
“INVESTIGATING THE INTER-RELATIONSHIPS BETWEEN AGGREGATE PROPERTIES, CONCRETE PROPERTIES, AND BOND PROPERTIES BETWEEN REINFORCING STEEL AND RECYCLED CONCRETE AGGREGATE”

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ABSTRACT

Sustainable resource management and development have been at the fore front of important issues concerning the construction industry for the past several years. Specifically, the use of sustainable building materials and the reuse and recycling of previously used building materials is gaining acceptance and becoming common place in many areas. As one of the most commonly used building materials in the world, concrete, composed of aggregate, sand, cement and water, can be recycled and reused in a variety of applications. Using crushed concrete as fill and sub-grade material under roads, sidewalks and foundations has been the most common of these applications. However, research has been ongoing over the past 50 years in many countries including Germany, India, Canada, Japan, the United States, China, and Australia investigating the use of crushed concrete from demolished old concrete structures to fully or partially replace the virgin aggregate used to produce new concrete for use in building and pavement applications. Producing concrete using recycled concrete aggregates (RCA) has several advantages, namely, the burden placed on non-renewable aggregate resources may be significantly decreased, the service life and capacity of landfill and waste management facilities can be extended, and the carbon dioxide emissions and traffic congestion associated with the transport of virgin aggregates from remote sites can be reduced. This research investigates the inter-relationships between aggregate properties, concrete properties and the bond properties between reinforcing steel and RCA concrete. Forty pullout tests were carried out in order to investigate the bond behavior between recycled coarse aggregate concrete and steel rebar. Four recycled coarse aggregate (RCA) replacement percentages (i.e., 0%, 30%, 60% and 90%) with water-cement ratio 0.42, 0.45, 0.48, 0.51, 0.55 are considered in this paper. Based on the test results, the influences of both recycled coarse aggregate replacement percentages and water-cement ratio on the bond strength between the recycled coarse aggregate concrete and steel rebar were investigated. It was found that under the equivalent mix proportion (i.e., the mix proportions are the same, except for different recycled coarse aggregate replacement percentages), the bond strength between the recycled coarse aggregate concrete and rebar initially decreases with an increase of the recycled coarse aggregate replacement percentage, whereas afterwards the bond strength increases with increase in replacement level of coarse aggregate. Bond strength is maximum for 90% replacement level. With the bond strength, compressive strength is also studied and it also shows the same trend as bond strength. A power series relationship exists between compressive strength and bond strength of recycled aggregate concrete. The existing models (ACI 408, Ogura-Koichi model) proposing the square root law underestimates the bond strength of concrete.

Key Words: Recycled concrete aggregates (RCA), Crushed Concrete, Equivalent mix proportion, Virgin Aggregate.

1. INTRODUCTION

Globally, the concrete industry consumes large quantities of natural resources, which are becoming insufficient to meet increasing demands. At the same time, utility of old structure is diminishing, so these building are demolished to pave way for new and modern construction. Building are demolished due to various reasons i.e. reconstruction for better economic gains, natural disasters and war-inflicted damages. The rate of demolition is increasing day by day and at the same time, the cost of dumping is increasing due to non-availability of appropriate site nearby. Besides scarcity of land, other problems associated with the landfill option include their silting; transportation cost and public opposition. Thus, recycling has been gaining wider attention as a viable option for handling of waste concrete. One of the materials that can be recycled in the demolished structure is coarse aggregate. Utilization of Recycled Aggregate in concrete has been engaged due to awareness of society in natural resources protection.

Advantages of RCA in Concrete Production: The study confirms that utilizing RCA in concrete production offers several advantages, including reducing the burden on non-renewable aggregate resources, extending the service life of landfill and waste management facilities, and decreasing carbon dioxide emissions and traffic congestion associated with transporting virgin aggregates.

Inter-relationships between Aggregate Properties, Concrete Properties, and Bond Properties: The research investigates the complex interplay between aggregate properties, concrete properties, and bond properties between RCA concrete and steel reinforcement. This understanding is crucial for optimizing the performance of concrete structures using recycled materials.

Influence of RCA Replacement Percentage and Water-Cement Ratio: The study examines the effects of varying RCA replacement percentages (0%, 30%, 60%, and 90%) and water-cement ratios on bond strength between RCA concrete and steel rebars. This analysis provides valuable guidance for concrete mix design and construction practices using recycled materials.

