Effect of recycled concrete aggregates on strength and stiffness gain of concrete and on bond strength of steel prestressing strand

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- This paper investigates the effect of recycled concrete aggregate (RCA) on the rate of concrete compressive strength and stiffness gain with time and on the bond strength between seven-wire steel prestressing strand and concrete.
- The use of RCA did not have a significant effect on the rate of concrete compressive strength or stiffness gain, but it did have a small effect on the strand bond strength.
- For the materials tested, RCA from precast concrete performed better than RCA from returned ready-mixed concrete and demolished concrete.

With an ever-increasing need to revitalize infrastructure, the construction of new concrete structures creates significant demands for coarse aggregates, such as crushed limestone and gravel, while the demolition of old concrete structures offers significant sources of recycled concrete aggregate (RCA). Currently, RCA use in the United States is largely limited to nonstructural applications, such as road base. Uncertainty and variability in RCA properties stemming from inherent variations in demolished concrete sources and conditions have prevented it from being implemented in engineered reinforced concrete applications.

Recent research by Knaack and Kurama[1–4] has shown that certain RCA properties, in particular water absorption and deleterious material content (such as wood and asphalt), significantly affect the behavior of RCA concrete. RCA concrete is made with RCA as a replacement for natural coarse aggregates. Importantly, the water absorption and deleterious material content of RCA can be measured and used to prequalify the material for use in structural concrete. In the precast concrete industry, recycling of discarded or rejected precast concrete products as RCA in new precast concrete members can provide unique opportunities involving consistent and high-quality materials. This is because the source material for precast concrete RCA is well known, is produced in a quality-controlled environment, and contains little or no deleterious materials. The repetitive construction environment for precast concrete would also allow the effects of RCA to be closely monitored and controlled. Ultimately, the ability for precast concrete plants to recycle their own discarded or rejected materials into new concrete would not only reduce the demand for natural coarse aggregates but also eliminate transportation costs for the RCA.

Although there has been increasing research in recent years on the use of RCA in structural reinforced concrete applications (for example, Pacheco et al.[5] and Xiao et al.[6]), no previous work exists in the United States on precast concrete RCA or on precast concrete structures using RCA. To show the feasibility of RCA in precast concrete, where prestressing is widely used, this paper describes the results from laboratory experiments investigating the effect of RCA on the bond strength between seven-wire steel prestressing strand and concrete. The rates of compressive strength gain and stiffness (Young's modulus) gain of the concrete with time, which are important properties for the transfer of the prestressing force to the precast concrete member, were also measured. In addition to RCA from rejected precast concrete, RCA from a returned ready-mixed concrete source (that is, RCA made using excess concrete returned from ready-mixed concrete deliveries) and from a traditional construction demolition recycling yard were also investigated for comparison because these RCA sources would be readily available for use in precast concrete production as well.

Background

Previous research on the use of RCA from precast concrete[7-10] or from returned ready-mixed concrete[11-13] is limited. Further, to the best of the authors' knowledge, no previous research exists on the effects of RCA on the bond strength of prestressing strand or on the rate of concrete strength or stiffness gain with time. In comparison, other related topics, such as the effect of RCA on the bond strength of deformed steel reinforcing bars[14-15] and on the 28-day strength and stiffness of concrete[16-18] have been investigated.

Directly addressing the inherent variability of RCA properties, recent research by Knaack and Kurama[1–4] included 16 RCA sources (mostly construction demolition recycling yards) from the Midwestern United States. The effects of RCA on the 28-day compressive strength and stiffness of concrete were quantified based on the properties of the RCA, the properties of the natural coarse aggregates being replaced, and volumetric replacement of natural coarse aggregates with RCA.[1] The regression relationships in Eq. (1) and (2) were proposed based on the data for the 28-day compressive strength and stiffness (Young's modulus) of concrete:

$$f'_{c,RCA} = f'_{c,NA}[1.0241 - 0.0241(A/A_{NA}) - 0.0138D + 0.0769R] \quad (1)$$

$$E_{c,RCA} = E_{c,NA}[1.0474 - 0.0474(A/A_{NA}) - 0.0113D] \quad (2)$$

where

$f'_{c,RCA}$ = compressive strength of RCA concrete

$f'_{c,NA}$ = compressive strength of natural aggregate concrete

A = combined water absorption of RCA and natural aggregate in RCA concrete

A_{NA} = water absorption of natural aggregate

D = combined deleterious material content of RCA and natural aggregate in RCA concrete

R = volumetric replacement ratio of natural aggregate with RCA

$E_{c,RCA}$ = stiffness of RCA concrete

$E_{c,NA}$ = stiffness of natural aggregate concrete

Following direct volume replacement[1] of natural aggregate with RCA, the replacement ratio R can be calculated using Eq. (3).

$$R = 1 - \frac{V_{NA}^{RCA}}{V_{NA}^{NA}} \quad (3)$$

where

V_{NA}^{RCA} = volume of natural coarse aggregate in RCA concrete

V_{NA}^{NA} = volume of natural coarse aggregate in natural aggregate concrete

Thus, R equal to 0 indicates conventional natural aggregate concrete with no RCA, and R equal to 1 indicates RCA concrete with full (100%) natural aggregate replacement by volume.

The time-dependent gain in the strength and stiffness of concrete involves the early-age stage (that is, the initial 72 hours from casting) as well as the mid- to long-term range.[19] The research described in this paper specifically investigates the period from 1 to 28 days after casting. For RCA to be a viable replacement option in the precast concrete industry, it is necessary that the recycled material not significantly affect the rapid strength gain needed for the daily casting schedule (that is, 1-day strength gain). Previous research has been conducted on the time-dependent strength gain of natural aggregate concrete during the initial 28 days.[20-22] As noted by Neville,[23] there are many factors that affect the rate of gain in the mechanical properties of concrete, such as the water-cement ratio *w/c* and curing conditions (such as temperature).

For RCA to be a viable material for precast concrete, it is also necessary that the bond between the steel prestressing strand and concrete not be significantly weakened so that the force in the prestressing strand can be effectively transferred to the concrete through bond. The bond between seven-wire steel prestressing strand and concrete is formed primarily by two factors. The first factor, as described by Stoker and Sozen,[24] is the chemical and mechanical interaction between the strand and the concrete. The second factor occurs due to the lateral expansion of a released strand (after a reduction in the strand diameter from Poisson's effect during prestressing), which improves the friction force between the two materials and is referred to as the Hoyer effect.[25]

The distance from the end of a prestressed concrete member over which the prestressing force is transferred through bond is defined as the transfer length l_t. To ensure adequate bond development at the critical section of the member, an additional development length is required by ACI 318-14[26] beyond the transfer length, resulting in a total development length calculated by Eq. (4).

$$l_{dt,ACI} = f_{pe}d_p/3000 + (f_{ps} - f_{pe})d_p/1000 \quad (4)$$

where

$l_{dt,ACI}$ = total development length of strand required by ACI 318-14

f_{pe} = effective strand stress after losses

d_p = diameter of strand

f_{ps} = strand stress at critical section

Other expressions for the development length of prestressing strand can be found in the literature.[27] The first term of Eq. (4) defines the transfer length $l_{t,ACI}$ over which both chemical and mechanical interaction and Hoyer effect contribute to bond development, resulting in a rapid increase in the rate of stress increase in the strand from the end of the prestressed member. After the effective prestress f_{pe} is reached, lateral expansion no longer occurs in the strand, eliminating the contribution of the Hoyer effect and resulting in a reduction in the rate of stress increase. Equations (5) and (6) can be developed from axial force equilibrium of a prestressing strand.

$$f_pA_p = U\pi d_pl_b \quad (5)$$

$$f_pd_p = 4Ul_b \quad (6)$$

where

f_p = stress in strand

A_p = cross-sectional area of strand (calculated as $\pi d_p^2/4$ for the derivation of Eq. [6])

U = bond stress between strand and surrounding concrete

l_b = bond length of strand

By combining Eq. (6) with the first term and second term of Eq. (4), respectively, it can be determined that Eq. (4) is based on a transfer bond strength U_t of 750 psi (5.2 MPa) and a development bond strength U_d of 250 psi (1.7 MPa), which imply that the Hoyer effect is assumed to contribute an additional 500 psi (3.4 MPa) to the transfer bond strength.[25]

Experimental program

Materials

The strand used in this research was ASTM A416[28] seven-wire, uncoated, low-relaxation steel prestressing strand with a nominal ultimate strength f_{pu} of 270 ksi (1860 MPa) and a nominal diameter d_p of 0.5 in. (13 mm). Strand samples S-0.5A1 and S-0.5A2 were saw cut from two different spools by one manufacturer, and strand samples S-0.5B1, S-0.5B2, and S-0.5B3 were saw cut from three different spools by a second manufacturer. The measured wire and strand diameters (**Table 1**) were all within ASTM A416 tolerance limits. Each measurement in Table 1 is an average from three strand samples. The area A_p of each strand was determined by measuring the steel unit weight of strand samples as described in Walsh and Kurama.[29,30] The measured areas were close to the areas provided by the strand manufacturers.

