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Behavior of shear-critical prestressed concrete beams with recycled concrete aggregates under ultimate loads

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ABSTRACT

This paper investigates the effect of recycled concrete aggregates (RCA) on the ultimate-load behavior of shear-critical precast/prestressed concrete beams. A total of eighteen simply supported, normal strength concrete beam specimens were tested under four point bending with normalized moment-to-shear ratios of 2 and 1, defined as the distance from the simple support to the point of load application divided by the depth to the prestressing strands. Two sources of high-quality RCA (from rejected precast members and a construction demolition recycling yard) were used to replace natural crushed limestone at 50% and 100% by volume. Two different levels of prestressing were used. In general, the use of RCA had a relatively small effect (as compared with the high levels of aggregate replacement) on the overall ultimate load versus deflection behavior of the beams or on the progression of failure. Importantly, the ability of closed-form code design methods and nonlinear numerical models to predict the measured behaviors of the beams was not significantly affected by the aggregate replacement.

1. Introduction

Vast amounts of crushed limestone, gravel, and other types of natural coarse aggregates (e.g., granite) are used to build and maintain the civil infrastructure around the world. The mining and transportation of these materials consume significant energy (and therefore contribute to CO_2 emissions) and also negatively impact the ecology of forested areas and riverbeds. Further, natural aggregate deposits from permitted quarries have been depleted in many urban regions, thus requiring aggregates to be transported over long distances.

The demands for natural coarse aggregates can be reduced by recycling old concrete into new construction. Even though RCA can pass the prescriptive requirements for coarse aggregates in structural concrete (ASTM C33 [1]), the variability in the properties and quality of the recycled material needs to be quantified and incorporated into design [2,3]. While not a focus of this paper, the durability (i.e., service life) of RCA concrete structures is another major concern that could have a significant impact on the use of RCA for new structural concrete.

The controlled environment and repetitive nature of precast concrete construction can allow better control and monitoring of RCA quality, properties, and effects. Specifically, precast concrete plants can recycle rejected precast members, discarded extremes of hollow-core, as well as over-batched or rejected batches of concrete as coarse aggregates in new structural members. The primary benefits of precast RCA (i.e., RCA sourced from precast concrete plant operations) are: (1) clean RCA with high quality and consistent properties (as compared with RCA from construction recycling yards); (2) reduced durability concerns (due to known original aggregate in precast RCA); (3) reduced aggregate transportation costs; and (4) reduced storage space for rejected concrete at the plant.

As compared to cast-in-place concrete structures, previous research on the use of RCA in precast concrete is extremely limited. This is the main focus of the current paper.

2. Background

Given the high demands of concrete on energy and the environment, sustainable construction practices must be investigated and transferred to practice in multiple avenues. To date, much of the previous research on this topic has focused on the use of industrial byproducts (e.g., slag, silica fume, fly ash) to replace Portland cement and the use of admixtures to reduce the amount of batch water. In comparison, research to reduce the demands for natural aggregates is relatively new and has mostly focused on material-level investigations and conventional (i.e., non-prestressed) cast-in-place reinforced concrete construction. The effect of RCA on the shear behavior of non-prestressed concrete beams

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has been investigated by many researchers (e.g., [4–9]). Vertical load, lateral load, and shake-table tests of reinforced concrete frame structures [10–14], some incorporating precast RCA, have generally supported the results from member tests that RCA is a feasible alternative to natural coarse aggregates in structural applications. In comparison with the ultimate-load behavior, the effect of RCA on the sustained service-load deflections of reinforced concrete structures has been found to be greater due to the reduced stiffness and increased creep and shrinkage of RCA concrete [2,3,15,16].

This paper contributes to and expands this knowledge by investigating the use of RCA in prestressed concrete, which is the predominant method of construction in the precast industry. To the best of the authors' knowledge, the only previous research on prestressed RCA concrete structural members has been on the ultimate flexural strength of railroad sleepers [17]. Several researchers have conducted material-level investigations on various properties of concrete (e.g., strength, stiffness, creep, shrinkage, durability) made with precast RCA (i.e., RCA from discarded precast concrete) [18–22]. In general, these studies have found that precast RCA is a suitable material as coarse aggregate in structural concrete, often outperforming traditional RCA from construction demolition recycling yards.

Specifically, the paper describes the measured results from 18 pre-tensioned concrete beam test specimens monotonically loaded to ultimate shear failure under 4-point bending. The primary test variables were the RCA source (rejected precast hollow-core members and traditional construction demolition waste), aggregate replacement ratio, prestress level, and moment-to-shear ratio. The beam specimens utilized two standard concrete mixture designs from a prominent precast production plant, but with crushed limestone replaced by RCA up to full (100%) replacement by volume. The measured results are compared with an existing structural analysis program for prestressed concrete, Response 2000 [23], as well as ACI 318-14 [24] design predictions.