Bond Behavior and Performance: Through pullout tests, the research assesses the bond behavior between recycled coarse aggregate concrete and steel rebars. The findings indicate that while bond strength initially decreases with increasing RCA replacement percentage, it eventually increases, with maximum bond strength observed at 90% replacement level. This suggests that high levels of RCA incorporation can enhance bond performance, potentially leading to more durable concrete structures.

Relationship between Bond Strength and Compressive Strength: The study reveals a relationship between bond strength and compressive strength of recycled aggregate concrete, with both exhibiting similar trends. Additionally, the research identifies a power series Relationship between these two properties, indicating a correlation that can inform concrete mix design and structural analysis.

Comparison with Existing Models: The research highlights discrepancies between existing models (such as ACI 408 and the Ogura-Koichi model) and the observed bond strength of recycled aggregate concrete. This underscores the importance of developing accurate predictive models tailored to the specific characteristics of recycled materials.

2. MATERIAL PROPERTIES

Cement, fine aggregates, coarse aggregates, recycled coarse aggregate, super-plasticizer and water is used for present investigation. The properties of these materials are discussed in the following sections.

Cement- Cement is a fine, grey powder. It is mixed with water and materials such as sand, gravel, and crushed stone to make concrete. The cement and water form a paste that binds the other materials together as the concrete hardens. The ordinary cement contains two basic ingredients namely argillaceous and calcareous. In argillaceous materials, clay predominates and in calcareous materials calcium carbonate predominates. Ordinary Portland cement of grade – 43 (Ultra tech cement) conforming to Indian standard IS: 8112-1989 has been used in the present study. The results of the various tests on cement properties are given in Table 3.1.

Table:1 Physical properties of Portland cement

Sr. No.	Characteristics	Values obtained	Standard values
1.	Normal Consistency	29.5%	-
2.	Initial setting time	1 hours 55 min	Not to be less than 30 minutes
3.	Final Setting time	3 hours 40 min	Not to be greater than 600 minutes
4.	Fineness	2.5%	<10%
5.	Specific gravity	3.38	-

3. RESULTS AND DISCUSSION

Introduction- In the first part of this chapter, the effect of replacement ratio of recycled coarse aggregate on compressive of concrete is discussed. The effect is studied at a range of w/c ratios. The second part consists of discussion on the effect of recycled coarse aggregate on the bond strength of concrete.

Compressive Strength- Three cubes (150mm) from each batch of concrete mix are casted and cured for 7 and 28 days in order to determine compressive strength of RCA concrete. All specimens are cast in a single mix and direct weight to weight replacement of natural coarse aggregate is carried out with recycled coarse aggregate at a replacement ratio of 0, 30, 60, and 90 %. The mixes are casted at water-cement ratio of 0.42, 0.45, 0.48, 0.51 and 0.55. This corresponds to range of strength varying from low strength concrete to moderate strength concrete. Table 4.1 shows the value of compressive strength of cube tested at 7 and 28 days. The data is further represented in the form of bar graphs in Figure 4.1 - 4.5, for water- cement ratio of 0.42, 0.45, 0.48, 0.51 and 0.55 respectively. The results obtained are discussed in the following sections:

Effect of recycled coarse aggregate on compressive strength

As can be seen from Figure 4.1 - 4.5, for all water-cement ratios, the 28 days compressive strength increases as the percentage of replacement increases. Maximum compressive strength is achieved at 90% replacement at all water-cement studied. However the same trend is not seen at 7 days strength, where the strength decreases initially and then increases. The final compressive strength is lesser than the compressive of control mixes. It may be because at 7 days, the hydration is not complete

Table2: Cube compressive strength 7 and 28-day

Specimen ID	Water-cement ratio	Replacement (%)	Compressive strength	
			7 days (MPa)	28 days (MPa)
A1-0	0.42	0	40.75	49.07
A1-30		30	35.80	43.65
A1-60		60	39.7	50.06
A1-90		90	40.7	52.31
A2-0	0.45	0	36.37	41.68
A2-30		30	29.13	41.28
A2-60		60	33.75	45.64
A2-90		90	35.50	50.66
A3-0	0.48	0	32.20	36.04
A3-30		30	26.04	39.65
A3-60		60	28.08	43.15
A3-90		90	31.56	44.73
A4-0	0.51	0	28.67	32.48
A4-30		30	19.07	33.30
A4-60		60	25.60	38.78
A4-90		90	28.03	40.97
A5-0	0.55	0	23.02	24.89
A5-30		30	16.40	30.03
A5-60		60	18.90	35.86
A5-90		90	19.87	37.68

Therefore, the bond between recycled aggregate and new concrete paste has not developed yet. The failure in this case will occur in the interfacial transition zone (ITZ) which is weaker in recycled coarse aggregate concrete as is observed by Xiao et al, (2012).