Three types of fine aggregates, three types of natural coarse aggregates, and seven types of RCA were used in the concrete mixtures (**Table 2**). The specific gravity and water absorption were measured based on ASTM C128[28] and C127[28] for fine and coarse aggregates, respectively. FA1, NA-CL1-I, and NA-CL1-M were acquired from a ready-mixed concrete plant, with the letters I and M indicating two different coarse aggregate gradations. RCA-PC1-I and RCA-PC1-M were produced from rejected hollow-core members at a precast concrete plant and were also sieved and recombined to form two different gradations. RCA-PC2-I and RCA-PC2-M were produced from rejected hollow-core members at a second precast concrete plant and were again sieved into the two gradations. The reasons for the rejection of these precast concrete members were not known; however, the compressive strength of the concrete satisfied the typical range of concrete strengths (f_c' between 6000 and 9000 psi [41 to 62 MPa]) used in each plant. RCA-RM1 was acquired from a construction demolition recycling yard that processes returned ready-mixed concrete. FA1, NA-CL1-I, NA-CL1-M, RCA-PC1-I, RCA-PC1-M, RCA-PC2-I, RCA-PC2-M, and RCA-RM1 were only used in a series of small-batch laboratory concrete mixtures. The same specific gravity and water absorption were measured for RCA-PC1-I/M and RCA-RM1, which is believed to be coincidental.

Table 1. Prestressing strand properties

Strand	d_{mw}, in.	d_{ow}, in.	d_p, in.	A_p, in.^{2}
S-0.5A1	0.170	0.165	0.496	0.147
S-0.5A2	0.168	0.163	0.490	0.146
S-0.5B1	0.169	0.164	0.500	0.148
S-0.5B2	0.169	0.165	0.504	0.150
S-0.5B3	0.169	0.165	0.499	0.150

Note: A_p = area of strand; d_{mw} = middle-wire diameter of strand; d_{ow} = outer-wire diameter of strand; d_p = diameter of strand. 1 in. = 25.4 mm.

Table 2. Aggregate properties

Aggregate	Type	Specific gravity		Water absorption, % weight	Deleterious material, % weight	Gradation
		Bulk dry	Saturated surface dry			
FA1	Sand	2.59	2.62	1.25	n/a	INDOT no. 23
FA2	Sand	n.d.	2.62	0.90	n/a	MDOT no. 2NS
FA3	Limestone sand	n.d.	2.80	0.60	n/a	MDOT no. 2NS
NA-CL1-I	Crushed limestone	2.67	2.70	1.00	n/a	INDOT no. 8
NA-CL1-M	Crushed limestone	2.67	2.70	1.00	n/a	MDOT no. 17A
NA-CL2	Crushed limestone	2.61	2.68	0.60	n/a	MDOT no. 17A
RCA-PC1-I	Rejected precast concrete	2.12	2.29	8.16	<1	INDOT no. 8
RCA-PC1-M	Rejected precast concrete	2.12	2.29	8.16	<1	MDOT no. 17A
RCA-PC2-I	Rejected precast concrete	2.42	2.51	3.71	<1	INDOT no. 8
RCA-PC2-M	Rejected precast concrete	2.42	2.51	3.71	<1	MDOT no. 17A
RCA-PC3	Rejected precast concrete	2.44	2.52	3.39	<1	MDOT no. 17A*
RCA-RM1	Returned ready-mixed concrete	2.12	2.29	8.16	<1	INDOT no. 8
RCA-T	Construction demolition concrete	2.49	2.60	4.36	<1	MDOT no. 17A*

Note: INDOT = Indiana Department of Transportation; MDOT = Michigan Department of Transportation; n/a = not applicable; n.d. = no data.

* Due to the large amount of material used, exact target gradation was not met for these aggregates (Fig. 1).

RCA-PC3 was used in small-batch laboratory concrete mixtures as well as large-batch precast plant concrete mixtures. This material was obtained from rejected hollow-core members at the same precast concrete plant as RCA-PC2-I and RCA-PC2-M; however, it was produced at a different time (and thus, from different hollow-core members). FA2, FA3, NA-CL2, and RCA-T were also used in large-batch mixtures at this precast concrete plant. RCA-T was acquired from a construction demolition recycling yard adjacent to the plant. Similar to RCA-RM1 from returned ready-mixed concrete, RCA-T included multiple unknown sources of concrete with varying properties.

Deleterious materials accounted for less than 1% of each type of RCA, even for the construction demolition material RCA-T. To maintain consistent fresh and hardened concrete properties, each type of coarse aggregate was graded according to either Indiana Department of Transportation (INDOT) no. 8 or Michigan Department of Transportation (MDOT) no. 17A standards.[31,32] The closest ASTM gradation for both INDOT no. 8 and MDOT no. 17A is ASTM 67.[28] For the coarse aggregate materials with the exception of RCA-PC3 and RCA-T, a specific gradation based on averages of the limits of percentage passing from INDOT no. 8 or MDOT no. 17A was used (Table 2 and **Fig. 1**). RCA-PC3 and RCA-T were acquired and used in large quantities; and thus, it was not possible to exactly meet the target gradation for these aggregates.

Concrete mixture proportions and mixing

For each concrete mixture, the direct volume replacement method was used by replacing a selected volume of coarse natural aggregate with an equal volume of RCA according to Eq. (3). Thus, for a given volume of concrete, the volumetric proportions of the total coarse aggregates (RCA plus natural aggregate), fine aggregates, cement, water, and all liquid admixtures remained constant between different RCA and natural aggregate concrete mixtures. As described in Knaack and Kurama,[1] the direct volume replacement method provides similar workability for RCA and natural aggregate concrete and is consistent with standard volume-based practice for concrete batching.

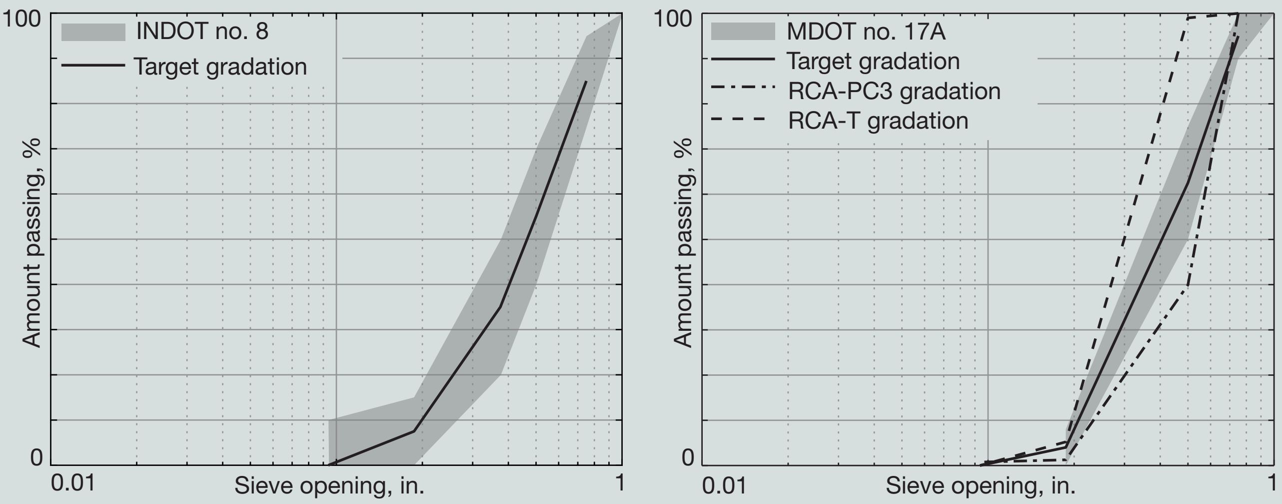


Figure 1. Coarse aggregate gradation curves. Note: INDOT = Indiana Department of Transportation; MDOT = Michigan Department of Transportation; RCA = recycled concrete aggregate. 1 in. = 25.4 mm.

Table 3 shows the dry-weight proportions for the target natural aggregate concrete mixtures used in the research, excluding admixtures, for a standard batch size of 1 yd^3 (0.8 m^3). Mixture M-NA1 (based on a mixture reported by Knaack and Kurama[1] and Smith et al.[33]) used Type III, high-early-strength portland cement and was proportioned with a *w/c* of 0.45 to result in a target slump of 5 ± 1 in. (150 ± 25 mm) and a 28-day compressive strength of 6000 psi (40 MPa). Mixtures M-NA2, M-NA3, M-NA4, and M-NA5 used Type I cement and were designed to achieve high early strength with a target spread of 22 ± 2 in. (560 ± 50 mm) by using relatively low *w/c* ratios (between 0.33 and 0.38) and finely tuned proportions of admixtures (not listed in Table 3). Based on these target natural aggregate concrete mixture designs, RCA concrete mixtures (**Table 4**) were determined for each RCA type using volumetric replacement ratios R of 0.5 and 1.0, which are 50% and 100% coarse aggregate replacement by volume, respectively. **Table 5** provides the resulting average slump or spread for each batch. For target concrete mixtures M-NA1, M-NA2, and M-NA3, a small-batch laboratory mixing procedure was followed. These mixtures were used for casting strand pull-out specimens as well as concrete strength and stiffness gain cylinders. Target concrete mixtures M-NA4 and M-NA5 were made using a large-batch mixing procedure in a precast concrete plant. These mixtures were only used for casting concrete strength and stiffness gain cylinders.

