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Mechanical Behavior of Recycled Concrete Aggregates (RCA) for Improved Sustainability of Reinforced Concrete Building Structures

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ABSTRACT

Concrete makes up a significant portion of both the existing (and aging) infrastructure of today and the planned infrastructure of tomorrow, with a corresponding large environmental impact. Rather than landfilling the concrete from obsolete applications, by crushing old concrete to make recycled concrete aggregates (RCA) for use in new concrete, the overall environmental impacts of concrete use can be reduced. Using RCA in new concrete does have issues that need to be addressed before full adoption can be realized. In particular, the strength and stiffness, workability, and durability of RCA concrete can all be different than those of natural aggregate concrete. Variability in RCA properties from source to source also must be addressed if guidelines for RCA use are to be created and adopted. The University of Norte Dame, the University of Texas at Tyler and New Mexico State University are currently participating in a research project designed to probe these issues. The current paper describes properties of RCA aggregates and of RCA concrete with RCA sourced from over thirty suppliers from four distinct areas of the United States (Northeast, South, Midwest and West regions), making this study the most geographically varied study of RCA known to the authors. Variability in aggregate properties and hardened concrete strength are addressed within the paper.

INTRODUCTION

Natural aggregate (NA) is a vital material that is required to meet the needs of society as well as providing the basic materials needed for construction. With concrete is the one most versatile building material on Earth and makes up a significant proportion of the past, present, and future infrastructure. It also possesses a major impact towards the environment. The idea of the conservation of natural aggregate has been largely ignored here in the United States despite the fact that coarse aggregates make up 40 to 50% of the concrete mix by volume (Mehta 2001) while cement makes up about 10%. The possibilities of using recycled concrete from the existing infrastructure to either partially or fully replace the natural coarse aggregate in any future construction has the potential to improve sustainability of mostly reinforced concrete structures. To date, the use of recycled concrete aggregate (RCA) in the U.S. has been limited to non-structural applications such as sidewalks and roadways even though the quality of the material is generally significantly higher than is required in these applications. Recycling old concrete into material suitable for structural applications is likely to be cost-effective (Davis et al 2015). Despite the above benefits, only a small amount of RCA has been used in structural engineering projects in the U.S. The primary obstacles against their increased utilization are:

1. Little or no previous work exists to quantify the economic and environmental benefits of using RCA in structural applications.
2. Little or no previous works exists on the service and ultimate load performance of prestressed and non-prestressed concrete structures utilizing RCA from U.S. sources.
3. Even though RCA can readily pass the prescriptive requirements for coarse aggregates in structural concrete (ASTM C33 2008), the variability in material properties and quality needs to be quantified and incorporated into design.
4. As a result, no engineering guidelines/standards currently exists for the design and construction of reinforced concrete utilizing RCA.

The current project team is addressing each of these four issues. Davis et al. (2014) and Davis et al. (2015) are directed at quantifying environmental and economic aspects of RCA use. Knaack and Kurama (2013, 2015a, 2015b, and 2015c) address the second issue noted. The current paper targets the issue of variability of RCA properties and of concrete made with RCA. The project team collected more than 36 RCA samples from over 10 states representing four distinct geographical areas: the Northeastern US, the Southwestern US, the Midwest, and Texas. In the current paper, the properties of a subset of these are discussed. After a brief background of RCA is presented, material properties describing this RCA subset are discussed, and then the behavior of concrete mixes incorporating these RCA is presented.

BACKGROUND

Through previous research, RCA tends to have a decreased specific gravity, increased absorption, and increased L.A. abrasion loss since they contain the mortar paste from the original concrete. Because of the increased absorption, RCA concrete also has greater water demand (ACI 555 2001), which can be resolved by increasing the amount of mix water and/or by using water reducing admixtures and fly-ash. Generally, RCA concrete has smaller compressive strength, smaller stiffness, greater creep, and greater shrinkage. At full aggregate replacement, the majority of the previous research found concrete compressive strength losses ranging from 10% to 20%. In comparison, the effect of RCA on the stiffness of concrete is greater with losses up to 33% at full replacement. An important limitation of the previous research has been the lack of quantitative evaluation of the variability in the RCA properties from different sources and the effect of this variability on the behavior of RCA concrete, with the objective to develop RCA qualification standards.

