Construction and Building Materials 53 (2014) 612–620

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An experimental study on shear strength of reinforced concrete beams with 100% recycled concrete aggregate

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HIGHLIGHTS

- The RAC beams possess 12% lower shear strength compared with the CC beams.
- The MCFT method predicts shear strength of the RAC beams very well.
- The RAC test results fall within a 95% confidence interval of the CC shear test database.

ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form 4 December 2013
Accepted 9 December 2013
Available online 8 January 2014

Keywords:
Recycled concrete aggregate
Conventional concrete
Shear strength
Experimental study

ABSTRACT

An experimental investigation was conducted to study the shear strength of full-scale beams constructed with 100% recycled concrete aggregate (RCA) as well as conventional concrete (CC). This experimental program consisted of 12 beams (six for each concrete type). The test parameters for this study include longitudinal reinforcement ratio and concrete type. The experimental shear strengths of the beams were compared with the shear provisions of both U.S. and international design codes (U.S., Australia, Canada, Europe, and Japan) as well as a shear database of CC specimens. The shear strengths of the beams were also evaluated based on different fracture mechanics approaches and the modified compression field theory (MCFT) method. Furthermore, statistical data analyses (both parametric and non-parametric) were performed to evaluate whether or not there was any statistically significant difference between the shear strength of the recycled aggregate concrete (RAC) and CC beams. Results of these statistical tests show that the 100% RCA beams possess approximately 12% lower shear strength compared with the CC beams.

1. Introduction

Recently, there has been an increasing trend toward the use of sustainable materials. Sustainability helps the environment by reducing the consumption of non-renewable natural resources. Concrete – the second most consumed material in the world after water – uses a significant amount of non-renewable resources. As a result, numerous researchers have investigated the use of recycled materials in the production of concrete such as fly ash [1–4] and recycled aggregate [5–12].

Unfortunately, global data on concrete waste generation is not available, but construction and demolition waste accounts for around 900 million tones every year just in Europe, the US, and Japan [13]. Recycling concrete not only reduces using virgin aggregate but also decreases landfills.

Comprehensive research has been done on both the fresh and hardened properties of recycled aggregate concrete (RAC), but limited, and often contradictory, research has been performed on the structural behavior of RAC. The early research on structural performance of RAC was published in Japan [5]. Maruyama et al. [6] tested beams with different longitudinal reinforcement ratios ranged between 2.4% and 4.2%. They also investigated three different water/cementitious material ratios, w/cm, (0.30, 0.45, and 0.60) for their mix designs. They reported that the crack patterns and failure modes of the RAC beams were identical with the conventional concrete (CC) beams. The RAC beams without stirrups showed 10–20% lower shear strength compared with the CC beams.

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http://dx.doi.org/10.1016/j.conbuildmat.2013.12.019

Gonzalez-Fonteboa and Martinez-Abella [7] tested eight beams with 3% longitudinal reinforcement ratio and 50% recycled coarse aggregate. Results of their study showed that in terms of both deflection and ultimate shear strength, no significant difference was observed between the RAC and CC beams, but they observed notable splitting cracks along the tension reinforcement. They concluded that existing code provisions for shear can be used for the RAC beams. González-Fonteboa et al. [8] repeated the previous study except for adding 8% silica fume to the mix designs. They observed that notable splitting cracks along the tension reinforcements were mitigated by the addition of silica fume.

Choi et al. [9] evaluated the shear strength of 20 reinforced concrete beams with different span-to-depth ratios (1.50, 2.50, and 3.25), longitudinal reinforcement ratios (0.53%, 0.83%, and 1.61%), and RCA replacement ratios (0%, 30%, 50%, and 100%). Results of their study showed that the shear strength of the RAC beams was lower than that of the CC beams with the same reinforcement ratio and shear span-to-depth ratio. They reported that beams with smaller span-to-depth ratios and higher percentage of recycled aggregate showed a higher reduction in shear strength.

Fathifazl et al. [10] used the equivalent mortar volume (EMV) method for their mix designs. They used both limestone (63.5% recycled aggregate replacement) and river gravel (74.3% recycled aggregate replacement) as a coarse aggregate for their mix designs. They tested beams with four different shear span-to-depth ratios ranging between 1.5 and 4, and also with four different effective depths (250, 375, 450, and 550 mm) to investigate size effect. They reported superior shear strength for the RAC beams. They also concluded that current code provisions for shear conservatively predicted the capacities of the RAC beams.

Schubert et al. [11] studied 14 slabs ($0.2 \times 0.5 \times 2.3$ m) with 100% recycled coarse aggregate under four point load condition. They concluded that RAC slabs can be designed using the same design equations as for CC.