To prepare the small-batch laboratory concrete mixtures, all RCA and natural aggregate were first graded using a dry sieve. Following the dry-sieve process, the coarse aggregates were washed over a no. 8 (2.36 mm) sieve to further remove excess fines. All RCA, natural aggregate, and fine aggregate were dried in an oven at 230°F (110°C) for at least 24 hours. The material was then blended according to the target gradations, weighed according to the dry weights in Tables 3 and 4, and soaked in water for 18 to 24 hours to allow full absorption. After soaking, the excess water was decanted from the coarse and fine aggregates, which were then weighed to determine the total amount of absorbed and residual water. Using the absorption values from Table 2, the amount of residual water beyond the saturated-surface-dry condition of the aggregates was subtracted from the required mixture water for each batch (Table 3) to determine the additional water needed to achieve the target *w/c*. The aggregate drying and presoaking process is not intended for full-scale applications; it was used in this research to consistently control the amount of free water in each small-batch laboratory mixture.

For each small-batch concrete mixture, a 3.5 ft^3 (0.10 m^3) rotary drum mixer was used to make a total batch volume of 1.0 to 1.1 ft^3 (0.028 to 0.031 m^3). A strict mixing procedure was followed to ensure consistency from batch to batch. First, all of the liquid admixtures and additional water were placed in the mixer. Then, the soaked natural aggregate and RCA were placed and the mixer was turned on to fully coat the aggregates with the admixtures. Next, the soaked fine aggregate was added and the mixer was again turned on to fully coat the natural aggregate and RCA with fine aggregate. With the mixer on and at an approximately 45-degree angle, the cement was added slowly and the concrete was mixed for an additional three minutes. After the three minutes, the slump or spread of the concrete, depending on the mixture, was measured to ensure that the target consistency was achieved. The concrete was then used to cast three 5 × 18 in. (130 × 460 mm) strand pull-out test cylinders and accompanying compressive strength and stiffness test cylinders. Even though the specimens were not placed in an environmental chamber, they were kept indoors and inside of their metal or plastic molds until testing; thus, differences in their curing conditions were minimal.

The mixing procedure for the large-batch concrete mixtures was the standard procedure of the precast concrete plant. First,

Table 3. Dry-weight proportions for target natural aggregate concrete mixtures (excluding admixtures)

Natural aggregate mixture	Water,* lb/yd³	Cement, lb/yd³	Cement type†	*w/c*	Coarse natural aggregate,‡ lb/yd³	Coarse natural aggregate type‡	Fine aggregate,‡ lb/yd³	Fine aggregate type‡
M-NA1	256.2	569.7	III	0.45	1899.6	NA-CL1-I	1171.5	FA1
M-NA2	223.0	700.0	I-1	0.33	1595.2	NA-CL1-M	1403.7	FA1
M-NA3	223.0	700.0	I-2	0.33	1595.2	NA-CL1-M	1403.7	FA1
M-NA4	235.0	700.0	I-2	0.34	1600.0	NA-CL2	1420.0	FA2
M-NA5	262.0	700.0	I-3	0.38	1600.0	NA-CL2	1443.0	FA3

Note: *w/c* = water-cement ratio. 1 lb/yd³ = 0.5926 kg/m³.

* Required mixture water over saturated-surface-dry condition of coarse and fine aggregates.

† Three different types of Type I cement were used.

‡ Oven-dry weights for mixtures M-NA1 through M-NA3 and saturated-surface-dry weights for mixtures M-NA4 and M-NA5. Table 2 lists aggregate properties.

Table 4. Dry-weight proportions for recycled concrete aggregate concrete mixtures

RCA concrete mixture	Target natural aggregate concrete mixture	RCA type	*R*	*w/c*	Natural aggregate,* lb/yd³	RCA,* lb/yd³
M-RCA1	M-NA1	RCA-PC1-I	0.5	0.45	950.7	753.4
M-RCA2	M-NA1	RCA-PC1-I	1	0.45	0	1506.9
M-RCA3	M-NA1	RCA-RM1	0.5	0.45	950.7	753.4
M-RCA4	M-NA1	RCA-RM1	1	0.45	0	1506.9
M-RCA5	M-NA1	RCA-PC2-I	0.5	0.45	950.7	859.6
M-RCA6	M-NA1	RCA-PC2-I	1	0.45	0	1719.2
M-RCA7	M-NA2	RCA-PC1-M	0.5	0.33	797.6	632.8
M-RCA8	M-NA2	RCA-PC1-M	1	0.33	0	1265.7
M-RCA9	M-NA2	RCA-PC2-M	0.5	0.33	797.6	721.8
M-RCA10	M-NA2	RCA-PC2-M	1	0.33	0	1443.6
M-RCA11	M-NA3	RCA-PC1-M	0.5	0.33	797.6	632.8
M-RCA12	M-NA3	RCA-PC1-M	1	0.33	0	1265.7
M-RCA13	M-NA3	RCA-PC3	0.5	0.33	797.6	727.9
M-RCA14	M-NA3	RCA-PC3	1	0.33	0	1455.7
M-RCA15	M-NA4	RCA-PC3	0.5	0.34	800.0	752.2
M-RCA16	M-NA4	RCA-PC3	1	0.34	0	1504.5
M-RCA17	M-NA5	RCA-PC3	0.5	0.38	800.0	752.2
M-RCA18	M-NA5	RCA-PC3	1	0.38	0	1504.5
M-RCA19	M-NA4	RCA-T	0.5	0.34	800.0	776.1
M-RCA20	M-NA4	RCA-T	1	0.34	0	1552.2

Note: *R* = volumetric replacement ratio of natural aggregate with RCA (Eq. [3]); RCA = recycled concrete aggregate; *w/c* = water-cement ratio. 1 lb/yd³ = 0.5926 kg/m³.

* Oven-dry weights for mixtures M-RCA1 through M-RCA14 and saturated-surface-dry weights for mixtures M-RCA15 through M-RCA20.

Table 5. Slump or spread, 1-day compressive strength and stiffness, and 28-day compressive strength and stiffness of concrete

Mixture	Slump or spread, in.	1-day strength, psi	1-day stiffness, psi	28-day strength, psi	28-day stiffness, psi
M-NA1	6.5*	4176	4,342,173	7444	6,086,357
M-RCA1	6.25*	3600	3,853,081	6501	4,485,788
M-RCA2	6.5*	3218	2,680,170	6099	3,531,201
M-RCA3	7*	3576	3,223,749	5998	4,308,394
M-RCA4	7.5*	3068	2,508,047	5361	3,310,061
M-RCA5	4.75*	4501	4,144,438	8167	5,488,008
M-RCA6	4.75*	4910	3,843,223	8447	4,907,055
M-NA2	21.75	4042	4,305,572	8228	6,447,620
M-RCA7	22	3372	3,340,845	7362	5,130,543
M-RCA8	23	3038	2,693,053	6897	4,289,194
M-RCA9	22	4176	4,017,258	8489	5,962,268
M-RCA10	20	4239	3,868,929	8493	5,333,451
M-NA3	22.75	6678	5,462,186	11,643	7,008,766
M-RCA11	22	6237	4,456,059	9848	5,465,485
M-RCA12	22.5	5310	3,653,162	8497	4,666,324
M-RCA13	22.5	6980	4,652,537	11,080	5,521,066
M-RCA14	18.5	7833	4,660,507	11,514	5,579,827
M-NA4-1	22.5	6077	4,747,140	9559	5,768,663
M-NA4-2	21.75	4489	4,241,704	8748	5,383,054
M-RCA15	21	6400	4,727,113	9855	5,564,224
M-RCA16	21.5	6410	4,453,795	10,167	5,123,049
M-RCA19	23.75	4345	4,000,725	8869	4,969,548
M-RCA20	19	4129	3,739,579	9008	4,875,110
M-NA5	21.5	5588	3,286,624	8417	4,749,102
M-RCA17	21.5	4959	3,101,669	8424	4,892,538
M-RCA18	20.5	5676	3,262,845	9046	4,489,122

Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

* Indicates slump was measured. For all others spread was measured.

all of the sand was placed in the mixer. Air-entertaining admixture was then injected into the sand, and all coarse aggregates were discharged into the mixer. After mixing for about 10 seconds, the cement was discharged and the constituents were mixed for about 20 seconds. Then, a reading was taken with a moisture probe to determine the moisture in the batch. Based on this reading and the mixture proportions, the amount of additional water was determined by the concrete batching software, weighed, and discharged. After 15 seconds of additional mixing, all liquid admixtures were added to the batch. The concrete constituents were then mixed for about 70 seconds and the batch was discharged. Each large-batch mixture yielded approximately 1 yd^3 (0.8 m^3) of concrete.

ASTM A1081 tests using mortar

For each strand spool, ASTM A1081[28] pull-out tests were conducted using three strand samples to determine the chemical and mechanical bond qualities of the strand used in the experimental program. This ASTM test calls for mortar made from Type III cement and sand (with no coarse aggregates) to be cast around a nonprestressed strand specimen inside a 5 in. (130 mm) diameter by 18 in. (460 mm) long steel cylinder tube (**Fig. 2**). To maintain consistency of fresh mortar properties, the flow rate of the mortar was measured using a flow table per ASTM C1437. For this purpose, a 4 in. (100 mm) diameter metal mold was filled with mortar on the flow table, and then the mold was removed. The table was subsequently dropped 25 times in 15 seconds using the automated mechanism of the table. Four measurements of the resulting mortar diameter were taken with calipers, and the average measurement was calculated as the flow diameter. The flow rate was determined as the percentage growth of the diameter from the initial 4 in. diameter. The flow rate was required to fall between 100% and 125%, which corresponded to a flow diameter of 8 to 9 in. (200 to 230 mm).

