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Recommended Citation

Kim, Yongjae; Sim, Jongsung; and Park, Cheolwoo (2012) "MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE WITH DEFORMED STEEL RE-BAR," *Journal of Marine Science and Technology*. Vol. 20: Iss. 3, Article 5.

DOI: 10.51400/2709-6998.1804

Available at: <https://jmstt.ntou.edu.tw/journal/vol20/iss3/5>

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MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE WITH DEFORMED STEEL RE-BAR

Yongjae Kim¹, Jongsung Sim¹, and Cheolwoo Park²

Key words: recycled aggregate concrete, bond strength, compressive strength, elastic modulus, replacement ratio.

ABSTRACT

This study investigates fundamental properties of the recycled aggregate which was produced through recent hi-technique of recycling. In addition, the mechanical properties of the concrete that was made by the recycled aggregate were compared to the concrete made of natural aggregate. The primary objective of this study was to characterize the concrete-rebar bonding properties of the recycled aggregate concrete.

The recycled aggregate concrete showed about 18% decreased bond strength as compared to the natural aggregate concrete. The current prediction equation of bond strength suggested by the design specification does not consider this decreased bond strength by the use of the recycled aggregate. Therefore, this study suggests an equation for predicting the bond strength for the recycled aggregate concrete considering the recycled aggregate replacement ratio and consequent compressive strength reduction.

I. INTRODUCTION

Aggregate is the essential basic construction material affecting the properties of concrete and taking approximately 70% of volume of Portland cement concrete and over 90% of asphalt concrete, respectively [5]. Such aggregate performs an important function when it is mixed with relatively expensive binders such as cement or bituminous materials, and enables economical construction. It also takes a role of maintaining the structure's stability against physical and chemical effects of cement.

In the past, generally in Korea, high quality river-run gravel and sand were collected and used in the construction industry but their amounts produced and used became very significant

due to its limits in reserves and ecosystem disturbance [11]. In these days, peoples are collecting the construction aggregate even from EEZ (Exclusive Economic Zone) of sea and tries to make the aggregate collecting plant equipment larger. However, it is expected that the natural resource of aggregate will run out within 30 to 40 years [8].

Recycled aggregate is a also aggregate produced through recycling process of waste concrete. It used to be employed for low value added use including land reclamation, filling, sub-base material for road and concrete secondary products manufacturing. However with a recent advancement of technology for processing the waste concrete it is possible to produce recycled aggregate as of similar quality as the natural aggregate. Therefore, the potential of its usage for a structural member, high-value purposes, has grown much higher [12].

It has been known that the workability of recycled aggregate concrete is lower than the natural aggregate concrete. Compressive strength and elastic modulus of recycled aggregate concrete are also lower about 15% to 20% than the natural aggregate concrete [9, 10]. Bond strength of recycled aggregate concrete reduces about 10% to 35% [6]. When only coarse aggregate is replaced with the recycled the bond strength dropped about 5% to 15%, and when both coarse and fine aggregate were replaced, about 20% [1, 2]. It was also reported that the replacement ratio was up to 30%, bending and shear strengths were maintained to a comparable level but over 30% the strengths were reduced significantly [13].

Only few researches are available on the bond strength of recycled aggregate concrete with varying replacement ratios. Therefore, this research investigates the bonding characteristics of recycled aggregate concrete with varying replacement ratios along with the fundamental physical properties.

II. EXPERIMENT SUMMARY

This study is intended to understand characteristics of recycled aggregate concrete and its bonding performance to the deformed re-bar and compare the bond strength to a natural aggregate concrete. Concrete specimens for two different mix proportions with varying levels of replacement of recycled coarse aggregate and recycled fine aggregate were made while diameter of deformed re-bar for the two specimens was kept

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Table 1. Experimental variables.

Specimen	Mixed aggregate		Deformed re-bar diameter (mm)
	Coarse aggregate	Fine aggregate	
NN	Natural 100%	Natural 100%	19
RN	Recycled 100%	Natural 100%	19
RR30	Recycled 100%	Recycled, 30% replaced	19
RR60	Recycled 100%	Recycled, 60% replaced	19
RR	Recycled 100%	Recycled, 100% replaced	19

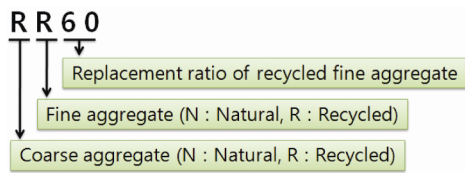


Fig. 1. Details of specimen description.

