells were installed on both sides of the support. Two linear variable differential transducers (LVDTs) were installed on the bottom surface located at the mid-span of the specimens. A monotonic load was applied to each specimen using a universal testing machine (UTM) that had a load capacity of 2,000 kN until the applied load dropped to approximately 80% of the maximum load in the post-peak descending branch.

3. Experimental Results and Discussion

3.1 Shear Force Versus Displacement Relationships

The shear force versus displacement relationships of the specimens measured in this test are summarized in Fig.4. All the specimens showed shear brittle failure before flexural yielding, as shown in Fig.4. It can be seen in Fig.5.(a) that the maximum strain of the tension reinforcement obtained from the strain gauges remained at approximately 0.001. Furthermore, it can be confirmed from Fig.5.(b) that the shear reinforced region did not fail in shear.

Fig.4. shows that the maximum shear force and stiffness of the RH- and RF-series specimens with recycled aggregates increase as the width and effective depth of the specimen increase. This tendency can also be seen in the specimen with natural aggregates. As shown in the test results summarized in Table 4., among the NA-series specimens with natural aggregates, the maximum shear forces of the NA-S2, NA-M2, and NA-L2 specimens with the same beam width and various effective depths increased to 75.5 kN, 106.9 kN, and 125.9 kN, respectively. On the other hand, the maximum shear forces of the RH-S2, RH-M2 and RH-L2 specimens, which utilized 50% recycled coarse aggregates, were 60.6 kN, 108.9 kN and 126.1 kN, respectively, whereas the RF-series specimens completely made of recycled coarse aggregates had a similar shear performance to the natural aggregate specimens. The influence of the effective depth on the size effect in shear strength of RC beams is described in detail in Section 3.3.

In the case of the M-series specimens with an effective depth of 450 mm, as the beam width increased from 200 mm (M2-series) to 300 mm (M3-series), the maximum shear force of the NA-, RH- and RF-series

| Specimens | Replacement ratio | Concrete (MPa) | b (mm) | d (mm) | Reinforcements |
|-----------|------------------|----------------|--------|--------|----------------|
| NA-S2     | 0%               | $f_{c'}=31.8$  | 200    | 300    | 3-D22 2-D19   |
| NA-M2     |                  | $E_c=2.19\times10^4$ | 200    | 450    | 2-D19, 3-D22 3-D19 |
| NA-L2     |                  |                | 200    | 600    | 6-D22 3-D22   |
| NA-M3     |                  |                | 300    | 450    | 4-D19, 4-D22 5-D19 |
| NA-L4     |                  |                | 400    | 600    | 12-D22 6-D22   |
| RH-S2     | 50%              | $f_{c'}=32.6$  | 200    | 300    | 3-D22 2-D19   |
| RH-M2     |                  | $E_c=1.98\times10^4$ | 200    | 450    | 2-D19, 3-D22 3-D19 |
| RH-L2     |                  |                | 200    | 600    | 6-D22 3-D22   |
| RH-M3     |                  |                | 300    | 450    | 4-D19, 4-D22 5-D19 |
| RH-L4     |                  |                | 400    | 600    | 12-D22 6-D22   |
| RF-S2     | 100%             | $f_{c'}=34.9$  | 200    | 300    | 3-D22 2-D19   |
| RF-M2     |                  | $E_c=2.00\times10^4$ | 200    | 450    | 2-D19, 3-D22 3-D19 |
| RF-L2     |                  |                | 200    | 600    | 6-D22 3-D22   |
| RF-M3     |                  |                | 300    | 450    | 4-D19, 4-D22 5-D19 |
| RF-L4     |                  |                | 400    | 600    | 12-D22 6-D22   |

Fig.3. Test Setup of Specimen
specimens increased by approximately 1.5, 1.4, and 1.7 times, respectively, as summarized in Table 4. In the case of the L-series specimens with an effective depth of 600 mm, as the beam width increased from 200 mm (L2-series) to 400 mm (L4-series), the maximum shear force increased by approximately two times, regardless of the aggregate type. These results confirm that the specimens with recycled aggregates had an increase in maximum shear force proportional to the beam width, similar to the specimens with natural aggregates.