During the strand pull-out tests, which were conducted within 24 ± 2 hours of mortar mixing, an average mortar compressive strength of 4500 to 5000 psi (31,000 to 34,000 kPa) was required. To satisfy this requirement, the strand pull-out tests for each spool were accompanied by three to nine 2 × 2 in. (50 × 50 mm) cube tests to determine the compressive strength of the mortar (according to ASTM C109). These compression tests were conducted at a constant axial stress rate of 50 psi/sec (340 kPa/sec) using a hydraulic testing machine.

ASTM A1081 tests adapted for natural aggregate and RCA concrete

For the adapted ASTM A1081 tests, the strand pull-out tests described previously were repeated using the setup in Fig. 2, but with the steel tube filled with natural aggregate or RCA concrete rather than mortar. These pull-out tests were conducted 24 hours after casting the concrete, with no strength requirement placed on the concrete at the time of pull-out testing. For both the mortar and concrete tests, each strand specimen was loaded in tension using a hydraulic testing machine according to ASTM A1081. The filled tube with the embedded strand was placed on a neoprene pad and a thick steel bearing plate above the top crosshead of the testing machine (Fig. 2). The bottom end of the strand was anchored to the bottom crosshead of the testing machine using a standard monostrand machined steel chuck-wedge anchorage system. A tension force was applied to the strand by moving the top crosshead of the testing machine upward at a constant rate of 0.1 in./min (3 mm/min). A linear variable displacement transducer was attached to the top free end of the strand to record the slip relative to the top surface of the concrete.

Compressive strength and stiffness gain tests for natural aggregate and RCA concrete

During or immediately after the testing of the three strand pull-out specimens for each spool, three 3 × 6 in. (75 × 150 mm) concrete cylinders made from the same batch as the pull-out cylinders were tested to determine the compressive strength and stiffness of the concrete according to ASTM C39 and C469, respectively. These compression tests were conducted at a constant axial stress rate of 35 psi/sec (240 kPa/sec) using a hydraulic testing machine. Unbonded steel caps with rubber bearing pads were used to evenly distribute the axial load on the top and bottom surfaces of each cylinder. Further, the testing machine was equipped with a swivel head, which helped to prevent eccentric loading. The concrete stiffness was determined by measuring the compressive

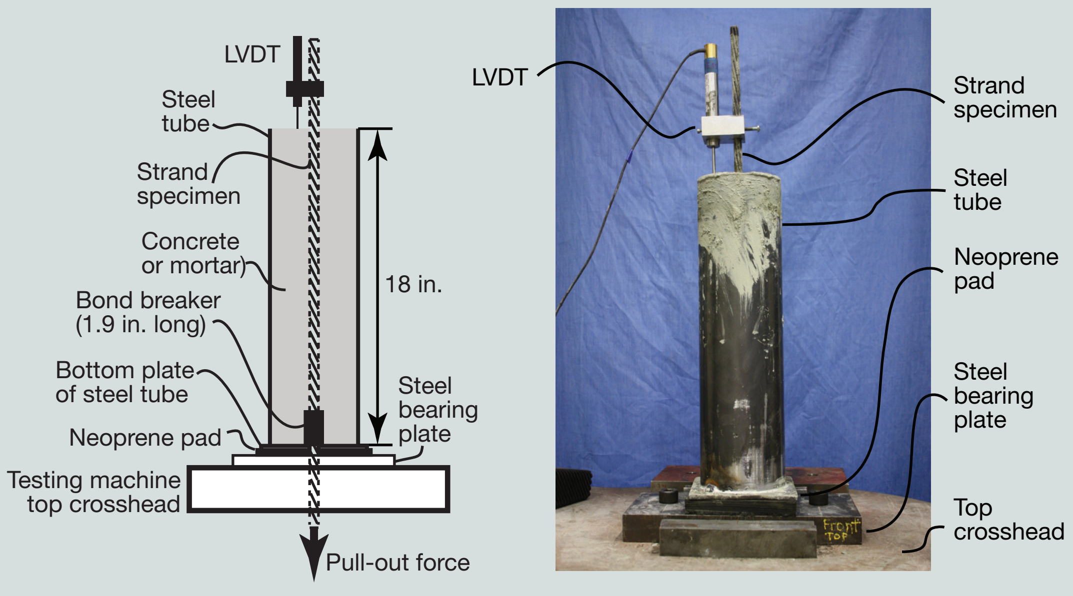


Figure 2. ASTM A1081 strand pull-out test setup. Note: LVDT = linear variable displacement transducer. 1 in. = 25.4 mm.

strains using a rock averaging extensometer with a 2 in. (50 mm) gauge length on the second and third compression test cylinders. To prevent damage to the extensometer, each test was briefly paused to remove the sensor at approximately half the compressive strength of the concrete measured from the first cylinder. The concrete compressive strength was determined as the peak strength, and the stiffness was determined as the slope of a trend line fit to the stress versus strain data between the point with a strain of 0.00005 in./in. and the point with a stress of 40% of the compressive strength. In addition to the 1-day tests, concrete strength and stiffness tests were conducted at 3, 7, and 28 days to investigate the time-dependent gain in these properties. For natural aggregate and RCA concrete based on target mixtures M-NA4 and M-NA5, the 1-day testing of the cylinders was conducted 18 hours (rather than 24 hours) after casting.

Results

Concrete compressive strength and stiffness gain

The five graphs in **Figure 3** show the normalized average concrete compressive strength results from the 1-, 3-, 7- and 28-day testing of the natural aggregate concrete and RCA concrete cylinders based on target mixtures M-NA1, M-NA2, M-NA3, M-NA4, and M-NA5, respectively. To evaluate the rate of concrete strength gain with time, the measured average compressive strength data was normalized with respect to the corresponding measured average 28-day compressive strength f_c' for each mixture. Thus, the normalized average 28-day strength for each mixture was equal to 1.0. Similarly, **Fig. 4** shows the measured average stiffness normalized with respect to the corresponding measured average 28-day stiffness E_c for each mixture. Table 5 shows the average 1-day compressive strength, average 1-day stiffness, average 28-day compressive strength, and average 28-day stiffness measurements for each batch. Each compressive strength average was computed from three cylinder tests, and each stiffness average was from two or one cylinder test(s).

The differences of the normalized strengths and stiffnesses of the RCA concrete cylinders from the strengths and stiffnesses of the corresponding natural aggregate concrete cylinders were less than 15%, with the differences for most of the specimens being less than 5%. Furthermore, there were no consistent trends in the normalized strengths and stiffnesses of the specimens with R of 0, 0.5, and 1.0. Given that the differences between the strength or stiffness gain of the RCA and natural aggregate concrete cylinders were generally within the inherent variability of concrete, it was concluded that the use of RCA did not significantly affect the rate of concrete strength or stiffness gain, even at the full aggregate replacement level R of 1.0.

The use of RCA resulted in decreases as well as increases in the concrete compressive strength compared with the corresponding natural aggregate concrete mixtures. In comparison, the RCA concrete mixtures generally had reduced

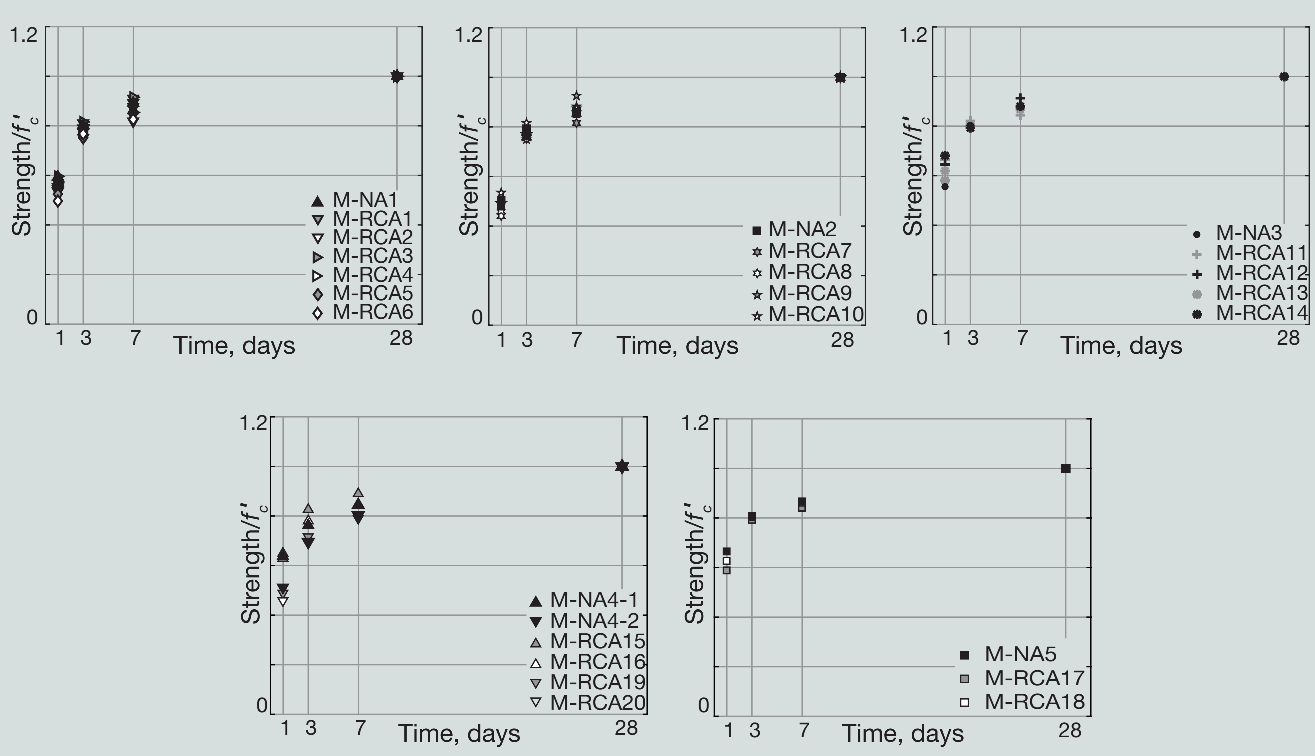


Figure 3. Compressive strength gain for concrete based on target mixtures M-NA1, M-NA2, M-NA3, M-NA4, and M-NA5. Note: f_c' = 28-day concrete compressive strength; RCA = recycled-concrete-aggregate. 1 psi = 6.895 kPa.