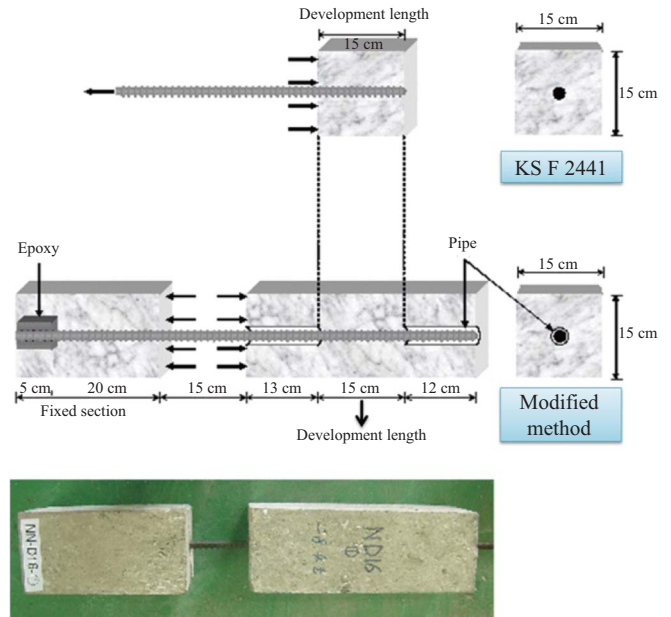


Fig. 2. Bond strength pull-out test specimen.

the same. The bond strengths was measured through the pull-out test of the prepared specimens.

1. Variables

According to results of previous researches, the characteristics of recycled aggregate concretes vary considerably depending upon the quality and replacement level of recycled aggregate used. In this experiment, recycled aggregate produced by advanced recycling method was used. The replacement level of aggregate was set as the major variable, so that the mix proportions were established with variations in the percentage of coarse and fine aggregate replacement.

The coarse aggregate used in the study showed about the similar properties as the natural aggregate. Therefore, 100% recycled coarse aggregate is used instead of fractioning it in mix proportions.

In addition, researches show that if a percentage level of replacement of fine aggregate exceeds 60%, there is significant reduction in the concrete quality and performance. Hence, the replacement percentage for fine aggregate were set as 30%, 60% and 100%.

Deformed re-bar of 19 mm diameter was used in the specimens. Fig. 1 shows an detailed description of specimen name used in this study. Table 1 addresses the specimen variables.

2. Preparation of Specimens

It is typical to use a pull-out specimen as shown in the upper part in Fig. 2 (KS F 2441). However, in our study, we modified the traditional pull-out test specimen to a different shape as shown in the lower part in Fig. 2 but maintained the bonded length of 15 cm. This modification may minimize the localized deformation, i.e. elongation, and slippage that can cause wrong reading of the deformation. In addition, the used speci-

men can allow variation of bonded length if desired and the first unbounded area of 13cm will provide evenly distributed stress though the bonded area rather the traditional specimen bring an excessive stress concentration at the contact area to the experimental jig.

3. Materials

The cement used was Type I Portland cement. Table 2 and Table 3 describe physical properties of the recycled and natural aggregate used in this experiment.

4. Mix Proportions

Table 4 shows the mix proportions for each variable. The primary mix proportion was based on the natural concrete mix and no extra alteration was made with the addition of recycled aggregate. Replacement level of recycled aggregate is based on the volume.

5. Specimen Curing

Compressive strength and elastic modulus were measured using the cylinder specimens, which were cured under water for 28 days. The pull-out specimens were also cured under water but all the exposed surface of the steel re-bar was covered with an oil in order to minimize corrosion. It was then wet cured in the normal temperature using curing blanket which kept it consistently wet.