SAMPLE DESCRIPTION

Generally, most retailers of RCA do not sell it to a specific gradation or other quality and performance measures. Figure 1 gives an illustration of the RCA subset (of the 36 samples collected) presented in this paper as received by the project team. The figure gives a three letter code for each aggregate that is used to identify it throughout the remainder to deidentify RCA wholesalers, of this paper.

BCL - 3” (TX)

BCB - Base (TX)

CCF - 1.5” Minus (PA)

CCN - 1.5” to 0.375” (PA)

TIL - 1.5” Minus (NJ)

Figure 1. Images of Samples

Coarse and fine aggregates should ideally be graded to ensure a workable and economical mix. Too much variability in aggregate size from mix to mix can affect the properties of concrete such as workability and strength.

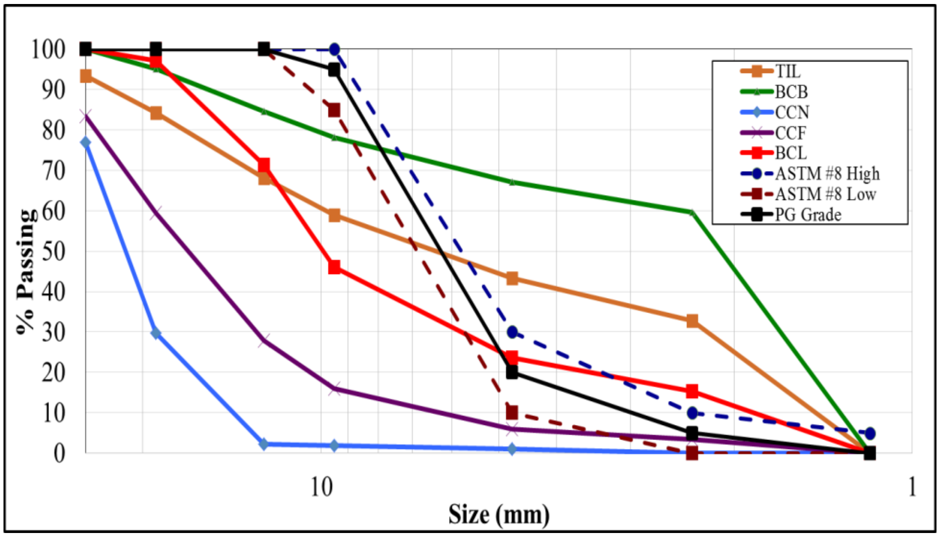

Figure 2. Gradations of ASTM C33 #8, NA, and RCA

Figure 2 displays the bounds of ASTM C33 #8 as well as the gradations of project NA and RCA samples. There was significant variability in the gradation of RCA samples as received. The PG Grade line in the figure denotes the target gradation for the concrete mixes described later in this paper. For all of the concrete described herein, the RCA were graded to the PG Grade to ensure consistency. Table 1 shows several important physical properties characterizing the RCA subset. Specific Gravity (Relative Density) and Absorption were determined by following ASTM C127 (2005) (Coarse Aggregate). For the fine aggregate (sand), the Specific Gravity and Absorption were found using ASTM C128 (2005), with the test performed by an outside laboratory.

D_{RCA} defines the percent (by weight) of the RCA that is deleterious. Some examples of deleterious material are asphalt, brick, glass, wood chips, and wire. These materials will negatively affect the properties of fresh concrete made with an RCA that includes them. The procedure followed to determine the amount of deleterious material was TxDOT standards TEX-221-F (2004) & TEX-217-F (2011). The identification of deleterious material is conducted by the examination of a particle and seeing if there is a presence of cement paste as well as coarse and fine aggregate. Color can also be an indication of whether a particle is deleterious or not, such as brick or asphalt.

Table 1 displays the absorption, SG, and D_{RCA} values determined for each sample. For this subset, the presence of deleterious material is much lower in the Texas samples as opposed to the samples from the Northeast. When examining the entire database available to the research team, it was noted that D_{RCA} was highly variable, ranging from 1.87% to 35.1%, with no distinct trends based on geography.