Fig. 6. shows that the behavior of the RH- and RF-series specimens made of recycled aggregates was similar to that of the NA-series specimens with natural aggregates, regardless of the size of the cross section. This means that high-quality recycled coarse aggregate (Korean Standards Association, 2011) with a water absorption of 1.67% or less has similar shear characteristics to the natural aggregate regardless of the recycled aggregate replacement ratio, and that existing equations can be used to predict the size effect in shear strength of RC beams with high-quality recycled coarse aggregate. The prediction of the shear strength by using existing equations will be described in detail in Chapter 4.

3.2 Crack Patterns

The crack patterns of the NA-, RH-, and RF-series specimens according to the replacement ratio and presence of the recycled aggregate are presented in Fig. 7. The initial flexural crack of each specimen formed near the mid-span, where the highest moment occurred. With increased load, the flexural cracks grew and the flexure-shear cracks were observed in the test region between the loading point and the support. Then, the typical shear brittle failure occurred after a diagonal crack reached the loading point of the specimens.

From Fig. 7., it was confirmed that the number of cracks occurring in the specimen increased as the effective depth increased, whereas it was not influenced by the variation of the width of the specimen. This was due to the fact that there was an increase in the effective depth of the specimen, which was an important factor for the crack spacing, whereas other factors such as the ratio and details of the reinforcement were almost similar in all the specimens (Collins and Mitchel, 1991). This phenomenon was observed in all the specimens, except Specimen NA-L2, regardless of the aggregate type.
Table 4. Comparison between Analytical and Experimental Results of Tested Specimens at Peak Load

| Specimens | $f'_c$ (MPa) | $b$ (mm) | $d$ (mm) | Test results | Analytical results |
|-----------|-------------|----------|----------|--------------|-------------------|
| NA-S2     | 31.8        | 200      | 300      | $V_{exp}$ (kN) | $V_{calc}$ (MPa) | $V_{exp} / V_{calc}$ | $V_{calc} / V_{exp}$ |
| NA-M2     | 32.9        | 200      | 450      | 106.9        | 1.19              | 1.05                 | 1.13                 |
| NA-L2     | 32.9        | 200      | 600      | 125.9        | 1.05              | 0.93                 | 1.06                 |
| NA-M3     | 34.9        | 300      | 450      | 156.7        | 1.16              | 1.02                 | 1.10                 |
| NA-L4     | 34.9        | 400      | 600      | 256.4        | 1.07              | 0.95                 | 1.08                 |
| RH-S2     | 31.8        | 200      | 300      | 60.6         | 1.01              | 0.88                 | 0.87                 |
| RH-M2     | 32.9        | 200      | 450      | 108.9        | 1.21              | 1.06                 | 1.14                 |
| RH-L2     | 32.9        | 200      | 600      | 126.1        | 1.05              | 0.92                 | 1.05                 |
| RH-M3     | 34.9        | 300      | 450      | 154.2        | 1.14              | 0.99                 | 1.07                 |
| RH-L4     | 34.9        | 400      | 600      | 261.5        | 1.09              | 0.95                 | 1.09                 |
| RF-S2     | 31.8        | 200      | 300      | 72.9         | 1.22              | 1.04                 | 1.03                 |
| RF-M2     | 32.9        | 200      | 450      | 96.4         | 1.07              | 0.91                 | 0.99                 |
| RF-L2     | 32.9        | 200      | 600      | 125.1        | 1.04              | 0.89                 | 1.02                 |
| RF-M3     | 34.9        | 300      | 450      | 159.8        | 1.18              | 1.00                 | 1.08                 |
| RF-L4     | 34.9        | 400      | 600      | 256.6        | 1.07              | 0.91                 | 1.04                 |

Mean: 0.97, COV (%): 7.23, 6.14, 7.41

Fig. 6. Shear Behavior of Tested Specimens According to Aggregate Type

3.3 Size Effect on Shear Strength of RC Beams with Recycled Aggregates

(1) Effect of effective depth of beam

Generally, the shear capacity carried by concrete in an RC beam is known to increase as the beam width and effective depth increase, and this concept is reflected in a lot of design codes for RC structures. However, in the case of increasing member size, the shear strength does not increase in proportion to the size of the cross section, and this tendency is prominent in the absence of shear reinforcement (Bazant and Kim 1984).