This trend of decrease in strength is very prominent at 30% replacement level. It may be due to at 30% replacement level, we have concrete with two types of aggregates (i.e. natural and recycled) therefore, and at this level interfacial transition zone is of mixed characteristic, which is rather playing a negative role in overall behavior of concrete. It can be concluded that if recycled coarse aggregate are used, they must be used at higher replacement levels. Infarct, 90% replacement levels gives the maximum efficient at 28 days.

As we increase the recycled aggregate content the, 28 day compressive strength increase. It is because at high recycled aggregate content, these aggregate absorb more water. Therefore, the effective water- cement ratio decreases and hence the strength increases. The similar trend is observed by Butler et al. (2011).On the basis of microstructure studies, they further concluded that recycled coarse aggregate improve the interfacial transition zone between the new mortar and aggregate. This improvement is due to more roughed surface texture of recycled coarse aggregate particles as compare to natural aggregate. Also, the hydration products formed will penetrate deep into the cracks of recycled coarse aggregate, thus improves the ITZ further. Similar observation was made by Kou et al.(2011) when recycled coarse aggregate was used along with various mineral admixtures.

Effect of water-cement ratio on compressive strength

it can be seen that as water-cement ratio decreases, compressive strength increases. Rate of increase of compressive strength for recycled coarse aggregate concrete with water-cement ratio is not as high as the corresponding rate when only natural aggregate are used. It is because strength gain with the use of recycled aggregate is very high at higher water-cement ratios. And as the water-cement ratio reduces, the strength gain is not very prominent as can be seen from figure 4.2. Similar trend was obtained by Rahal (2007).

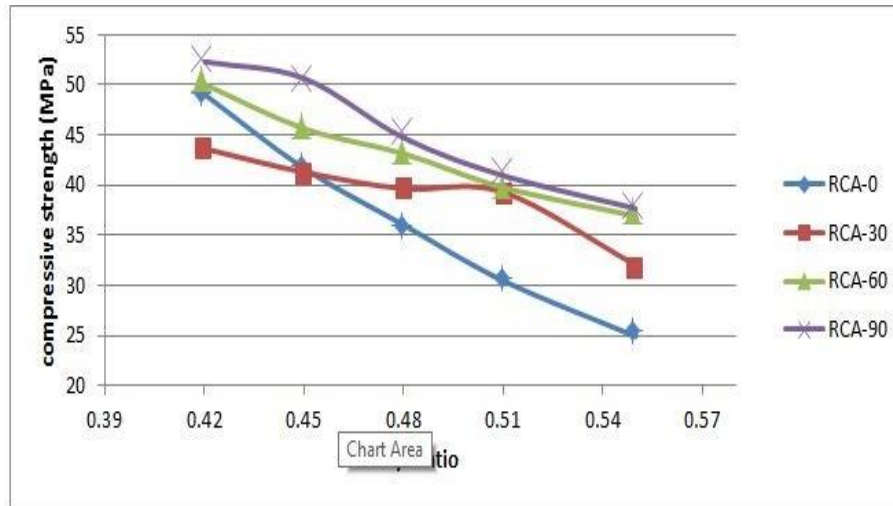


Figure1: 28 days compressive strength versus w/c ratio

BOND STRENGTH

Two cubes for each batch of concrete mix are casted and cured for 28 days in order to determine bond strength of all the mix concrete. The mixes are casted at water-cement ratio 0.42, 0.45, 0.48, 0.51 and 0.55. Table 4.2 shows bond strength of cubes tested at 28 day curing. The data is further represented systematically in the form of bar graphs as shown in Figure 4.7. Bond strength between concrete and deformed steel bars increases as percent of recycled aggregate increases. The results obtained are discussed in the following sections:

Effect of RCA on Bond Strength

As can be seen from Figure 4.7, with the increase of recycled coarse aggregate replacement initially bond strength decreases and then increases. Bond strength is maximum at coarse aggregate replacement level of 90%. Similar trend is observed at all water-cement ratios. This increase in bond strength is may be due to same modulus of elasticity of recycled coarse aggregates and the cement paste of recycled coarse aggregate concrete which at the level of concrete microstructure should improve composite action between these two phases and reduce incompatibilities of deformations under applied loads as suggested by Poon et al. (2004)

