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Behavior of Confined Recycled Aggregate Concrete

M. Mahgoub[1], M. Ala Saadeghvaziri[2], and Amin Jamali[3]

[1] Dept. of Engineering Technology, New Jersey Inst. of Technology, Newark, New Jersey, USA
[2] Dept. of Civil and Environmental Eng., New Jersey Inst. of Technology, Newark, New Jersey, USA
[3] Dept. of Civil and Environmental Eng., New Jersey Inst. of Technology, Newark, New Jersey, USA

ABSTRACT: From the standpoint of preserving the environment and saving the natural resources, it is very beneficial to recycle the waste concrete into concrete aggregates. A concrete made with such recycled aggregates is called Recycled Aggregate Concrete (RAC), as opposed to Normal Aggregate Concrete (NAC). Due to its higher porosity resulted from old cement mortar adhered to the surface, RAC is generally acknowledged to be slightly less strong than NAC, restraining its use to only non-structural applications. Widespread application of RAC, such as seismic application, requires knowledge of the material behavior under different state of stresses and loading conditions.

An experimental study was launched which objective was to study the behaviour of RAC as structural members. Plain RAC cylinder specimens and reinforced RAC columns with different reinforcement configurations were tested under monotonic and cyclic loadings. This paper presents the experimental setup and preliminary test results.

1 MOTIVATION

The earth's natural resources are being consumed at a very high rate for many years. This urges the waist recycling as well as reducing consumption rate. All sectors of the society are responsible for recycling, including the construction industry. Construction materials including concrete are increasingly judged by their environmental impacts. Any possible use of the readily available material as a source for new constructions is becoming very important.

1.1 Saving natural resources

On average there is a 38 million tons annual increase in sand and gravel production in the US. Continuation of such a dramatic extraction of natural resources will have serious environmental impacts.

1.2 Landfills

Another significant benefit to recycling construction and demolition debris is elimination of landfills. In 1994 there were 1889 Construction and Demolition (C&D) waste landfills across the United States (EPA530-R-95-019) while the number of C&D waste landfills in 2004 was

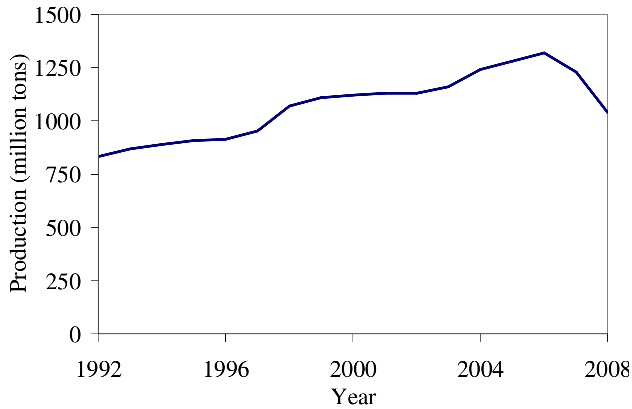

Figure 1. The US annual production of sand and gravel (data is compiled from USGS Annual Mineral Commodity Summaries report, 2009).

about 1500. The declining trend demonstrates the difficult challenge faced by authorities in charge of municipal waste management. Some states like Iowa, New Hampshire and Rhode Island have no or as low as only one available C&D waste landfill. The landfill tipping fees vary from state to state and it can be as high as $100 per ton in the northeast states.

1.3 Current applications of RAC

Within the past 25 years, the use of RAC in base or sub-base applications has been widely accepted by many highway agencies. The Federal Highway Administration (FHWA) National Review on the use of RAC shows that in many states RAC has been primarily used as a fill or a sub-base material, and less often, as an aggregate in new concrete pavements. The use of crushed concrete as an aggregate in high-grade concrete, however, been restricted by a lack of experience and knowledge on RAC behavior.

2 PROPERTIES OF PLAIN RAC

2.1 Compressive strength

Buck (1977) observed an average of 20% less strength in the RAC compared to its parent concrete. In general, the majority of researchers have reported 5 to 30% decrease in the compressive strength of concrete made of coarse recycled aggregate, depending on the quality of the parent concrete and mix design (Hansen and Narud 1983, Ravindrarajah and Tam 1985, Topcu and Guncan 1995, Yamato et al. 1998, Ajdukiewicz and Kliszczewicz 2002, Topcu and Sengel 2004, Rahman et al. 2009). The use of fine recycled aggregates seems to require extra prudence as it can dramatically decreases the strength and workability.