Table 1. NA and RCA Properties

State of Origin	Sample	Type	Absorption	Bulk SG	Bulk SSD	Apparent SG	D_{RCA} (%)
NJ	TIL	RCA	5.41	2.31	2.43	2.64	4.63
PA	CCF	RCA	5.01	2.33	2.45	2.64	5.95
PA	CCN	RCA	5.02	2.33	2.44	2.63	10.33
TX	BCB	RCA	5.95	2.28	2.42	2.64	2.29
TX	BCL	RCA	5.52	2.29	2.42	2.62	2.96
TX	PG	NA	1.83	2.55	2.60	2.68	N/A
TX	Sand	NA	1.00	2.62	2.65	2.69	N/A

Figures 3(a) – 3(c) shows some of the relationships among these parameters for nearly the full data set of the research team – the samples from the Southwest have not been completed and are not included. Figure 3(a) shows that there is a noisy inverse relationship between the deleterious content and absorption. This was unexpected. Figure 3(b) shows that there is only a weak relationship between the specific gravity of RCA and the amount of deleterious material it contains – one might expect a stronger one since most (i.e. brick and asphalt) deleterious materials have low specific gravity. Figure 3(c) shows that there is a strong linear relationship between the absorption of RCA and its specific gravity – a useful finding for mix designers.