6. Bond Strength Measurement

This experiment employed a modified pull-out testing scheme in which deformed re-bar is not directly pulled out. Additional metal parts were prepared and the right-hand side in Fig. 3 where re-bar fixing epoxy bulb was embedded was pulled out. In order to minimize the anticipated errors which

Table 2. Properties of coarse aggregate.

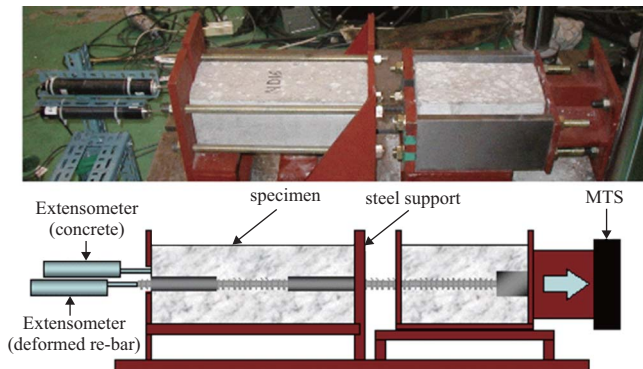
	Specification for recycled coarse aggregate			Used recycled coarse aggregate	Specification for natural coarse aggregate	Used natural coarse aggregate
	Class 1	Class 2	Class 3			
water absorption ratio (%)	Less than 3.0	Less than 5.0	Less than 7.0	1.82	Less than 3.0	0.47
density	greater than 2.2			2.61	More than 2.5	2.64
abrasion loss (%)	Less than 40			21.5	Less than 40	24.1
solid volume percentage (%)	Greater than 55			60.3	Greater than 55	55.4

Table 3. Properties of fine aggregate.

	Specification for recycled fine aggregate		Used recycled fine aggregate	Specification for natural fine aggregate	Used natural fine aggregate
	Class 1	Class 2			
water absorption ratio (%)	Less than 5.0	Less than 10.0	4.55	Less than 3.0	1.16
density	Greater than 2.2		2.43	Greater than 2.5	2.61
solid volume percentage (%)	Greater than 53		-	Greater than 53	-

Table 4. Mix Proportion (unit: kg/m³).

Variable	Water	Cement	Fine Aggregate		Coarse Aggregate		H.R.W.A.	A.E.
			Natural	Recycled	Natural	Recycled		
NN	189.10	580.49	661.74	0	851.37	0	4.4	0.022
RN	189.10	580.49	661.74	0	0	841.70	4.4	0.022
RR30	189.10	580.49	463.22	184.83	0	841.70	4.4	0.022
RR60	189.10	580.49	264.70	369.66	0	841.70	4.4	0.022
RR	189.10	580.49	0	616.10	0	841.70	4.4	0.022

**Fig. 3. Bond strength testing scheme.**

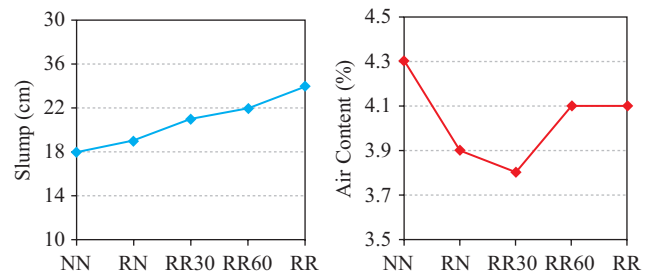
could occur due to deformation of metal parts left-hand side, the steel support and other fixtures left-hand side were fixed to the bottom of floor using bolts. Only the concrete part on the right-hand side was pulled.

Loading equipment was the MTS actuator with a capacity of 250 kN and the loading was strain-controlled at 0.5 mm/min per the experimental specifications.

III. TEST RESULTS

1. Basic Characteristics of Recycled Aggregate Concrete

1) Slump and Air Content

**Fig. 4. Slump and air content.**

The result of measurements of the slump and air with varying replacement level of recycled aggregate concrete is shown in Fig. 4.