2.2 Modulus of elasticity

Usually the modulus of elasticity of a RAC made of fine and coarse recycled aggregates is about 25 to 40% less than the parent concrete while for a concrete made with only recycled coarse aggregates (Sri Ravindrarajah and Tam 1985, Topcu and Guncan 1995, Domingo-Cabo et al. , 2009. Berndt (2009) suggested the use of 50% blast furnace slag and fly ash to increase the modulus of elasticity of RAC.

2.3 Tensile and flexural strength

The majority of findings indicate that RAC made from recycled coarse aggregates and natural fine aggregates generally shows, at most, 10% reduction in tensile strength. Generally, concrete made from recycled coarse and fine aggregates has reductions in tensile strengths of less than 10% and a maximum of 20% for the worst case (Hansen 1986).

2.4 Bond strength

Xiao and Falkner (2007) examined the bond strength and observed that with equivalent mix proportions, the bond strengths of RAC and NAC were similar, irrespective of the recycled aggregate replacement percentage. For the same compressive strength, RAC showed even higher bond strengths. Eguchi et al. (2007), Etxeberria et al. (2007) and Corinaldesi and Moriconi (2009) studied the bond strength of reinforced RAC concrete and observed no specific issues.

2.5 Creep and shrinkage

Sri Ravindrarajah and Tam (1985) observed that RAC creep was about 30% to 60% more than its parent concrete. Domingo-Cabo et al (2009) observed that 50% replacement of natural coarse aggregate with RCA caused more than 40% increase in creep and 20% increase in shrinkage. In the case of complete replacement of coarse aggregate, more than 50% increase in creep and 70% increase in shrinkage was observed. On the other hand, Kou et al. (2007) found that the use of 25% to 35% fly ash as a partial replacement of cement can considerably reduce the creep of RAC.

2.6 Freeze-thaw resistance

Buck (1977) observed that the freeze-thaw resistance of RAC is higher than the corresponding original concrete while Hansen (1986) reported no difference between freeze-and-thaw resistances of RAC and parent concrete.

2.7 Permeability, carbonation and chloride ion penetration

Hansen (1986) reported that concrete made of recycled aggregates with water/cement ratio of 0.5 to 0.7 shows permeability of two to five times more than NAC. Levy and Helene (2004) observed that the high alkaline reserved in RAC, helped the reinforcement remain passive (PH>7) for much longer. This can significantly delays the corrosion of the steel compared to NAC. Corinaldesi and Moriconi (2009) also reported that RACs prepared with lower water/cement did not present any evidence of corrosion danger. In general, RAC also has higher chloride ion penetration (sea water, de-icing salt, etc.) depth. Khan (1984) showed that the reduction in water/cement ratio can significantly improve the corrosion resistant of the RAC and Kou et al., 2007 encouraged the use of 25%-35% fly ash to reduce chloride penetration depth.

2.8 Density and workability

Recycled aggregates generally have densities slightly less than their parent natural aggregates which causes a workability issues. This may also be attributed to the rougher surface texture, greater angularity and presence of mortar residue adhered to the crushed recycled aggregates (Hansen and Narud 1983). To improve the workability of the RAC, sometimes the use of drysurface saturated aggregates is suggested (Hansen 1992). To improve RAC workability, the use of plasticizers is always helpful.

3 EXPERIMENTAL STUDY

3.1 General

To study the different variables influencing the behavior of confined RAC, an extensive experimental investigation was carried out at the High Performance Concrete Laboratory at New Jersey Institute of Technology. A total of forty-four 10 x 10 x 32 inch columns were tested under monotonic and cyclic concentric axial loadings. The core size (measured from center to center of the exterior ties) was kept constant at 8 x 8 inches for all column specimens. This yielded a constant core area equal to 64% of the total gross cross sectional area. A variety of arrangements for lateral reinforcement was considered. Casting and testing of the forty-four columns was completed over a period of consecutive 58 days.