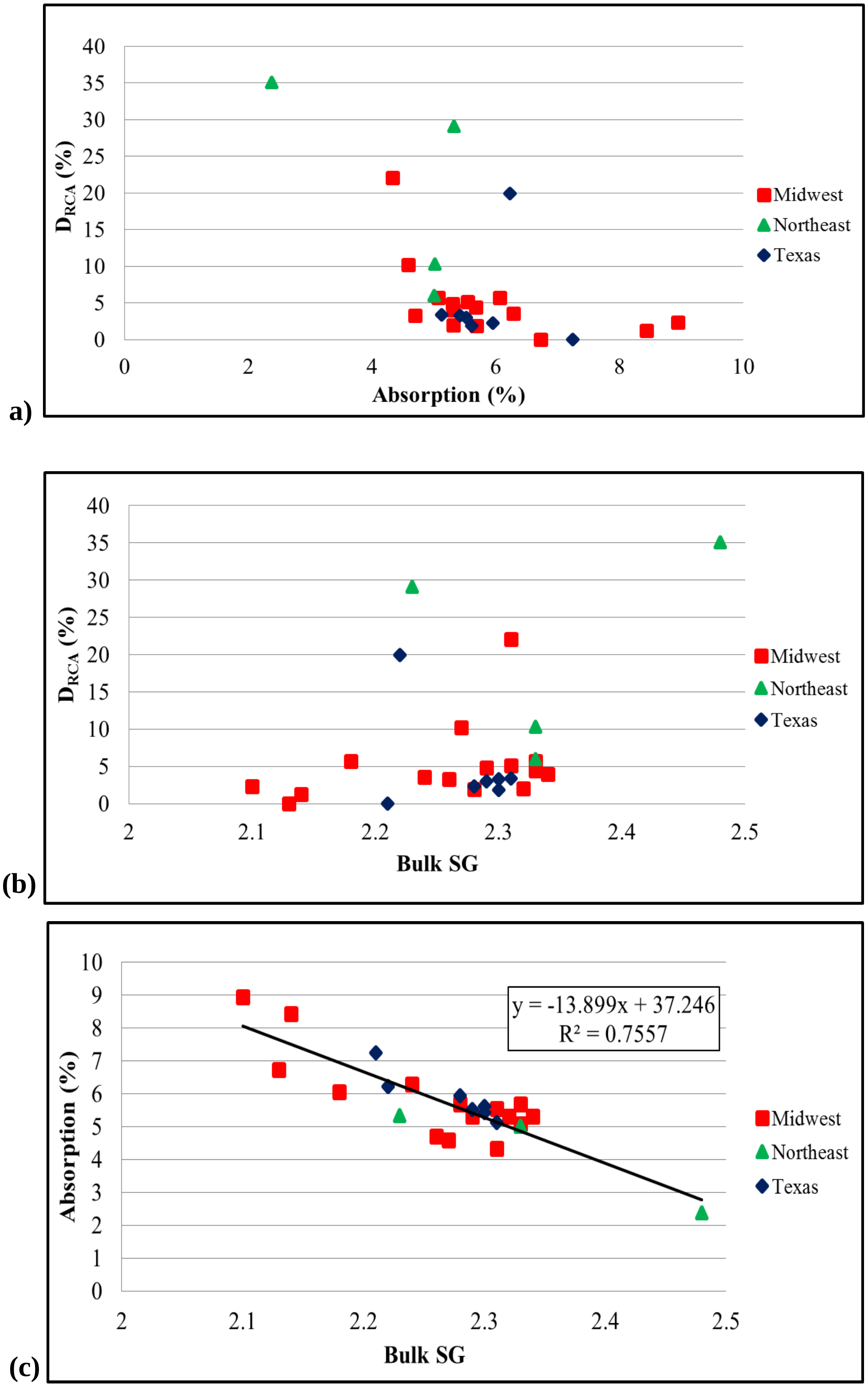

Figure 3. Relationship of RCA properties: a) D_{RCA} vs Absorption, (b) D_{RCA} vs Bulk SG, (c) Absorption vs Bulk SG

FRESH CONCRETE MIX DESIGN

The design mix is referred to as a PG M1 Mix. The coarse aggregate is graded to that of the Pea Gravel Gradation, shown in Figure 1, and the mix is considered to be a normal strength mix, with a target compressive strength of 6000 psi. The target air content is 6%, and target water cement ratio is 0.44. The only admixture that was used for this mix design is PS 1466, a high range water reducing admixture, which can improve strength development as well as improve finishability and surface appearance. The target dosage for an M1 Mix is 6 oz./cwt. of PS 1466. The cement that was used was Portland Cement Type I/II; with an assumed SG of 3.15.

For these mixes, RCA will replace Natural Coarse Aggregate not by weight, rather volume. This method is called The Direct Volume Replacement Method (DVR). DVR takes a given volume of Coarse Natural Aggregate and replaces it with an equal volume of RCA. This allows for the total amount by volume of coarse aggregate (CA), fine aggregate (FA), cement, and water to remain consistent from mix to mix. This allows there to be little loss in the workability of the RCA concrete, given the absorption of the RCA is incorporated into the mix design. The three replacement percentages that were used for the mixes were 0% RCA, 50% RCA, and 100% RCA. Table 2 displays the amount of PS 1466, Cement, CA, FA, and water for each mix. The weights for the coarse and fine aggregate are all saturated surface dry (SSD) weights, which eliminate the need to account for the absorption of the aggregate. Each mix was adjusted to account for mortar loss-the weight of mortar (cement, water, and sand) predicted to be lost to the mixer sides.

Table 2. PG M1 Mixes

Sample	Replacement (%)	PS 1466 (mL)	Cement (lbs.)	CA Added (lbs.)	FA Added (lbs.)	Water Added (lbs.)	Weight in Mixer (lbs.)
PG	0	7.79	4.40	11.80	9.96	0.553	26.7
BCB	50	7.89	4.45	12.30	9.94	0.000	26.7
	100	7.99	4.51	12.02	10.11	0.098	26.7
BCL	50	7.89	4.44	11.90	10.10	0.260	26.7
	100	7.99	4.51	11.85	10.25	0.093	26.7
TIL	50	7.89	4.45	11.80	10.15	0.30	26.7
	100	7.99	4.50	11.90	10.25	0.049	26.7
CCN	50	7.89	4.45	11.95	9.98	0.297	26.7
	100	7.99	4.50	12.07	10.04	0.106	26.7
CCF	50	7.89	4.44	11.86	10.05	0.357	26.7
	100	7.99	4.49	11.85	10.20	0.159	26.7

MIX DESIGN PROCEDURE

A 0.5-HP cement mixer was used with the following mixing procedure:

1. Place Saturated surface dry fine & coarse aggregate, PS 1466, and water into the mixer

2. Run the mixer for three minutes
3. Stop momentarily to add cement
4. Run the mixer again for three minutes
5. Stop the mixer then place a moist towel over drum to avoid any drying in the mix for three minutes
6. Run the mixer for two more minutes
7. Remove concrete from the drum, then weigh the yield

COMPRESSIVE STRENGTH

The cylinders were removed from the molds after 24 hours and placed into a curing tub, then were left in the tub for 27 days. On the 28th day, the cylinders were removed from the tub, wiped with a paper towel then subjected to compressive testing following ASTM C49. Based on an initial subset of the overall project RCA sample data (16 samples from the Midwest), EQ. 1was developed to estimate the compressive strength for RCA mixes by taking into account Absorption for NA (A_{na}) and RCA (A), D_{RCA} (D), and Replacement Percentage (R). $\beta_{f\,1}$, $\beta_{f\,2}$, $\beta_{f\,3}$, and $\beta_{f\,4}$ are regression coefficients previously developed (Knaack et al 2013) shown in Table 3.