It can be seen that by replacing the natural aggregate with recycled aggregate, the slump value increased while the air content reduced up to a certain point and then increased slightly. The increment of slump may be due to the grain shape originated by the production process. Crushed stone used as natural aggregate had rough and angular shape because of the crushing process. The recycled coarse aggregate was mainly river run gravel which had round shape due to wear and tear in the crusher. This difference in the shape of coarse aggregate may have contributed to the workability improvement. The workability increased as the fine recycled aggregate replacement ratio increased. This may be due to the additional fine particles from the recycled fines.

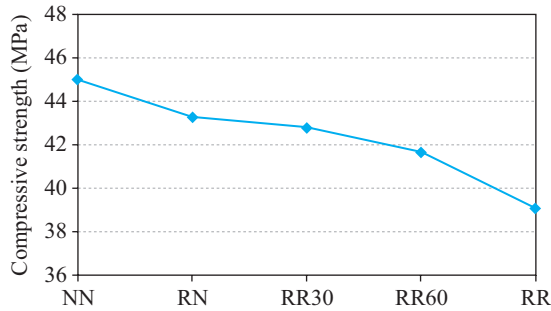


Fig. 5. Compressive strength.

Air content decreased with 100% recycled coarse aggregate and up to 30% of recycled fines. However with greater than 60% of the recycled fine aggregate the air content increased slightly. The included additional fine particles may helped the internal air void within the mixture.

2) Compressive Strength

The results of compressive strength measurement is shown in Fig. 5.

When only the coarse aggregate was replaced with the recycled the compressive strength decreased about 2MPa. As the fine aggregate replacement ratio increased the compressive strength kept decreasing. Especially when the recycled fine aggregate replacement was over 60% the strength drop was significant. The strength drop with the recycled can be attributed to the remained mortar on the surface of the recycled aggregate, cracks in the aggregate itself (which could occur during the crushing) and the original aggregate's strength etc. From, the observations, it is recommended that the fine aggregate should better be replaced with the recycled less than 60% in the consideration of compressive strength.

3) Elastic Modulus

Elastic modulus was measured by attaching a strain gauge on to the surface of the cylinder specimens. Based on the obtained stress-strain curves, elastic modulus was determined. In addition, by using the measured compressive strength and unit weight, the elastic modulus was calculated following the equation for the comparison purposes.

$$E = 0.077m_c^{1.5}\sqrt[3]{f_{ck}} \quad (1)$$

Where m_c is the unit weight of concrete and f_{ck} is the measured compressive strength.

Table 5 shows both the measured and calculated elastic modulus.

Similar to the results of the compressive strength, it was obvious that the elastic modulus decreased with the increase of the replacement ratio as shown in Table 5. However, the calculated values are much higher than the measured. From this comparison, it is not recommended to use the currently available equation for the calculation of the elastic modulus.

Table 5. Elastic modulus.

Variable	Compressive strength (MPa)	Measured elastic modulus (MPa)	Calculated elastic modulus (MPa)
NN	45.0	24,185	29,836
RN	43.3	20,440	29,417
RR30	42.8	17,981	29,292
RR60	41.7	20,000	28,870
RR	39.1	16,516	28,325

Table 6. Calculations of bond strength.

Equation	Bond strength equation
Direct calculation	$\tau_{\max} = \frac{P_{\max}}{O \cdot l_d}$
CEB-FIP MC90	$\tau_{\max} = 2.0\sqrt{f_{ck}}$
ACI 318-08	$\tau_{\max} = 5.91\frac{\sqrt{f_{ck}}}{d_b}$
Orangun	$\tau_{\max} = [0.2652 \times (1.2 + \frac{3c}{d_b} + \frac{50d_b}{l_d})] \times \sqrt{f_{ck}}$
MacGregor	$\tau_{\max} = 0.59\sqrt{f_{ck}}(\frac{c}{d_b} - 0.5)$

Therefore, for the recycled aggregate concrete, an appropriate calculation equation for elastic modulus should be developed.