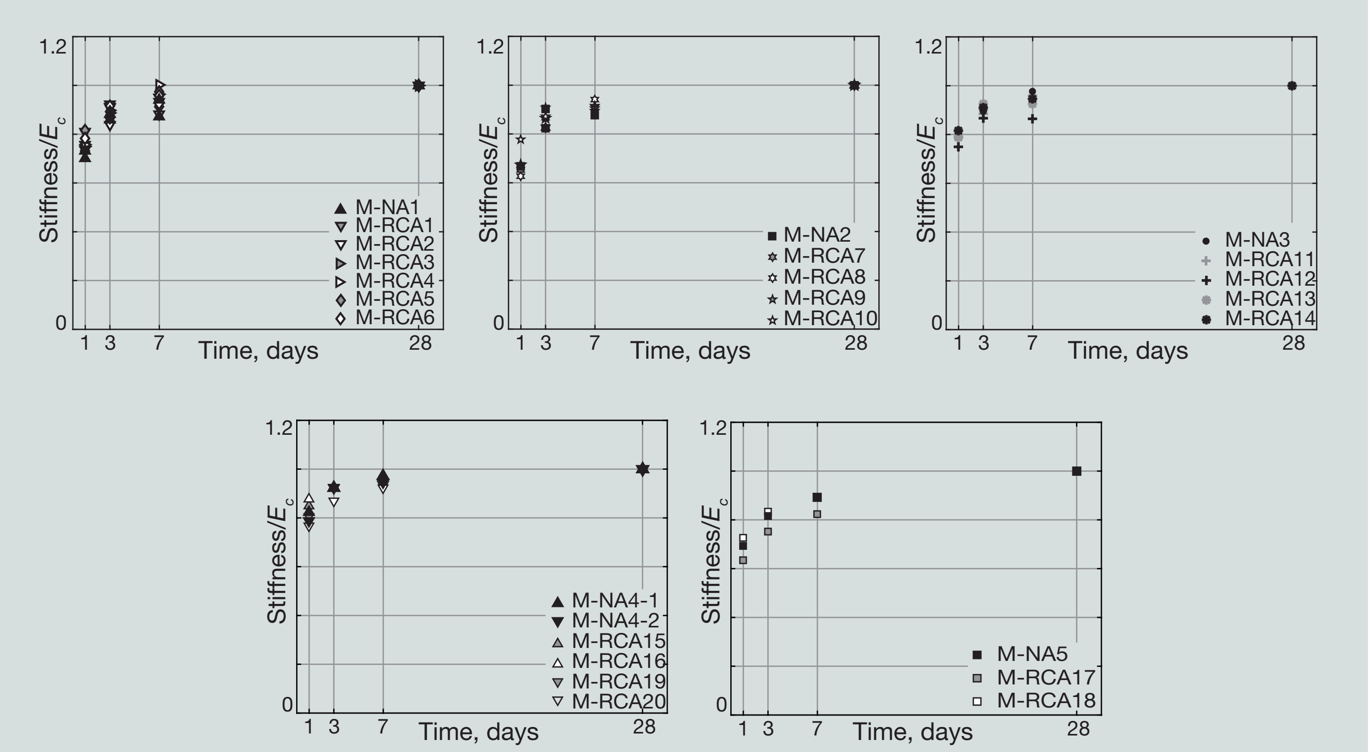


Figure 4. Stiffness gain for concrete based on target mixtures M-NA1, M-NA2, M-NA3, M-NA4, and M-NA5. Note: E_c = 28-day concrete stiffness. 1 psi = 6.895 kPa.

stiffness compared with the corresponding natural aggregate concrete mixtures. These findings are consistent with previous research.[1] **Table 6** compares the RCA concrete 1-day and 28-day compressive strengths predicted using Eq. (1) from Knaack and Kurama[1] with the corresponding measured average strengths. Similarly, **Table 7** shows comparisons for the RCA concrete 1-day and 28-day stiffnesses predicted using Eq. (2) with the measured average 1-day and 28-day stiffness data. The predictive equations provided reasonable estimations of the effect of RCA on both the 1-day and 28-day concrete compressive strength and stiffness, with most of the predictions within ±10% of the measured values. For the large-batch concrete based on target mixtures M-NA4 and M-NA5, the equations somewhat underpredicted the measured strength and stiffness, which could be because the predictive equations in Knaack and Kurama[1] were developed based on small-batch laboratory mixtures. Overall, it was concluded that Eq. (1) and (2), which were originally developed based on 28-day test data, can also be used to predict the effect of RCA on the compressive strength and stiffness of concrete at earlier ages. Furthermore, the use of different sources of RCA and different concrete mixture constituents and proportions in this paper compared with those used in the development of Eq. (1) and (2) supports the applicability of these predictive equations to a wider range of materials and concrete mixtures.

As an additional finding, the rejected precast concrete RCA used in this research performed better and more consistently than the construction demolition concrete RCA and the returned ready-mixed concrete RCA, both in terms of compressive strength and stiffness of concrete. This indicates that the quality of the precast RCA was superior to the quality of the construction demolition and returned ready-mixed concrete RCA. Although more research is certainly needed in this area, these results may suggest possible general trends for the higher quality and consistency of RCA obtained from precast concrete since the source material for precast concrete RCA is well known because it is limited to the standard concrete mixture designs used at the precast concrete production plant. Precast concrete RCA is also produced in a quality-controlled environment and contains little or no deleterious materials. In comparison, construction demolition and returned ready-mixed concrete can include many sources with unknown properties, and returned ready-mixed concrete can also be negatively affected by poor setting conditions such as delayed setting, the addition of wash water, and potentially low temperatures or other outdoor conditions.

Strand bond strength

Figure 5 shows sample measured tension force versus slip curves for strand S-0.5A3 embedded in concrete mixture M-RCA14. The pull-out force P_s for each test was taken as the tension force when the slip displacement of the strand reached 0.1 in. (3 mm).[28] Because the strands were not stressed prior to casting inside the steel tubes, the measured pull-out force did not include the Hoyer effect. Although the bond stress was likely not constant along the embedment length of the strand, the average development bond strength was determined by Eq. (7).

$$U_d = P_s/(c_p l_b) \quad (7)$$

Table 6. Predicted compressive strength versus measured strength of concrete

Mixture	1-day compressive strength			28-day compressive strength		
	Predicted, psi	Measured, psi	Predicted/measured	Predicted, psi	Measured, psi	Predicted/measured
M-RCA1	4018	3600	1.12	7162	6501	1.10
M-RCA2	3777	3218	1.17	6732	6099	1.10
M-RCA3	3902	3576	1.09	6957	5998	1.16
M-RCA4	3777	3068	1.23	6732	5361	1.26
M-RCA5	4207	4501	0.93	7499	8167	0.92
M-RCA6	4224	4910	0.86	7531	8447	0.89
M-RCA7	3889	3372	1.15	7916	7362	1.08
M-RCA8	3655	3038	1.20	7441	6897	1.08
M-RCA9	4072	4176	0.98	8288	8489	0.98
M-RCA10	4089	4239	0.96	8323	8493	0.98
M-RCA11	6425	6237	1.03	11,201	9848	1.14
M-RCA12	6039	5310	1.14	10,529	8497	1.24
M-RCA13	6751	6980	0.97	11,770	11,080	1.06
M-RCA14	6807	7833	0.87	11,868	11,514	1.03
M-RCA15	5982	6400	0.93	9409	9855	0.95
M-RCA16	5863	6410	0.91	9222	10,167	0.91
M-RCA17	5500	4959	1.11	8285	8424	0.98
M-RCA18	5391	5676	0.95	8121	9046	0.90
M-RCA19	4331	4345	1.00	8440	8869	0.95
M-RCA20	4156	4129	1.01	8100	9008	0.90
Average			1.03	**Average**		1.03
Standard deviation			0.12	**Standard deviation**		0.11

Note: 1 psi = 6.895 kPa.

where

c_p = strand circumference[34,35]

= $(4/3)\pi d_p = (4/3)\pi(0.5) = 2.09$ in. (53.1 mm)

l_b = 18 – 1.9 (bond beaker length, Fig. 2) = 16.1 in. (410 mm)