Table 3. Compressive Strength Regression Coefficients and Statistics

Mean Value of Unnormalized Regression Coefficients	βf_1	1.0241	95% Confidence Interval For Unnormalized Regression Coefficients	βf_1	[1.0026, 1.0456]
	βf_2	-0.0241		βf_2	[-0.0300 ,-0.0182
	βf_3	-0.0138		βf_3	[-0.0172, -0.0104]
	βf_4	0.0769		βf_4	[0.0299,0.1239]

$$\frac{f'_{c,RCA}}{f'_{c,NA}} = \beta_{f\,1} + \beta_{f\,2} \times \frac{A}{A_{na}} + \beta_{f\,3} \times \mathrm{D} + \beta_{f\,4} \times \mathrm{R} \qquad (1)$$

Figure 4(a) displays the compressive strength of the five samples' (CCN, CCF, BCL, BCB and TIL) as well as the theoretical values using eq. 1. Figure 4(b) and 4(c) displays BCB's and CCN's compressive strength and its relationship with EQ.1, and show the 95% confidence interval based on the regressed relationship of EQ.1. The 95% confidence intervals for the other mixes were similar, with some capturing the experimental results and some not. Table 4 presents the percent difference between the theoretical strength versus the actual strengths for the samples at 50% and 100%. Potentially important parameters that could not be directly included in the regression model are the surface texture, angularity, porosity, stiffness, and strength of the aggregates as well as the properties of the Interfacial Transition Zone (ITZ). Furthermore, given the generally small effect of RCA on the concrete strength (as compared to the stiffness), it is possible that any small variation between the actual cylinders properties and the mix design Properties (e.g., specific gravity, absorption, batch weights, inherent variation between cylinders of the same mix) could be a cause of increased variance (Knaack and Kurama et al 2013).