2. Bond Strength Characteristics of Recycled Aggregate Concrete

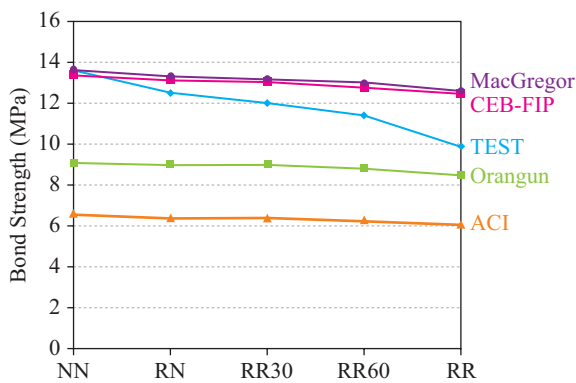
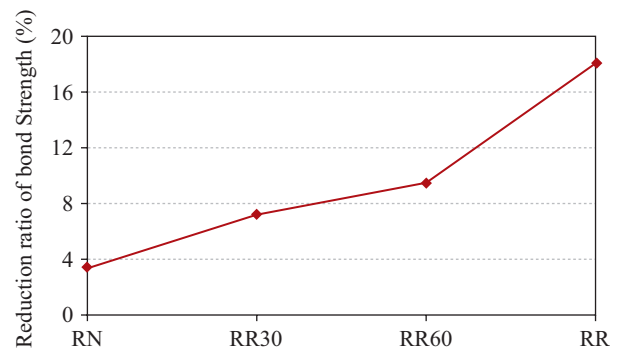
The measured bond strengths were described in Table 7 and compared with the variables in Fig. 6. For the further analysis of the bond strength characteristics, four additional bond strength equations were considered in the study, as shown in Table 6. Actually the four additional equations were developed for natural aggregate concrete and are from CEB-FIP MC90, ACI 318-08, Orangun correlation [7] and MacGregor [4]. They all directly depending on the compressive strength of concrete, f_{ck} , developed or embedded length of re-bar, l_d and the diameter, d_b .

For the concrete with only natural aggregate, the MacGregor's and CEB-FIP's equations developed almost coincided results with the experiments but the rest of two equations, ACI and Orangun, significantly underestimated the bond strength. The test results shows a decreased bond strength as the recycled aggregate content increased. However, the four equations did not take account of the bond strength reduction due to the addition of the recycled aggregate even though they accounted the reduced compressive strength. This is a similar observation of the results of the elastic modulus.

In the occasion of replacing only coarse aggregate with the recycled, there was about 3% decrease of bond strength and additional replacing 30% of fines with the recycled, approximately 7% decrease while replacing the whole quantity,

Table 7. Result of bond strength assessment.

Parameter	Compressive strength (MPa)	Bond strength by test (MPa)	CEB-FIP MC90 (MPa)	ACI 318-08 (MPa)	Orangun (MPa)	MacGregor (MPa)
NN	45.0	13.5	13.4	6.6	9.1	13.6
RN	43.3	12.5	13.2	6.4	9.0	13.3
RR30	42.8	12.0	13.1	6.4	9.0	13.2
RR60	41.7	11.4	12.8	6.3	8.8	13.0
RR	39.1	9.9	12.5	6.1	8.5	12.6

**Fig. 6. Comparison of bond strength predictions.****Fig. 7. Reduction rate of bond strength.**

18% decrease. This reduction rate with respect to the replacement ratio is shown in Fig. 7.

With the results above, it can be said that even though the recycled aggregate concrete has the same level of compressive strength, the bond strength is not as comparable as that of natural aggregate concrete. There must be various reasons for that difference but no clear answer can be made at this point. However, for the structural design purposes, the test results in the study here can be used to make a correlation between the bond strength and the recycled aggregate with respect to the replacement ratio. The provided correlation is very important as it can be used for the determination of the secured development length of the recycled aggregate concrete.

IV. SUGGESTION OF BOND STRENGTH PREDICTION

As shown earlier, the prediction equation of natural aggregate concrete is thought to be inappropriate for recycled aggregate concrete. Therefore, this study is about to suggest a new equation suitable to predict bond strength of recycled aggregate concrete. Experimental results shows that in a case of natural aggregate concrete, the bond strength prediction equation by MacGregor seems to be relatively accurate. Therefore, the form of MacGregor equation was adopted as a basic form to calculate the bond strength of recycled aggregate concrete with respect to the replacement ratio. The basic component of the prediction equation by MacGregor's equation is as following Eq. (2).