As seen in Table 4., the size effect in shear strength of the specimens with recycled aggregates was similar to the results reported in previous studies using natural aggregates. In other words, when the effective depth was increased from 300 mm to 600 mm and the width was maintained at 200 mm, the maximum shear force increased regardless of the aggregate type, whereas the maximum shear stress decreased by up to approximately 17%. For instance, in the case of the RF-series specimens, which only had recycled coarse aggregate, RF-L2 ($d = 600$ mm) had a maximum shear force of 125.1 kN, which was approximately 1.7 times higher than that of RF-S2 ($d = 300$ mm), whereas its maximum shear stress was approximately 14% lower at 1.04 MPa. This tendency was also observed in the NA-series specimens with only natural aggregate, as well as the RH-series specimens with a replacement ratio of 50% recycled aggregate, with the exception of the RH-S2 specimen which had a somewhat low shear strength.

Fig.8. shows the maximum shear stresses of all the specimens according to their effective depths. It can be confirmed from Fig.8. that the peak shear stress decreases as the effective depth of the specimens decreases, which means that the shear capacity of an RC beam does not increase in proportion to its effective depth. It should be noted that the analytical results calculated by using the ACI 318-11 shear equation overestimate the experimental results as the effective depth of the specimen increases, as illustrated in Fig.8. The accuracy of the existing shear equations for size effect in shear strength of RC beams will be described in detail in Chapter 4.

(2) Effect of beam width

In contrast to the effective depth of the beam, the beam width has been reported to have no effect on the
size effect in the shear failure of RC beams in previous studies (Kani 1967; Collins and Kuchma 1999). Fig.9.
shows the maximum shear stresses of the specimens according to the beam width.

In the case of the M2-series (b = 200 mm) and M3-series (b = 300 mm) specimens with the same effective
depth of 450 mm but with different beam widths, RH-M3 had a maximum shear force that was 1.4 times
higher than that of RH-M2, whereas its maximum shear stress was measured to be 0.94 times that of RH-
M2. This is similar to the results of natural aggregate specimens, of which the maximum shear strength
increased by 1.5 times and the maximum shear stress was 0.98 times. The maximum shear strength and peak
shear stress of RF-M3 with recycled coarse aggregate only increased by 1.7 and 1.1 times that of RF-M2,
respectively. Such an increase is somewhat higher than that of natural aggregate specimens, but it should be
noted that the beam width is not a significant factor concerning the size effect in the shear strength of RC
beams, as seen in Fig.9.

In the case of the L2-series (b = 200mm) and L4-series (b = 400 mm) specimens with an effective depth
of 600 mm, the maximum shear force increased by approximately two times with an increase in width
regardless of the aggregate type, whereas the maximum shear stress remained almost the same. This tendency
can be clearly observed in Fig.9. Based on these test results, it can be concluded that the size effect in
shear strength of RC beams with recycled coarse aggregates is not influenced by the beam width, which
is consistent with the results of previous studies using natural aggregates (Kani 1967; Collins and Kuchma
1999).

4. Prediction of Shear Strength
Three types of existing equations proposed by the
ACI 318-11 (ACI 2011), CEB-FIP MC 90 (CEB-FIP 1991), and AIJ 2010 (AIJ 2010) were used to predict
the deterioration of the strength of RC beams resulting from the size effect in shear strength.
4.1 Existing Equations
The shear strength equation proposed by the ACI
318-11 Code (ACI 2011) for RC beams without
shear reinforcement includes variables of concrete
compressive strength, ratio of tension reinforcement,
and shear span-to-depth ratio, as follows:

\[ V_{ACI} = 0.16 \sqrt{f_c'} + 17.6 \rho_t \frac{V_d}{M_u} b_w d \]  

where \( f_c' \) is the compressive strength of concrete, \( \rho_t \) is
4.2 Comparison of Analytical and Experimental Results

Table 4. presents a comparison of the experimental and analytical results obtained using the existing shear equations. It can be confirmed from the test results that the effective depth of the specimen had a greater effect on the shear strength than did the beam width. Based on this test result, the ratio of the experimental result to the analytical result \(V_{exp}/V_{ana}\) according to the effective depth of the specimens was determined, and is shown in Fig.10.

As shown in Table 4., the shear equation proposed by the ACI 318-11 Code predicted the shear strength obtained from the experimental results with a mean of 0.97 and a coefficient of variation (COV) of 7.2%. However, as seen in Fig.10.(a), the ACI 318-11 overestimated the experimental results as the effective depth of the specimens increased. This is due to the fact that the ACI 318-11 does not consider the size effect in shear strength of the RC beams when the shear span-to-depth ratio is the same, as described in Eq. (1). On the other hand, Fig.10.(b) shows that the analytical results obtained from the CEB-FIP MC 90, which considered the size effect of shear strength in RC beams using the factor \(\varsigma\), agreed well with the experimental results of the specimens. Furthermore, as clearly shown in Table 4., the CEB-FIP MC 90 not

![Fig.8. Shear Strength of Tested Specimens According to d](image1)

![Fig.9. Shear Strength of Tested Specimens According to b](image2)

![Fig.10. Comparison of Experimental and Analytical Results](image3)
only predicted the experimental results safely with a mean of 1.06, but also showed superior accuracy with a COV of 6.1%.