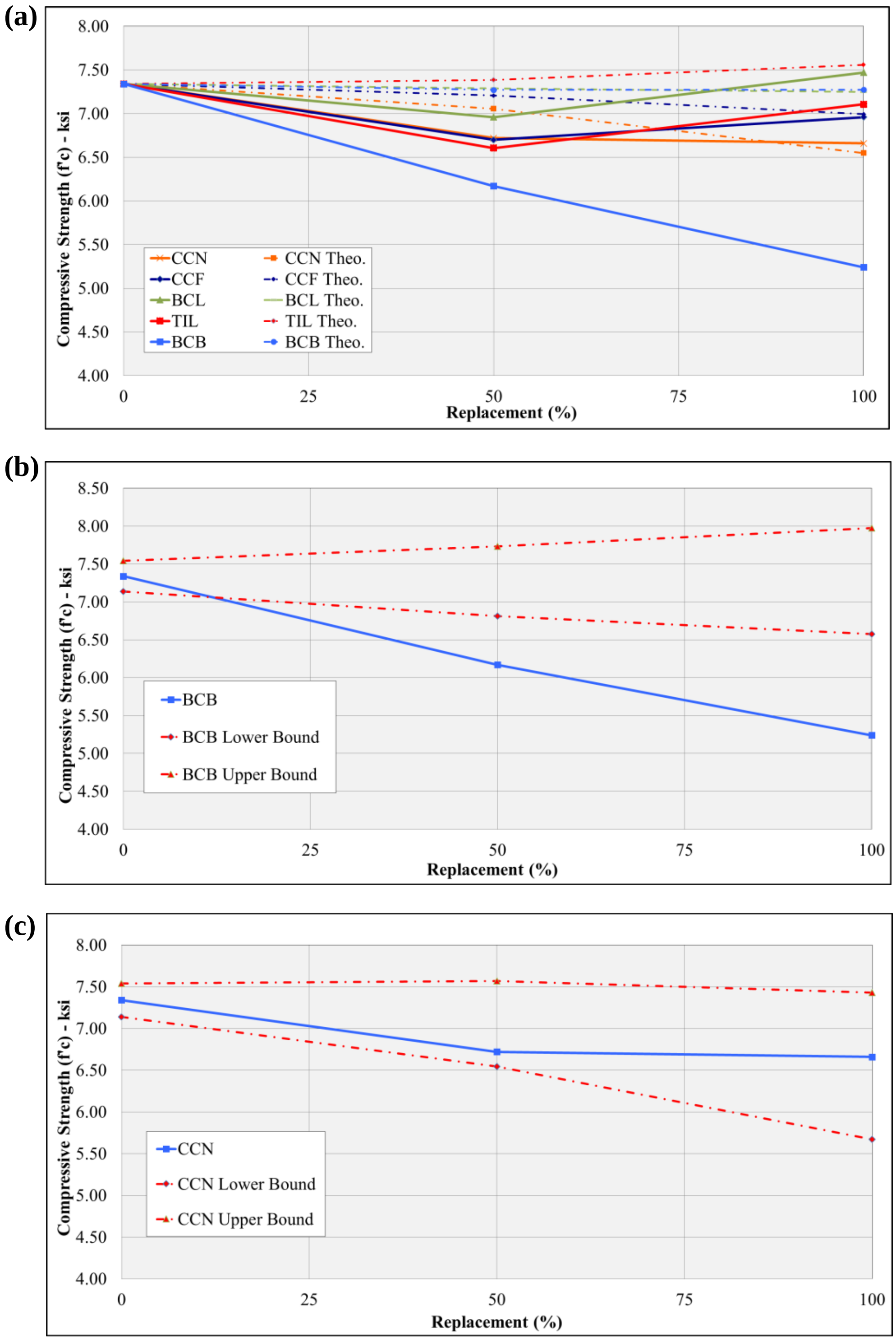

Figure 4 Relationship between Theoretical Values and Measured Values: (a) Compressive Strength for PG M1 Mixes, (b) 95% Confidence Intervals for BCB, (c) 95% Confidence Intervals for CCN

Table 4. Measured Values vs. Theoretical Values

Sample	Measured f'c at 50% R (ksi)	Theoretical f'c at 50% R (ksi)	Percent Difference (%)	Measured f'c at 100% R (ksi)	Theoretical f'c at 100% R (ksi)	Percent Difference (%)	Percent Difference from 0 to 50%	Percent Difference from 0 to 100%
BCB	6.17	7.27	16.39	5.24	7.27	32.5	-17.32	-33.4
BCL	6.96	7.29	4.59	7.47	7.25	3.00	-5.31	1.80
CCF	6.70	7.21	7.30	6.96	6.99	0.50	-9.12	-5.3
CCN	6.72	7.06	4.88	6.66	6.55	1.70	-8.82	-9.71
TIL	6.61	7.39	11.2	7.11	7.56	6.17	-10.53	-3.24

Figure 4 shows that EQ 1, that was developed using only the Midwest project samples, cannot accurately predict the compressive strength of the mixes described herein, which included RCA from Texas and the Northeast. The values in Table 4 shows that the theoretical values were much closer for 50% replacements rather than 100%, which could be a result of the change of absorption from NA to RCA as well as the increased amount of D_{RCA}. From these evaluations, it can be concluded that further testing and evaluation of other samples are needed to refine the previously developed prediction model.

CONCLUSION

The following conclusions are made:

1. Quality concrete can be made with RCA following the DVR method. The strengths of the mixes with 50% RCA replacement differed from their NA counterparts by approximately ± 20%; for 100% RCA replacement the difference was ± 35%.
2. A model created to predict the strength of RCA concrete mixes based on the absorption and DCRA of a subset of all available data needs further development – this is future work planned by the project team.
3. The variability of RCA properties available for purchase was reasonably large for gradation (many sold as road base or for other applications other than concrete making) and for deleterious material (with ranging from 1.87% to 35.1% over the data set studied).
4. The specific gravity of the RCA samples was also variable ranging from 2.1 to 2.5
5. The absorption of the RCA data set ranged from approximately to 10%, and it was linearly related to the RCA specific gravity.

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