3.2 Fabrication and materials

3.2.1 Recycled Coarse Aggregates (RCA)

Approximately 3/8” maximum size recycled coarse aggregate was obtained from five cubic yards of discarded concrete mass. At the age of 21 days, this concrete was crushed down to 1/2” and graded to conform to ASTM C33-3 grading requirements for coarse aggregates. Limiting the maximum size of the RCA to 3/8” was to ensure that the RAC would easily pass through the reinforcements. The crushing process was the same as crushing normal stones to obtain natural aggregate. The discarded concrete was fed to rotary crushers and the product was passed through layers of shaking screens to obtain the size of interest. Larger aggregates were automatically fed back to the crushers again.

3.2.2 RAC mixing

A small laboratory-scale 6 cubic feet electric concrete mixer was used for mixing. To ensure homogeneity of the concrete, only 2.0 cubic feet concrete were mixed in each load, enough to cast one column at a time and few 4 x 8 inch cylinder specimens. In order to improve the quality, a “Two-Stage Mixing Approach (TSMA)” was employed as shown in Figure 2. Through experiments, Tam et al (2005) have shown that their proposed TSMA improved the strength of aggregate-paste Interfacial Transition Zone (ITZ), and hence enhanced the strength. It was observed that during the first stage of mixing, TSMA uses half of the required water for mixing leading to formation of a thin layer of cement slurry on the surface of RCA which will permeate into the porous old cement mortar, filling up the old cracks and voids. At the second stage of mixing, the remaining water is added to complete the concrete mixing process.

The RAC mix proportions and physical properties of the constituent materials are presented in Table 1. The design was obtained through a trial-an-adjustment procedure such that a 21-day compressive strength of 4.25 ± 0.25 ksi can be achieved while the slump remains approximately 5 inches. This slump was necessary to ensure reasonable flow of the RAC through the reinforcement. In the absence of high early strength cement, 20% of the cement was replaced by silica fume which, with the use of accelerators, helped in obtaining most of the concrete strength within the first two weeks. An average compressive strength of 4.3 ksi was obtained which was very close to the strength of original concrete.

Figure 2. Utilized TSAM mixing approach suggested by Tam et al, 2005.

Table 1 RAC mix proportions (per one cubic foot).

Cement Type I	Silica Fume	RCA	Sandclay	Water	Accelerator[1]	Water reducer[2]
12.25 lb	3.25 lb	60.50 lb	53.00 lb	10.25 lb	4 oz	6 oz

[1]PRO-SET® CaCl, [2] Sikament® 86

3.2.3 Longitudinal and lateral reinforcement

Deformed steel bars of #3 through #6 with yield stress of 72 ksi were used for the longitudinal reinforcement. For transverse steel, plain 3/16" cold-rolled galvanized steel wires were used. Using 0.2% offset method, a yield stress of 63 ksi was obtained.

3.2.4 Reinforcing cages

Three different reinforcement configurations were under consideration, as shown in Figure 5. Details of reinforcement are presented in Table 5. By utilizing three different tie spacings of 1, 2 and 3 inches, a quite wide range of transverse steel volumetric ratio (the volume of transverse steel per unit volume of core concrete) was achieved. Each column was designated by a generic name in which first letter represented the tie configuration (Figure 5), the first number showed the tie spacing and the last number represented the column number. In order to localize most of the damage in the middle of the columns, extra ties were consider at the ends of the columns and the ends were warpped in GFRP fabric. In order to facilitate the development of yield strength of the steel wires, 135-degree hooks with at least 3-inch extension were provided. For those Type B and C columns which spacing was 1 inch, no extra ties were provided due to the lack of room available for additional ties. Some of the column ends were further confined with two layers of 6-inch wide SikaWrap® GFRP sheets. In total, 2300 ties were fabricated.

3.3 Instrumentation and test setup

Approximately 20 inches of the mid region of the columns was instrumented with Direct Current Differential Transformers (DCDTs) to monitor the axial deformation of the test specimens. These sensors were frequently calibrated during the experiments. To ensure good contact surface between the loading heads and the column ends, column ends were capped with slef-leveling hydro-stone® gypsum cement. The columns were concentrically loaded with a 1000-kip MTS815 servo-hydraulic loading unit as shown in Figure 6. All test loads and actuator positions were controlled via MTS TestStar® digital controller. Automatic loading processes were also programmed and introduced to the MTS machine through TestWare® software (version 4.0D), a MTS product.