Equation (8) expresses the average development bond strength in psi using the bond strength index U'_d.[27,35,36]

$$U_d = U'_d\sqrt{f'_{ci}} \tag{8}$$

where

f'_{ci} = compressive strength of mortar or concrete at the time of strand pull-out testing (that is, at an age of around 1 day)

From the ASTM A1081 tests conducted on each strand sample embedded in mortar, the bond strength index U'_d was determined by fitting a constrained (passing through the origin at 0,0) straight line to the U_d versus $\sqrt{f'_{ci}}$ data (Fig. 5), where f'_{ci} was taken as the compressive strength of a single mortar cube specimen (tested during or immediately after strand pull-out testing), based on Eq. (8). Each point in Fig. 5 represents the bond strength U_d from a single strand pull-out test plotted against the $\sqrt{f'_{ci}}$ value from the corresponding mortar cube. The data for each point were matched based on increasing f'_{ci} and U_d values within each series of three accompanying

Table 7. Predicted stiffness versus measured stiffness of concrete

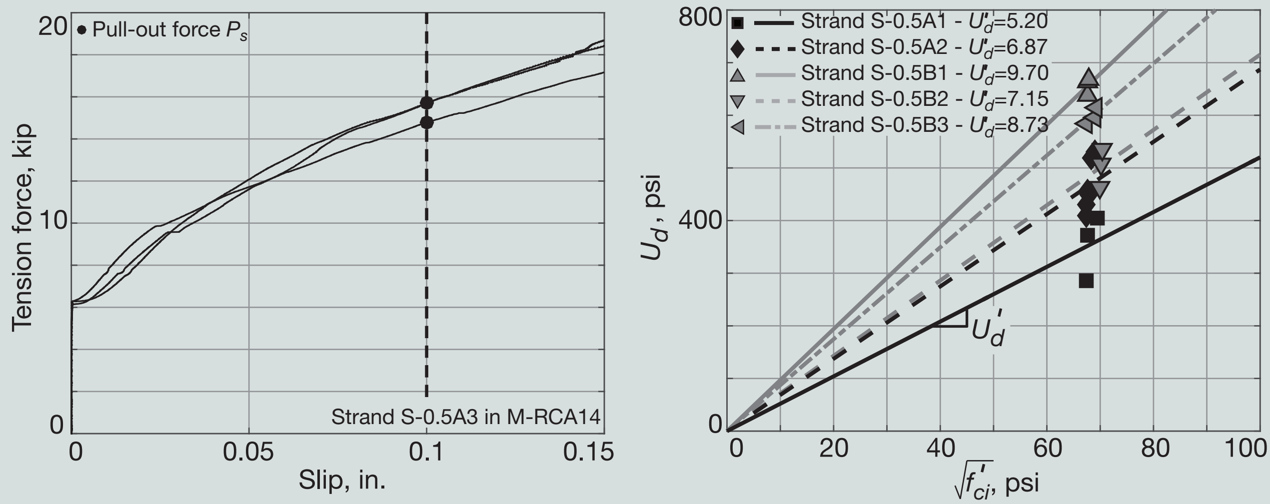
Mixture	1-day stiffness			28-day stiffness		
	Predicted, psi	Measured, psi	Predicted/measured	Predicted, psi	Measured, psi	Predicted/measured
M-RCA1	3,689,946	3,853,081	0.96	5,172,140	4,485,788	1.15
M-RCA2	2,868,509	2,680,170	1.07	4,020,745	3,531,201	1.14
M-RCA3	3,591,813	3,223,749	1.11	5,034,588	4,308,394	1.17
M-RCA4	2,868,509	2,508,047	1.14	4,020,745	3,310,061	1.21
M-RCA5	4,076,986	4,144,438	0.98	5,714,648	5,488,008	1.04
M-RCA6	3,784,404	3,843,223	0.98	5,304,540	4,907,055	1.08
M-RCA7	3,658,843	3,340,845	1.10	5,479,139	5,130,543	1.07
M-RCA8	2,844,330	2,693,053	1.06	4,259,401	4,289,194	0.99
M-RCA9	4,042,620	4,017,258	1.01	6,053,848	5,962,268	1.02
M-RCA10	3,752,504	3,868,929	0.97	5,619,398	5,333,451	1.05
M-RCA11	4,641,725	4,456,059	1.04	5,955,997	5,465,485	1.09
M-RCA12	3,608,407	3,653,162	0.99	4,630,103	4,666,324	0.99
M-RCA13	5,166,717	4,652,537	1.11	6,629,637	5,521,066	1.20
M-RCA14	4,843,397	4,660,507	1.04	6,214,771	5,579,827	1.11
M-RCA15	4,241,593	4,727,113	0.90	5,154,328	5,564,224	0.93
M-RCA16	3,700,823	4,453,795	0.83	4,497,192	5,123,049	0.88
M-RCA17	2,936,615	3,101,669	0.95	4,243,346	4,892,538	0.87
M-RCA18	2,562,219	3,262,845	0.79	3,702,352	4,489,122	0.82
M-RCA19	3,626,549	4,000,725	0.91	4,602,374	4,969,548	0.93
M-RCA20	2,981,748	3,739,579	0.80	3,784,072	4,875,110	0.78
Average			0.99	**Average**		1.03
Standard deviation			0.10	**Standard deviation**		0.13

Note: 1 psi = 6.895 kPa.

mortar strength and strand pull-out tests in an attempt to eliminate some of the inherent variability in the mortar strength and strand bond strength from the analysis. **Table 8** summarizes the results from these ASTM A1081 strand pull-out tests and accompanying mortar tests. The strand spools used in the experimental program represented a range of bond strength characteristics, with strands S-0.5A1, S-0.5A2, S-0.5B2, S-0.5B3, and S-0.5B1 providing the lowest to highest bond strength indices U'_d of 5.20, 6.87, 7.15, 8.73, and 9.70, respectively.

The five graphs in **Figure 6** show the data from the adapted pull-out tests associated with strands S-0.5A1, S-0.5A2, S-0.5B1, S-0.5B2, and S-0.5B3, respectively, embedded in natural aggregate and RCA concrete. Each point in these plots represents the bond strength U_d from a single pull-out test against the $\sqrt{f'_{ci}}$ value from a single concrete compressive cylinder test. Like the mortar pull-out tests in Fig. 5, the data for each point in Fig. 6 were matched based on increasing f'_{ci} and U_d values. The replacement of natural aggregate with RCA resulted in mixed effects on the strand bond strength, with decreases in bond strength when target mixture M-NA1 was used, as well as increases seen in some cases when using target mixtures M-NA2 and M-NA3.

The three regression lines in each graph of Fig. 6 were determined by fitting a constrained (passing through the origin at 0,0) straight line through the data sets associated with R of 0, 0.5, and 1.0, respectively. Therefore, the slope of each line represents the bond strength index U'_d of each strand embed-



Sample strand tension force versus slip curves

ASTM A1081 strand pull-out tests in mortar

Figure 5. Strand pull-out tests. Note: f'_c = 28-day concrete compressive strength; U_d = development bond strength; U'_d = bond strength index. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

ded inside concrete with different R. **Figure 7** shows the same data points, but the regression lines were fit through the data sets defined by aggregate type regardless of R. Looking at the regression lines between the different plots, the biggest differences in U'_d occurred between the different strand spools. In comparison, the effects of RCA type or replacement ratio R on U'_d were relatively small. To determine a mean bond strength index from the adapted ASTM A1081 tests, a regression line was fit through all of the data points collected for each strand (regardless of aggregate type or R). Strands S-0.5A1, S-0.5B2, S-0.5A2, S-0.5B3, and S-0.5B1 provided the lowest to highest mean bond strength indices U'_d: 6.06, 6.38, 6.46, 7.15, and 10.02, respectively. The corresponding coefficient of determination values for these linear regression results were 0.45, 0.68, 0.46, 0.65, and 0.69, respectively. The coefficient of determination can range from 0 to 1, with a value of 0 suggesting that the regression model accounts for none of the variability in the data (that is, a complete lack of fit) and a value of 1, suggesting that the regression model accounts for all variability in the data (that is, a perfect fit). The calculated coefficient of determination values reflect the reasonable effectiveness of the bond strength index, considering the assumed simple linear relationship between U_d and $\sqrt{f'_{ci}}$ in Eq. (8).

The U'_d results from the strand pull-out tests conducted in concrete were consistent with the standard tests conducted in mortar (Table 8) except that strands S-0.5B2 and S-0.5A2 switched order, but in both cases the indices were relatively similar. In comparison, for a given strand spool, the largest percentage difference in U'_d for RCA concrete with R of 0.5 or 1.0 compared with natural aggregate concrete (that is R of 0) was only a 10% drop for strand S-0.5A1 in concrete with R of 0.5, and the largest percentage difference in U'_d for concrete with different RCA types compared with natural aggregate concrete (R of 0) was only a 9% drop for strand S-0.5A1 in concrete with RCA-PC2-I. To put these results in context,

Table 8. ASTM A1081 pull-out test results of strand embedded in mortar

Strand	U'_d	f'_{ci}, psi	Mortar flow rate, %
S-0.5A1	5.20	4652	114
S-0.5A2	6.87	4665	104
S-0.5B1	9.70	4552	105
S-0.5B2	7.15	4894	102
S-0.5B3	8.73	4700	103

Note: f'_{ci} = compressive strength of mortar at approximately 1 day; U'_d = bond strength index. 1 psi = 6.895 kPa.