Fig.10.(c) shows the prediction results obtained using the AIJ 2010 shear equation. As shown in Table 4. and Fig.10.(c), the AIJ 2010 showed relatively good accuracy with a mean of 1.03 and a COV of 7.4%. However, the AIJ 2010 somewhat overestimated the test shear strength of the L-series specimens with an effective depth of 600 mm. This is due to the fact that the AIJ 2010 shear equation does not take into account the reduction of the shear strength of RC beams with an effective depth greater than 400 mm, as seen in Eq. (3). Based on the comparison of analytical and experimental results, it can be concluded that the existing equations, which can adequately consider the size effect in shear strength of RC beams with natural aggregates, can be used to predict the shear strength of large-sized RC beams with recycled aggregates, irrespective of the replacement ratio of the recycled aggregates.

5. Conclusions

In this study, an experiment with various aggregate types and cross sectional sizes of RC beams was performed to evaluate the size effect in shear strength of RC beams with recycled aggregates. Based on the experimental results, the following conclusions were drawn:

1. This test results with an effective depth of up to 600 mm indicated that the shear response of RC beams with 50% and 100% recycled aggregates were similar to that of RC beams with natural aggregates in terms of shear behavior, crack patterns, and strength characteristics. This means that high-quality recycled aggregates with water absorption of 1.67% or less give shear performances similar to those of RC beams with natural aggregates, regardless of the replacement ratio of the recycled aggregates.

2. With increasing effective depth of the specimen, the maximum shear force of the specimens increased whereas the maximum shear stress decreased. However, the beam width had no influence on the size effect in shear strength of the specimens. These tendencies were found in all specimens irrespective of the replacement ratio of recycled aggregates and the type of aggregate.

3. A comparison of the analytical and experimental results showed that the existing shear equations, which adequately consider the size effect on the shear strength of RC beams with natural aggregates, will provide good predictions of the shear strength of large-sized RC beams with recycled aggregates.

References

1) ACI Committee 318. (2011) Building code requirements for structural concrete (ACI 318M-11) and commentary. American Concrete Institute, Farmington Hill, MI, p.503.
2) AIJ. (2010) AIJ standard for structural calculation of reinforced concrete structure. Architectural Institute of Japan, pp.525.
3) Bazant, Z. P. and Kim, J.-K. (1984) Size effect in shear failure of longitudinally reinforced beams. ACI Journal Proceedings, 81(5), pp.456-468.
4) Collins, M. P. and Mitchell, D. (1991) Prestressed concrete structures. Prentice Hall, Englewood Cliffs, NJ.
5) Collins, M. P. and Kuchma, D. (1999) How safe are our large, lightly reinforced concrete slabs, slab, and footings? ACI Structural Journal, 96(4), pp.482-490.
6) CEB-FIP. (1991) CEB-FIP model code for concrete structures, Comité Euro-International du Béton, p.437.
7) Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., and Foo, S. (2009) New mixture proportioning method for concrete made with coarse recycled concrete aggregate. Journal of Materials in Civil Engineering, ASCE, pp.601-611.
8) Kani, G. N. J. (1967) How safe are our large reinforced concrete beams? ACI Journal Proceedings, 64(3), pp.128-141.
9) Katz, A. (2004) Treatments for the improvement of recycled aggregate. Journal of Materials in Civil Engineering, ASCE, pp.597-603.
10) Korean Standards Association. (2011) Recycled aggregate for concrete. Korean Strands Association, p.14. (in Korean)
11) Morohashi, N., Sakurada, T., and Yanagibashi, K. (2007) Bond splitting of high-quality recycled coarse aggregate concrete beams. Journal of Asian Architecture and Building Engineering, 6(2), pp.331-337.
12) Sneed, L. H. and Ramirez, J. A. (2010) Influence of effective depth on shear strength of concrete beams - Experimental study. ACI Structural Journal, 107(5), pp.554-562.