Xiao et al. [12] tested 32 shear push-off specimens with different percentages of recycled coarse aggregate replacement. They reported no significant difference observed in terms of shear stress-slip curves, crack propagation path, and shear transfer performance across cracks between the RAC and CC specimens. They also concluded that recycled aggregate replacement up to 30% did not affect ultimate shear load, but for higher percentages of RCA replacement, the ultimate shear load decreased.

2. Research significance

Based on a review of the existing literature, there is a lack of full-scale shear testing of RAC specimens, particularly with 100% replacement of virgin aggregate. Without this background, there is no quantitative basis for safely implementing RAC in structural design. Consequently, the authors, in conjunction with the Missouri Department of Transportation (MoDOT), developed a testing plan to evaluate shear strength of RAC specimens with local materials. The mix designs, based on standard mixes currently used by MoDOT, was on the lower end of cement content in order to develop a relatively harsh mix to investigate constructability issues common to RAC. The experimental program, test results, and analyses for this study are presented in the following discussion.

3. Experimental investigation

3.1. Materials and mixture proportions

For the CC mix, ASTM Type I portland cement, crushed limestone with a maximum nominal aggregate size of 25 mm from the Potosi quarry (Potosi, MO) were used. The fine aggregate was natural sand from Missouri River Sand (Jefferson City, MO).

This mix design was used to construct control specimens to serve as baseline comparisons to the RAC mix and will also serve as parent material for the RCA source. The resulting concrete was ground at 28 days of age into aggregate with a maximum nominal aggregate size of 25 mm. Test results for the coarse aggregate used in the CC mix design as well as the resulting RAC are shown in Table 1. As expected, the RCA had lower specific gravity and unit weight and considerably higher absorption. The Los Angeles abrasion test results were virtually identical. For the RAC mix, all the ingredients were the same except the coarse aggregate was 100% recycled coarse aggregate (by volume) that contained 46.1% residual mortar (by mass).

The longitudinal and shear reinforcement steel consisted of ASTM A615-12 [14], Grade 60, (414 MPa) material. All of the reinforcing bars were from the same heat of steel, used the same deformation pattern, and met the requirements of ASTM A615-12. Table 2 shows the tested mechanical properties of the reinforcing steel.

The concrete mixtures with a target compressive strength of 35 MPa were delivered by a local ready-mix concrete supplier (Rolla, MO). The purpose of using the ready-mix supplier was to validate the RAC concept in actual concrete production runs. The mixture proportions, fresh and hardened properties of both the CC and RAC mixes are given in Tables 3 and 4, respectively.

3.2. Details of test beams

Six beams without stirrups were constructed for each concrete type. Beams with three different longitudinal reinforcement ratios (1.27%, 2.03%, and 2.71%) were designed to preclude flexural failure and satisfy the minimum and maximum longitudinal reinforcement requirements of ACI 318-11 [15]. All beams tested in this program had a rectangular cross section with a width of 300 mm, a height of 460 mm, a length of 4300 mm, and shear span-to-depth ratios of 3.0 or greater (Fig. 1). The beam designation included a combination of letters and numbers: NS stands for no stirrups and numbers 4, 6, and 8 indicate the number of #22 (22 mm diameter) longitudinal reinforcement bars within the tension area of the beam section. For example, NS-6 indicates a beam with no stirrups within the shear test regions and 6 #22 bars within the bottom of the beam.

3.3. Fabrication and curing of test specimens

Specimens were constructed, cured, and tested in the Structural Engineering High-Bay Research Laboratory (SERL) at Missouri University of Science and Technology. After casting, the beam specimens and the quality control/quality assurance companion cylinders (ASTM C39-12 [16] and C496-11 [17]) and beams (ASTM C78-10 [18]) were covered with both wet burlap and plastic sheeting. All of the beams and companion cylinders were moist cured for seven days and, after formwork removal, were stored in a semi-controlled environment with a temperature range of 18–24 °C and a relative humidity range of 30–50% until they were tested at an age of 28 days.

3.4. Test setup and procedure

3.4.1. Testing facilities

A load frame was assembled and equipped with two 490-kN, servo-hydraulic actuators intended to apply the two point loads to the beams. The load was applied in a displacement control method with a rate of 0.50 mm/min. The shear beams were supported on a roller and a pin support, 300 mm from each end of the beam, creating a four-point loading situation with the two actuators (Fig. 1).

Table 1
Aggregate properties.

Property	CC	RCA
Bulk specific gravity, oven-dry	2.72	2.35
Dry-rodded unit weight (kg/m^3)	1600	1440
Absorption (%)	0.98	4.56
LA abrasion (% loss)	43	41

Table 2
Mechanical properties of reinforcing steel.

Bar no.	Yield stress (MPa)	Ultimate stress	Modulus of elasticity	Elongation (%)
10	494	746	206,890	11.7
13	510	698	196,570	13.3
22	449	687	193,140	16.3