Table3: Experimental results of the pull out test specimen

Specimen ID	Replacement ratio	Water-cement ratio	Pull out load (KN)	Bond strength (MPa)
A1-0	0	0.42	84.64	22.29
A1-30	30		84.65	21.05
A1-60	60		93.03	23.134
A1-90	90		96.53	24.0
A2-0	0	0.45	81.51	20.07
A2-30	30		80.25	19.95
A2-60	60		82.0	20.39
A2-90	90		84.55	21.02
A3-0	0	0.48	77.25	19.21
A3-30	30		73.16	18.19
A3-60	60		79.10	19.67

A3-90	90	0.51	82.20	20.44
A4-0	0		68.50	17.03
A4-30	30		64.12	15.94
A4-60	60		72.25	17.96
A4-90	90		74.25	18.46
A5-0	0	0.55	57.13	14.20
A5-30	30		52.50	13.05
A5-60	60		67.16	16.70
A5-90	90		69.52	17.28

In order to study the effect of type of aggregate only, many researchers have suggested the use of normalized

RELATION BETWEEN BOND STRENGTH AND COMPRESSIVE STRENGTH

In order to see that if any relation exists between bond strength and compressive strength of recycled coarse aggregate, Figure 4.9 is plotted containing all the data obtained from previous tests. From the best fit line the following relationship is observed.

$$\text{Bond strength} = 1.1244(\text{compressive strength})^{0.7639}$$

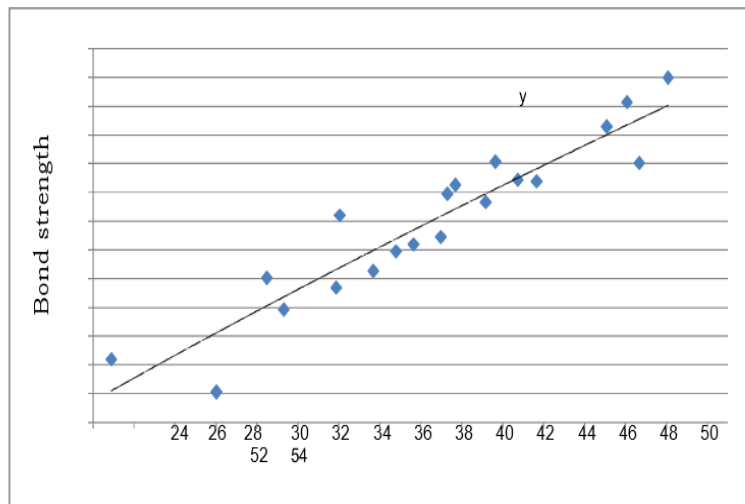


Figure2: Relation between bond and compressive strength

The data points compared with the models already existing in literature i.e. ACI 408 model and Ogura- Koichi model (Figure 4.10). From Figure 4.10 it is observed ACI 408 model highly underestimates the value of bond strength. Ogura – Koichi model also underestimate the values but to the lesser extent.

Therefore, if the square – root model is to be followed to calculate the values of lap length and anchorage length of reinforced concrete structure Ogura – Koichi model will be more economical.

4. CONCLUSION

- The 28 day compressive strength of concrete increases as the percentage of recycled aggregate. Increase in compressive strength for 28 days for 90% replacement of coarse aggregates are 7.92%, 21.54%, 24.54%, 24.11%, 34.41 and 51.38% for water ratio 0.42, 0.45, 0.48, 0.51, 0.55 respectively. It shows that major advantage of using recycled aggregates is achieved in low strength concretes made with higher w/c ratio.
- The bond strength of concrete decreases for 30% replacement and afterwards it increases. Bond strength is maximum at 90% replacement. Increase in bond strength at 90% replacement level is 7.67, 3.70, 6.40, 8.39 and 21.69 for respective water-cement ratio 0.42, 0.45, 0.48, 0.51 and 0.55.
- Recycled aggregate must be used at higher replacement levels. At this level, maximum benefit in terms of compressive strength and bond strength are achieved.
- A power series relationship exists between compressive strength and bond strength of recycled aggregate concrete. The existing models proposing the square root law underestimates the bond strength of concrete.

5. REFERENCES

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