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

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ABSTRACT

The following paper presents the results of an experimental investigation of the flexural strength of full-scale reinforced concrete beams constructed with both 100% recycled concrete aggregate (RCA) as well as conventional concrete (CC). This experimental program consisted of eight beams (four for each concrete type). The test parameters for this study include longitudinal reinforcement ratio and concrete type. The beams were tested under a simply supported four-point loading condition. The experimental cracking, yielding, and ultimate moment of the beams were compared with the ACI 318-11 and Eurocode 2-05 provisions and the modified compression field theory (MCFT) method. Furthermore, the experimental flexural strengths of the beams were compared with both flexural test databases of CC and RCA specimens. Results of this study show that the RCA beams have comparable ultimate flexural strength and approximately 13% higher deflection corresponding to the ultimate flexural strength of the CC beams.

1. Introduction and research significance

Sustainability is at the forefront of our society. Unfortunately, concrete, our most common construction material uses a significant amount of non-renewable resources. Consequently, many researchers have investigated the use of recycled materials in the production of concrete such as fly ash [1–7] and recycled aggregate [8–17].

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 [18]. Recycling concrete not only reduces using virgin aggregate but also decreases landfills.

Comprehensive research [19–25] has been done on both the fresh and hardened properties of recycled concrete aggregate (RCA), recycled aggregate resulting from crushed concrete, but very little research has been performed on the structural behavior of RCA. The early research on structural performance of RCA was published in Japan [9]. Mukai and Kikuchi [8] tested 150 × 150 mm cross section and 1.8-m long beams with both 15% and 30% RCA replacement and reported no significant difference in ultimate moment, but lower cracking moment for RCA beams. Yagashita et al. [9] used three types of recycled aggregate with 100% replacement as follows: low grade RCA, using only impact crusher (R3); medium grade RCA, impacting R3 with roll crusher (R2); and high grade RCA, crushing R2 once again with roll crusher (R1). Their results showed using high grade RCA slightly decrease (around 10%) the flexural capacity of RCA beams. Ajdukiewicz and Kliszczewicz [10] used partial or full recycle aggregate. All the beams were rectangle 200 × 300 mm and 2600 mm long with two longitudinal reinforcement ratios (0.90% and 1.60%). They reported that the RCA beams had slightly (3.5% in average) lower moment capacity and higher deflection compared with the CC beams. Sato et al. [11] tested 37 beams with three different longitudinal reinforcement ratio (0.59%, 1.06%, and 1.65%). They used 100% recycled aggregate for their mix designs. Results of their study showed that the RCA beams had larger deflection compared with the CC beams. In terms of crack spacing no significant difference observed between the RCA and CC beams; however, the RCA beams had wider cracks compared with the CC beams. They also reported almost the same ultimate moment for the RCA and CC beams. Maruyama et al. [12] tested beams with 1% longitudinal reinforcement ratio and reported that the RCA beams cracks were

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wider and spaced closer compared with the CC beams. The RCA beams had larger deflection, but no significant difference between the flexural capacity of the RCA and CC beams. Fathifazl et al. [13] used equivalent mortar volume (EMV) method for their mix designs. They used both limestone (63.5% recycled aggregate) and river gravel (74.3% recycled aggregate) as a coarse aggregate for their mix designs. Their beams had three different longitudinal reinforcement ratio ranged between 0.49% and 3.31%. They reported comparable and even superior flexural behavior for RCA beams at both service and ultimate states. They concluded that current codes flexural provisions can be used for RCA beams. Bai and Sun [14] used 8–10 years old RCA with different replacement levels (50%, 70%, and 100%). They observed similar crack pattern, but deflection and crack width increased with the increment of RCA replacement level. They also concluded that RCA replacement level does not significantly affect the cracking ultimate moment of beams. Ignjatovic et al. [15] studied nine full scale beams with 0%, 50%, and 100% recycled coarse aggregate and 0.28%, 1.46%, and 2.54% longitudinal reinforcement ratio. They reported no noticeable difference between load–deflection behavior, service load deflection, and ultimate flexural strength of RCA and CC beams. But they observed that the beams with higher range of recycled aggregate showed higher level of concrete destruction at failure. Kang et al. [16] used beams with longitudinal reinforcement ratio ranged between 0.5% and 1.8% with RCA replacement level up to 50% for both normal and high strength concrete. They observed greater number of cracks and lower cracking moment for RCA beams. They also reported no significant decrease in flexural capacity up to 30% RCA replacement level. Knaack and Kurama [17] tested 150×230 mm cross section and 2000 mm long beams. They used RCA from late 1920s foundation and with both 50% and 100% replacement level. They reported higher deflection for the RCA beams, but they concluded that the existing analytical models and code provisions can be used for the RCA beams.

In summary, only using EMV method by Fathifazl et al. [13] resulted in superior flexural strength performance of RCA beams compared with CC beams, otherwise using RCA instead of virgin aggregate showed either lower flexural strength or almost the same flexural strength for RCA beams compared with CC beams.

Based on a review of the existing literature, there is a lack of full-scale flexural testing of RCA specimens, particularly with 100% replacement of virgin aggregate and also some conflicting results. Consequently, the authors, in conjunction with the Missouri Department of Transportation (MoDOT), developed a testing plan to evaluate flexural strength of RCA 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 RCA concrete. The experimental program, test results, and analyses for this study are presented in the following discussion.

2. Experimental program

2.1. Specimen design

A total of eight beams were constructed (four CC and four RCA). Beams have two different longitudinal reinforcement ratios (0.47% and 0.64%) with shear reinforcements to preclude shear failure and satisfy the minimum and maximum longitudinal reinforcement requirements of ACI 318-11 [26]. All beams had a rectangular cross section with a width of 300 mm, a height of 460 mm (see Fig. 1). The beam designation included a combination of letters and numbers: F stands for flexural beams and numbers 6 (19 mm diameter) and 7 (22 mm diameter) indicate the size of longitudinal reinforcement bars within the tension area of the beam section. For example, F-6 indicates a beam with 2#6 (19 mm diameter) within the bottom of the beam.

2.2. 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 RCA mix and will also serve as parent material for the RCA source. The resulting concrete was ground 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 RCA 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 RCA 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 weight). The residual mortar content of RCA was determined based on a method developed by Abbas et al. [27] which involved immersion of RCA in sodium sulfate solution and its subjection to three freeze-and-thaw cycles. Both the CC and RCA had a similar gradation.

The longitudinal and shear reinforcement steel consisted of ASTM A615 [28], 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. 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 RCA concept in actual concrete production runs. The mixture proportions, fresh and hardened properties of both the CC and RCA mixes are given in Tables 3 and 4, respectively.

2.3. 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 [29], C469 [30], and C496 [31]) and beams (ASTM C78 [32]) 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.

2.4. Flexural test setup and procedure

2.4.1. Testing facilities

A load frame was assembled and equipped with two 490-kN (980-kN in total), servo-hydraulic actuators intended to apply the two point loads to the beams (Fig. 1). The load was applied in a displacement control method at a rate of 0.50 mm/min. The flexural 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.

2.4.2. Instrumentations

A Linear variable differential transformer (LVDT) and strain gauges were used to measure the deflection at the beam center