Fig. 8 shows estimated differences for the transfer length l_t (the first term in Eq. [4]) of a 0.5 in. (13 mm) diameter prestressing strand as a function of the bond strength index U'_d for concrete compressive strengths at transfer f'_{ci} of 4000 and 5000 psi (28 and 34 MPa) and effective prestress f_{pe} values of $0.5f_{pu}$ and $0.7f_{pu}$, where f_{pu} is 270 ksi (1860 MPa). The transfer length was calculated as l_b from Eq. (5) by assuming that an additional 500 psi (3.4 MPa) of bond strength was provided due to the Hoyer effect, resulting in Eq. (9).

$$l_t = \frac{f_{pe}A_p}{\left(500 + U'_d\sqrt{f'_{ci}}\right)\pi d_p} \tag{9}$$

Figure 8 also shows estimated differences for the total development length l_{dt} (the second term in Eq. [4]) of a 0.5 in. (13 mm) diameter prestressing strand as a function of U'_d for 28-day concrete compressive strengths f'_c of 6000 and 7500 psi (41 and 52 MPa) and an ultimate strand stress f_{ps} of $0.9f_{pu}$ as calculated by Eq. (10).

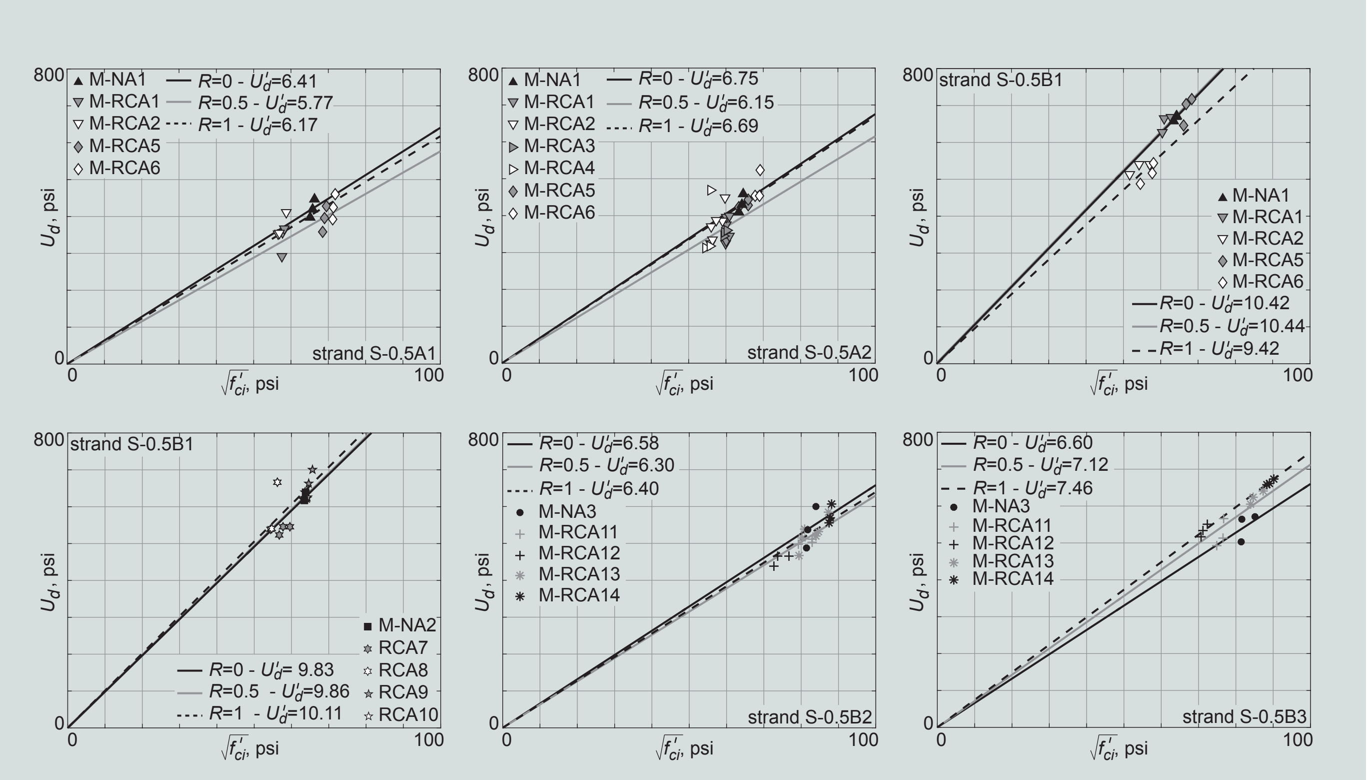


Figure 6. Bond strength index for strand tested in concrete with regression based on R. Note: f_c' = 28-day concrete compressive strength; R = volumetric replacement ratio of natural aggregate with recycled concrete aggregate; U_d = development bond strength; U_d' = bond strength index. 1 psi = 6.895 kPa.

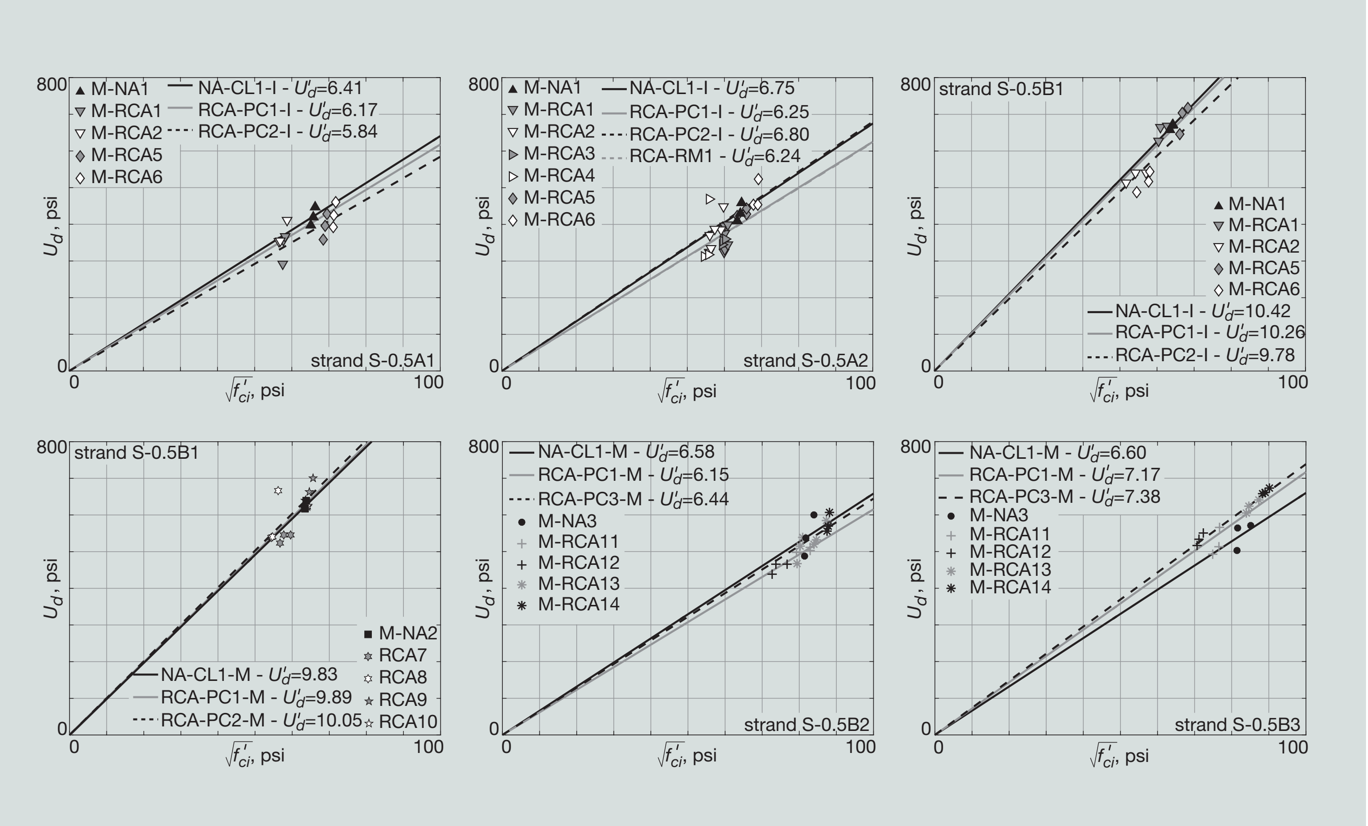


Figure 7. Bond strength index for strand tested in concrete with regression based on type of recycled concrete aggregate (RCA). Note: f_c' = 28-day concrete compressive strength; R = volumetric replacement ratio of natural aggregate with RCA; U_d = development bond strength; U_d' = bond strength index. 1 psi = 6.895 kPa.

$$l_{dt} = \frac{f_{pe}A_p}{\left(500 + U_d'\sqrt{f_c'}\right)\pi d_p} + \frac{\left(f_{ps} - f_{pe}\right)A_p}{U_d'\sqrt{f_c'}\pi d_p} \quad (10)$$

Changes in U_d' (Fig. 8) consistent with changes from Fig. 6 and 7 due to RCA type or replacement ratio R, respectively (for example, U_d' of 6.25 and 6.80 for RCA-PC1-I and RCA-PC2-I, respectively, or U_d' of 6.75 and 6.69 for R of 0 and 1.0, respectively, for strand S-0.5A2), have small effects compared with changes in U_d' from the use of different strand spools (for example, U_d' of 6.06 and 10.02 for strands S-0.5A1 and S-0.5B1, respectively). These comparisons support the conclusion that the effect of RCA on the bond strength index was not significant compared with the inherent variabilities in the properties of strand or concrete.