3. Precast/prestressed beam specimens

Elevation views and cross-section for the precast/prestressed beam test specimens are shown in Fig. 1. The 18 specimens were saw-cut from nine 5791 mm (228 in.) long beams that were previously subjected to service-level loads for a period of 103 days or more [25]. These nine beams were produced at Kerkstra Precast, Inc., Grandville, Michigan, according to the daily batching, casting, and prestressing procedures of the plant. The beam cross section width was b = 152 mm (6 in.) and height was h = 229 mm (9 in.), with the following reinforcement (Fig. 1): (1) two d_b = 12.7 mm (0.5 in.) diameter steel prestressing strands at a depth of d_p = 191 mm (7.5 in.); (2) two Grade 420 (U.S. Grade 60) No. 10 (U.S. No. 3) longitudinal bars at the top; and (3) Grade 420 No. 10 stirrups at s_v = 171 mm (6.75 in.) on center. The two No. 10 top bars were to control cracking on the top surface from

Table 1
Aggregate properties.

Aggregate	Type	Specific gravity		Water absorption (% weight)
		Bulk dry	Saturated surface dry	
RCA-PC3	Rejected precast	2.44	2.52	3.39
RCA-T	Demolition waste	2.49	2.60	4.36
NA-CL2	Crushed limestone	2.61	2.68	0.60
FA2	Sand	–	2.62	0.90
FA3	Limestone sand	–	2.80	0.60

prestress transfer. The strands in six of the beams were pre-tensioned (jacked) to a stress of $f_{pj} = 0.7f_{pu}$ [where, f_{pu} = 1862 MPa (270 ksi) is the specified ultimate strand strength] to prevent immediate cracking of the bottom surface under service loads (consistent with Class U member definition in ACI 318-14). The other three beams were pre-tensioned to $f_{pj} = 0.5f_{pu}$ to result in concrete tension stresses within the range defined for ACI 318-14 Class C (cracked) members under service loads.

RCA from two different sources were used (Table 1). RCA-PC3 was rejected hollow-core members (Fig. 2a) at Kerkstra Precast, Inc., and RCA-T was a traditional construction demolition waste acquired from a recycling yard near the precast plant in Grandville, MI. The gradation for the coarse aggregates was close to ASTM C33 [1] No. 67 [MDOT [26] No. 17A]. Both RCA sources were clean, with less than 1% deleterious materials (e.g., wood, asphalt). The use of high-quality RCA in the project represented the rigorous quality requirements used in the precast concrete industry. The natural coarse aggregate (NA) was crushed limestone (NA-CL2), and typical concrete sand (FA2) as well as limestone sand (FA3) were used to cast the beams. ASTM C127 and ASTM C128 [1] were used to determine the specific gravity and absorption for the coarse and fine aggregates, respectively.

Table 2 shows the dry weight proportions (for a standard batch size of 0.76 m^3) of the two target NA concrete mixtures and the corresponding RCA concrete mixtures used in the beams. The RCA concrete mixtures were determined using the direct volume replacement (DVR) method [2] by replacing a selected volume of coarse NA with an equal volume of RCA according to

$$R = 1 - V_{NA}^{DVR}/V_{NA}^{NAC} \quad (1)$$

where R = volumetric replacement ratio, tested at R = 0.5 (i.e., 50% volumetric replacement) and 1.0 (100% replacement); V_{NA}^{DVR} = volume of natural coarse aggregate in RCA concrete mixture; and V_{NA}^{NAC} = volume of natural coarse aggregate in NA concrete mixture. The DVR method ensures that for a given volume of concrete, the volumetric proportion of each component of the mixture (e.g., total coarse

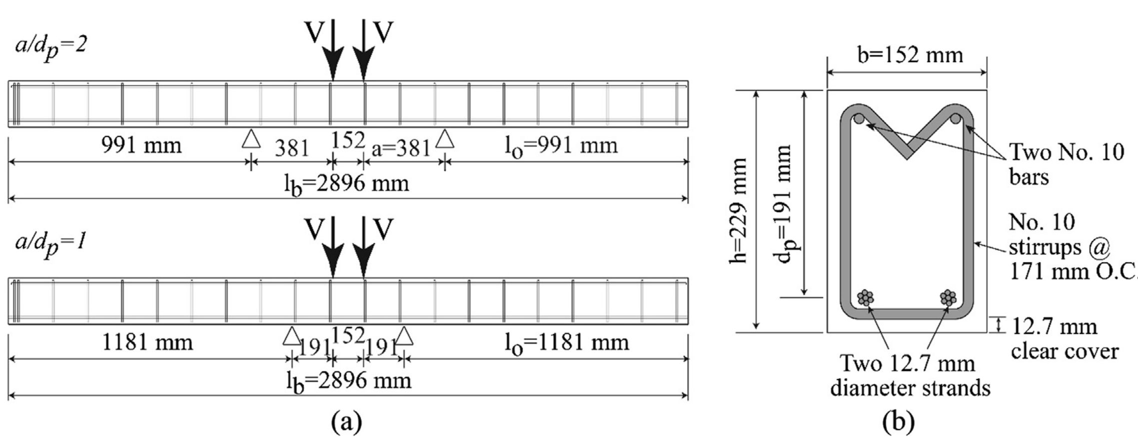

Fig. 1. Shear-critical test beams: (a) a/d_p = 2 and 1 elevation; and (b) beam cross-section. (*Note:* 1 mm = 0.0394 in.)