$$\tau_{\max} = \alpha \cdot \sqrt{f_{ck}} \left[\frac{c}{d_b} - \beta \right] + \lambda \quad (2)$$

In this equation, α is the coefficient to calculate the tensile strength of the concrete, and β is the coefficient that decides cut-tensile section which the concrete takes care of when the tensile force is applied to the deformed steel re-bar due to load, and λ is the coefficient that decides gradient on variations of bond stress with α , β . Through the analysis it was found that the recycled aggregate concrete changes α from 0.590 into 0.614, β from 0.50 to 0.55 to adapt the property that has relatively lower tensile strength and small cut-tensile section compared to natural aggregate concrete. Also to apply the property according to changing replacement ratio of recycled aggregate, λ became $-0.4203e^{0.0172S} - 0.007G$ [3].

Again, the f_{ck} , the compression strength, has been replaced with f_{ckr} , the recycled aggregate concrete compression strength, to reflect the compressive strength drop of recycled aggregate concrete. The modified equation is suggested as follow.

$$\tau_{r\max} = 0.614 \sqrt{f_{ckr}} \left[\frac{c_c}{d_b} - 0.55 \right] - (0.4203e^{0.0172S} + 0.007G) \quad (3)$$

where,

- $\tau_{r\max}$: maximum predicted bond stress of recycled aggregate concrete
- f_{ckr} : compressive strength of recycled aggregate concrete according to replacement ratio

Table 8. Comparison of measured and predicted bond strength.

Compressive strength (MPa)	Bond strength by test (MPa)	Prediction equation by MacGregor (MPa)	Suggested equation (MPa)
NN	13.3	13.6	13.5
RN	12.5	13.3	12.5
RR30	12.0	13.2	12.2
RR60	11.4	13.0	11.4
RR	9.9	12.6	9.9

- C_c : distance from the deformed steel re-bar core to the concrete surface
- d_b : diameter of deformed steel re-bar
- S : replacement ratio of recycled fine aggregate
- G : replacement ratio of recycled coarse aggregate

The bond strength predicted by using the suggested Eq. (3) that incorporated the bond characteristics between deformed steel re-bar and recycled aggregate is shown in Table 8. From the comparison it is known that the suggested equation can predict the bond strength of recycled aggregate concrete with varying replacement ratio within a very appropriate error level.

V. CONCLUSIONS

Recycled aggregate produced these days has much better performance as comparable to natural aggregate. Engineers begin to use the recycled aggregate for a normal concrete structures. However, its basic characteristics have not been not yet thoroughly investigated. Particularly in order extend the use of the recycled aggregate for the structural concrete, its bonding performance should be fundamentally explored. This research examined the strength and elastic modulus properties with respect to the addition ratio of the recycled aggregate. In addition, through the modified pull-out test its bonding property was studied. From the experimental study herein the conclusions below are drawn.

- (1) Recycled aggregate concrete showed an increased workability as the recycled aggregate replacement ratio increased. This may be due to the increased amount of fine particles from the recycling process.
- (2) Air content slightly reduced up to 30% replacement of the recycled fines with 100% recycled coarse aggregate. With a greater amount of the recycled fines, the air content tended to increase. However the air content did not vary significantly and seemed to be controlled with the addition of air entraining admixture.
- (3) Compressive strength decreased when the coarse aggregate was replaced with the recycled. Additional replacement of the fine aggregate reduced the strength as the recycled fines amount increased. When the fine aggregate replacement was greater than 60% the strength reduction became more significantly. Elastic modulus showed a

similar tendency. However the currently available formula for the elastic modulus, which depends on compressive strength, did not properly predict when the recycled aggregate was used.

- (4) Bond strength decreased with the increased amount of the recycled aggregate. The bond strength prediction formulas, which relatively accurately calculated for natural aggregate concrete, did not take an account of the addition of the recycled. This study suggested a newly developed bond strength predicting equation conjunctionally considering the addition of the recycled aggregate. The suggested equation relatively close prediction with the variation of the recycled aggregate replacement. The suggested equation can also be used for the calculation of the development length of reinforcing steel, which is the most important structural design criteria.

Based on the structural performance investigated in this study, it is expected that the application of the recycled aggregate can be further extended for the structural concrete members.

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