As a direct consequence of the findings that the use of RCA did not significantly affect the bond strength index U_d' or the compressive strength gain of concrete, the small effect of RCA on the strand bond strength at transfer can be quantified by Eq. (11) and (12) based on Eq. (8) and (1).

$$U_d = U_d'\sqrt{f_{ci,RCA}'} \quad (11)$$

$$f_{ci,RCA}' = f_{ci,NA}'[1.0241 - 0.0241(A/A_{NA}) - 0.0138D + 0.0769R] \quad (12)$$

where

$f_{ci,RCA}'$ = RCA concrete compressive strength at transfer

$f_{ci,NA}'$ = natural aggregate concrete compressive strength at transfer

The resulting strand transfer length l_t in RCA concrete can be determined by substituting $f_{ci,RCA}'$ from Eq. (12) for f_{ci}' in Eq. (9). Similarly, the total development length l_{dt} can be found by substituting $f_{c,RCA}'$ from Eq. (1) for f_c' in Eq. (10).

Because the strand pull-out tests conducted in this research did not include the effect of prestressing, tests of structural members (such as beams and slabs) are needed for a more representative evaluation of the effect of RCA in precast, prestressed concrete applications.

Conclusion

This paper experimentally investigated the effect of RCA from rejected precast concrete, returned ready-mixed concrete, and construction demolition concrete on the bond strength between steel prestressing strand and concrete and on the rate of compressive strength and stiffness gain of concrete between 1 and 28 days after casting. The important findings and conclusions are summarized here. These results may be limited to the materials and specimens that were tested.

- The use of RCA led to decreases as well as increases on the concrete compressive strength but more consistently led to reduced stiffness compared with natural aggregate concrete.
- The use of RCA did not have a significant effect on the rate of concrete compressive strength or stiffness gain with time.
- The prediction equations from Knaack and Kurama,[1] which were originally developed based on 28-day test data, can also be used to predict the effect of RCA on the compressive strength and stiffness of concrete at earlier ages. The comparisons also support the applicability of these predictive equations to a wider range of materials and concrete mixtures.

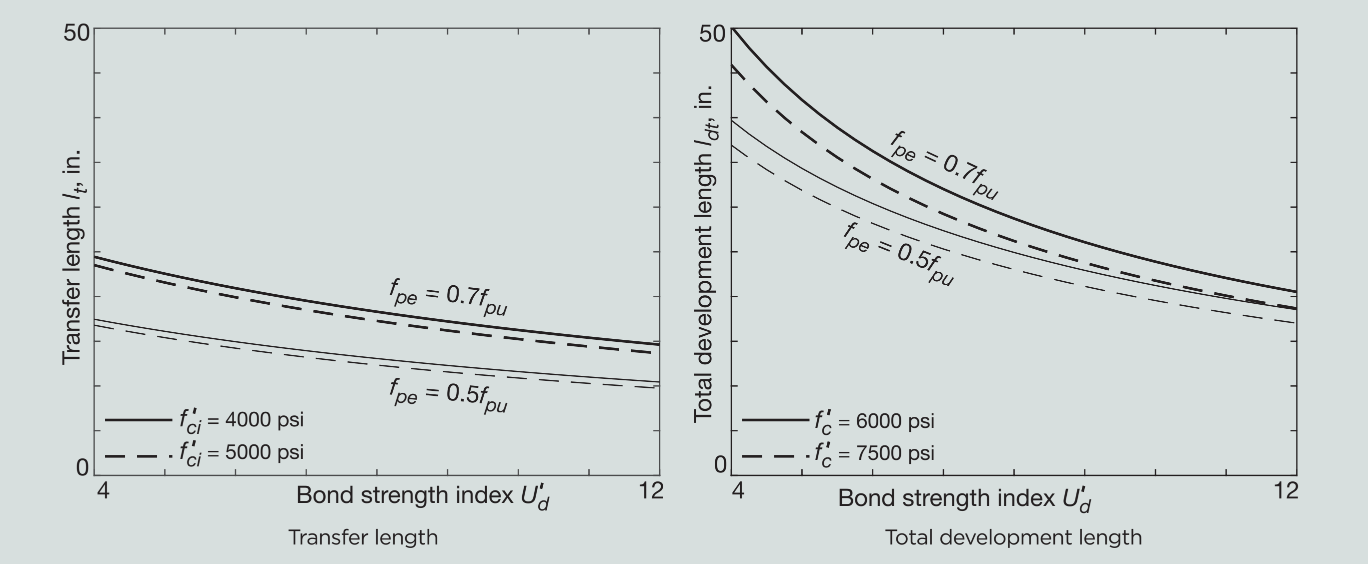


Figure 8. Transfer and total development length of strand as a function of bond strength index. Note: f_c' = 28-day concrete compressive strength; f_{ci}' = concrete compressive strength at transfer; f_{pe} = effective strand stress after losses; f_{pu} = nominal ultimate strength of strand. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

- RCA had a relatively small effects (increases as well as decreases on the bond strength of seven-wire steel prestressing strand.

- The effect of RCA on the bond strength index for seven-wire steel prestressing strand was not significant, considering the much greater inherent variabilities in the properties of strand and concrete. Thus, the bond strength of strand in RCA concrete can be quantified based on the effect of RCA on the compressive strength of concrete, specifically by using the predictive equation from Knaack and Kurama[1] with the strand bond strength index.

- The RCA from rejected precast concrete tested in this research performed better (resulted in smaller decreases in concrete compressive strength and stiffness while sometimes increasing the strength) and more consistently than RCA from construction demolition concrete and from returned ready-mixed concrete. More research is needed to investigate whether this finding can be generalized. Research is also needed on precast, prestressed concrete structural members (such as beams and slabs) for a more representative evaluation of the effect of RCA.

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Notation

A = combined water absorption of RCA and natural aggregate in RCA concrete

A_{NA} = water absorption of natural aggregate

A_p = cross-sectional area of strand

c_p = circumference of strand

D = combined deleterious material content of RCA and natural aggregate in RCA concrete

d_{mw} = middle-wire diameter of strand

d_{ow} = outer-wire diameter of strand

d_p = diameter of strand

E_c = 28-day concrete stiffness (Young's modulus)

$E_{c,NA}$ = stiffness (Young's modulus) of natural aggregate concrete

$E_{c,RCA}$ = stiffness (Young's modulus) of RCA concrete

f_c' = compressive strength of concrete

$f_{c,NA}'$ = compressive strength of natural aggregate concrete

$f'_{c,RCA}$ = compressive strength of RCA concrete

f'_{ci} = compressive strength of concrete or mortar at approximately 1 day

$f'_{ci,NA}$ = compressive strength of natural aggregate concrete at approximately 1 day

$f'_{ci,RCA}$ = compressive strength of RCA concrete at approximately 1 day

f_p = axial stress in strand

f_{pe} = effective strand stress after losses

f_{ps} = strand stress at critical section

f_{pu} = nominal ultimate strength of strand

l_b = bond length of strand

l_{dt} = total development length of strand

$l_{dt,ACI}$ = total development length of strand required by ACI 318-14

l_t = transfer length of strand

$l_{t,ACI}$ = transfer length of strand required by ACI 318-14

P_s = pull-out force of strand

R = volumetric replacement ratio of natural aggregate with RCA

U = bond stress between strand and surrounding concrete

U_d = development bond strength of strand

U'_d = bond strength index of strand

U_t = transfer bond strength of strand

V_{NA}^{RCA} = volume of natural coarse aggregate in RCA concrete

V_{NA}^{NA} = volume of natural coarse aggregate in natural aggregate concrete

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Abstract

This paper presents an experimental investigation on the use of recycled concrete aggregate (RCA) as a replacement for natural coarse aggregates (such as crushed limestone and gravel) in precast, prestressed concrete structures. Specifically, the paper investigates the effect of RCA on the bond strength between seven-wire steel prestressing strand and concrete and on the rate of concrete compressive strength and stiffness gain with time.

Bond characteristics of strand samples were determined through ASTM A1081 pull-out tests using mortar. Then, ASTM A1081 was adapted to conduct pull-out tests of strand embedded in concrete with different types and amounts of RCA. In addition, the compressive strength and stiffness of RCA concrete compared with natural aggregate concrete were measured at 1, 3, 7, and 28 days. The RCA sources included rejected precast concrete, construction demolition concrete, and returned ready-mixed concrete. The use of RCA did not have a significant effect on the rate of concrete compressive strength or stiffness gain. Furthermore, RCA resulted in an effect (decrease or increase) in the strand bond strength that was consistent with the effect of RCA on the concrete compressive strength.

Based on these findings, a predictive model was developed for the strand bond strength in RCA concrete. For the materials tested, RCA from precast concrete performed better than RCA from construction demolition concrete and returned ready-mixed concrete.

Keywords

Recycled concrete aggregate, returned ready-mixed concrete, strand bond, strength gain, stiffness gain.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

Please address any reader comments to *PCI Journal* editor-in-chief Emily Lorenz at elorenz@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal*, 200 W. Adams St., Suite 2100, Chicago, IL 60606.