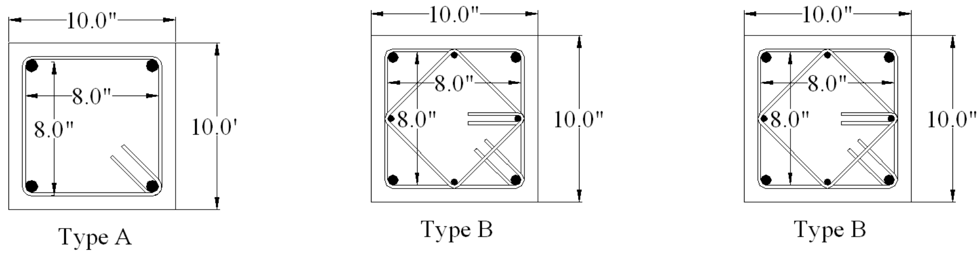

Figure 3. Tie configurations.

Figure 4. 1000-kip MTS815 servo-hydraulic loading unit and hardwares.

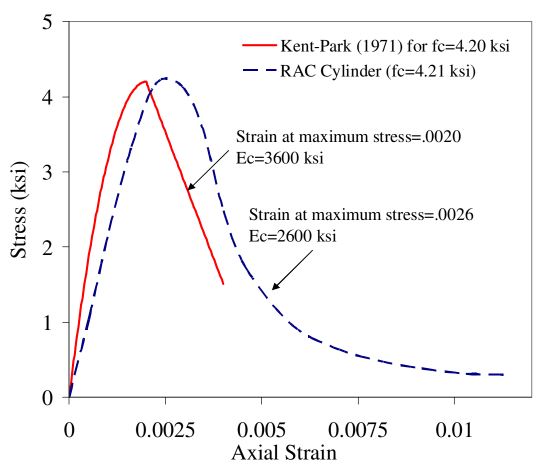

Figure 5. Typical RAC stress strain curves.

The load and displacement generated by the loading unit as well as all of the DCDT and the internal sensor data were fed to a System 5000 data acquisition hardware which in turn was managed through StrainSmart® program, a Vishay-Micromeasurement product.

4 TEST OBSERVATIONS

4.1 Plain RAC cylinders

The RAC cylinder specimens demonstrated relatively smaller modulus of elasticity, compared with modulus of elasticity for normal concrete with the same strength as shown in Figure 7. In addition, the strain corresponding to maximum strength was observed to be appreciably more than the common value of 0.002 for normal concrete, as can be seen from Figure 7. Another intersting observation was that the slope of the ascending branch of the stress-strain curves (i.e moulus of elasticity) did not show any significant change. In other words, the modulus of elasticity remained almost constant untill the peak strength approached. This is quite different than normal concrete which tangent and secant moduli are significantly different.

4.2 Cracking behavior of the RAC columns

The behavior of concrete cover was continuously observed, particularly for development of cracks in vertical direction. For almost all of the RAC columns, vertical hair cracks were observed at all four corners of the columns at a longitudinal strain of approximately 0.0015. These cracks, however, started widening at a longitudinal strain of approximately 0.002 to 0.0025 and the concrete cover gradually started spalling off in a rather evenly manner on all sides. It should be noted that for NAC columns, the spalling off strain was observed to initiate in the range of 0.0015 to 0.0020 according to Sargin (1971), Sheikh and Uzumeri (1978).

4.3 Effect of confinement on load-deformation behavior

The behavior of the RAC column under the axial compression was not much different from normal aggregate concrete. Figure 8 shows the load-deformation curves obtained for columns A1-1, B2-1 and C3-1. These specimens had approximately the same amount of lateral reinforcement volumetric ratio, ρ_s. The behaviors of the columns were quite similar which indicates the predictability of RAC as a structural material. As it can be seen from Figure 9, the failure mode was not any different from expected failure of normal concrete columns. In the RAC columns, while approaching the maximum strength, small vertical cracks appeared on the concrete cover. Further axial deformation then caused the cracks to widen and the cover to gradually spall off. Eventually the core concrete carried the entire axial load. The failure was usually a combination of crushing the concrete as well as buckling of the longitudinal rebars, precisely similar to normal concrete columns. Significant ductility values were observed for the columns with proper tie configuration of type B and C specially for those with higher ρ_s values, as shown in Figure 10. It is obvious that that ductility could not be of any issue in reinforced RAC. Table 2 presents the theoretical and experimental values of the ultimate strength. It is apparent that the column could easily meet the design strength as well. These results and observation do not show any weakness and inferiority in the use of RAC in reinforced columns.

5 SUMMARY ABD DISCUSSION OF THE PRELIMINARY RESULTS

Although there are significant environmental advantages in recycling concrete and use it as an aggregate for new concrete, there has always been a hesitation in the use of RAC as a reliable structural material. Due to its higher porosity resulted from old cement mortar adhered to the surface, RAC is generally acknowledged to be slightly less strong than NAC. However, the available research work on RAC durability and mechanical properties in no way refutes the use of RAC as a structural material. Currently the use of RAC is limited to low-grade applications like road work sub-base, embankments, drainage and at the best in pavements. Widespread application of RAC, such as seismic, requires knowledge on other behavioral characteristics i.e. ductility, material behavior under biaxial and triaxial state of stresses, loading rate, strength degradation, etc.

Preliminary results of the comprehensive study on plain and reinforced RAC seismic properties conducted by the authors of this paper showed that similar to normal concrete, RAC concrete can gain significant strength and ductility if properly reinforced with lateral reinforcement.

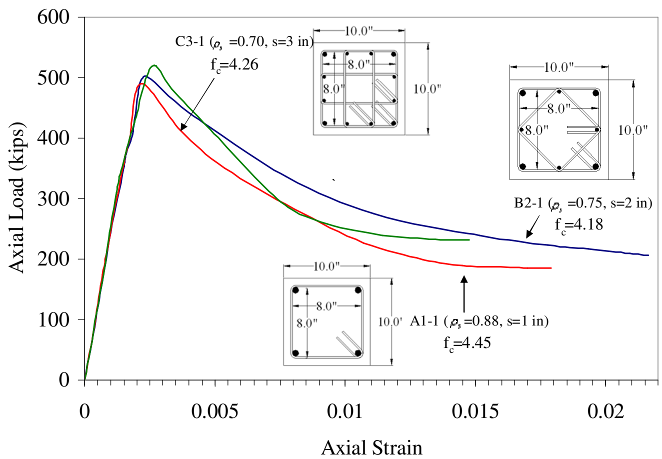

Figure 6. Effect of transverse steel configuration on RAC column behavior.

Figure 7. Failure of columns A1-1, B2-1 and C3-1.

Table 2 Design and test strengths values.

Specimen	Concrete Cylinder Strength (ksi)	Lateral steel, ρ_s (%)	Longitudinal steel, ρ_l (%)	Calculated Strength (kips)	Test strength (kips)	Percent difference
A1-1	4.26	.88	1.74	478	492	3%
A2-1	4.12	.44	1.74	466	449	-4%
A3-1	4.26	.29	1.74	478	449	-6%
B1-1	4.23	1.51	1.68	475	511	8%
B2-1	4.18	.75	1.68	471	501	6%
B3-1	4.36	.50	1.68	486	495	2%
C1-1	4.23	2.10	1.68	475	546	15%
C2-1	4.34	1.05	1.68	484	524	8%
C3-1	4.45	.7	1.68	493	518	5%

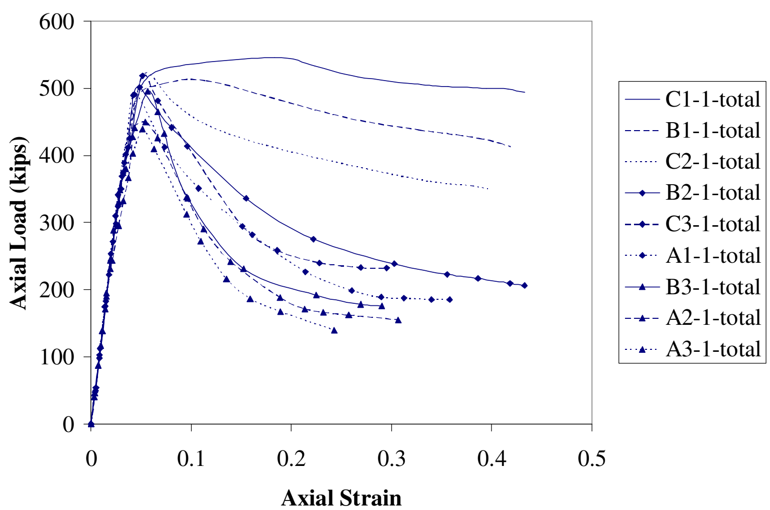

Figure 8. Effect of increase in tie volumetric ratio on ductility of RAC columns.

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