Replacement of Coarse and Fine Aggregate in Concrete Pavement Mixtures with Recycled Concrete Aggregate

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Abstract
This study considered the effects of recycled concrete aggregate (RCA) as a replacement of both coarse and fine aggregate in concrete. The coarse portion was replaced by 100% RCA and the fine portion was replaced with RCA at various amounts up to 50%. In addition, fly ash and ground granulated blast furnace slag were utilized as partial replacements of cement. All mixtures were prepared using the two-stage mixing approach and the coarse and fine RCA were in a partially saturated condition. The use of RCA fine aggregate (RFA) reduced the concrete strength. However, it was found that the concrete can have a statistically similar compressive strength to concrete with 100% coarse RCA and no RFA. The shrinkage for almost all recycled concrete mixes was statistically similar at early ages, but at later ages, concrete containing RFA can potentially shrink more, especially if slag and fly ash are used to replace cement. The findings suggest that, with proper design, both RCA and RFA can be used in concrete pavement applications.

Introduction

Present and ongoing reconstruction programs, agencies are faced with accumulating quantities of concrete waste. The resultant crushed concrete can be separated into coarse and fine fractions of recycled concrete aggregate (RCA). A previous study by the authors (Brand *et al.*, 2015) investigated the use of higher quality RCA from an airfield as 100% replacements of the virgin coarse aggregate in concrete and found that the concrete compressive and split tensile strengths can be improved by utilizing a partially saturated (~80% of saturated surface dry) aggregate condition in conjunction with the two-stage mixing approach (TSMA). The TSMA, or double mixing approach, and its modified versions (Ryu, 2002; Tam *et al.*, 2005; Tam and Tam, 2008) have been utilized in a number of studies of concrete with RCA, as summarized by Brand *et al.* (2015), as a potential method to improve the cement-RCA bond by coating the RCA with a "cement slurry" in order to fill the cracks and pores in the RCA aggregate.

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This study expands upon the previous work by the authors (Brand *et al.*, 2015) by investigating the potential of using 100% coarse RCA as well as fine RCA as a partial replacement of the virgin fine aggregate in concrete. In general, the inclusion of RCA fine aggregates (RFA), relative to virgin fine aggregate, in concrete has been found to reduce compressive strength (Sri Ravindrarajah *et al.*, 1987; Khatib, 2005; Fumoto and Yamada, 2006; Tangchirapat *et al.*, 2008; Yang *et al.*, 2008; Kou and Poon, 2009a; Sim and Park, 2011; Yaprak *et al.*, 2011; Zega and Di Maio, 2011; Lovato *et al.*, 2012; Khoshkenari *et al.*, 2014), increase compressive strength (Rasheeduzzafar and Khan, 1984), or have mixed results on the compressive strength (Evangelista and de Brito, 2007; Kou and Poon, 2009b); reduce split tensile strength (Sri Ravindrarajah *et al.*, 1987; Evangelista and de Brito, 2007; Tangchirapat *et al.*, 2008; Yang *et al.*, 2008; Zega and Di Maio, 2011; Lovato *et al.*, 2012; Pereira *et al.*, 2012; Khoshkenari *et al.*, 2014) or have mixed results on the split tensile strength (Kou and Poon, 2009b; Kim *et al.*, 2011); reduce the flexural strength (Sri Ravindrarajah *et al.*, 1987; Yang *et al.*, 2008; Kim *et al.*, 2011); reduce the modulus of elasticity (Sri Ravindrarajah *et al.*, 1987; Khatib, 2005; Evangelista and de Brito, 2007; Tangchirapat *et al.*, 2008; Yang *et al.*, 2008; Zega and Di Maio, 2011; Lovato *et al.*, 2012; Pereira *et al.*, 2012); and increase the drying shrinkage (Sri Ravindrarajah *et al.*, 1987; Khatib, 2005; Fumoto and Yamada, 2006; Yang *et al.*, 2008; Kou and Poon, 2009a; Kou and Poon, 2009b). Additional information can be found in a recent overview document that summarizes the use of RFA and its effect on concrete properties (Evangelista and de Brito, 2014).

Some studies have found that, at low replacement contents, RFA may not significantly affect the concrete properties. With 20-30% RFA, the drying shrinkage of concrete is similar to normal concrete (Zega and Di Maio, 2011), and 30% RFA may not greatly affect the concrete compressive strength (Evangelista and de Brito, 2007). Another study found that, for structural concrete, 100% coarse RCA and 60% RFA could be used (Sim and Park, 2011) while other researchers suggest 50% RFA (Kim *et al.*, 2011). Some authors found that the use of fly ash (Kou and Poon, 2009b) or rice husk bark ash (Tangchirapat *et al.*, 2008) in conjunction with RFA may have a positive influence on the concrete strength properties. In contrast, one report (Hansen, 1992) suggested that any RCA under 2 mm in size should not be used in concrete because of its negative impact on concrete properties.

Based on the literature, RFA can potentially have a negative influence on the concrete strength and shrinkage properties, although supplementary cementitious materials may improve the properties. The primary objective of this study was to investigate sustainable concrete pavement solutions by incorporating high volumes of construction waste (RCA and RFA) and supplementary cementitious materials (fly ash and blast furnace slag). This study examined ten concretes with RFA and two control mixes and tested the compressive, split tensile, and flexural strengths and free drying shrinkage. All mixtures contained binary or ternary cementitious blends. In addition, the Tukey test was employed to determine if the RFA had any statistical effect on the concrete properties. The research significance of this work is to provide engineers and practitioners with a practical observation of the effect of using both

RCA and RFA in concrete mixtures. In particular, this study evaluated a higher quality RCA and RFA source, so the quality of the material is known and relatively consistent.

Experimental Design

Cementitious Materials. Three different cementitious materials were used in this study: Type I portland cement, Class C fly ash, and Grade 100 ground granulated blast furnace slag (GGBFS). Different binary and ternary blends of cementitious materials were investigated to evaluate the potential for further potential improvement to the strength and shrinkage properties. Additional details on the cementitious materials can be found in Salas *et al.* (2013).

Aggregate Properties. Three coarse aggregates and two fine aggregates were utilized in this study. There were two virgin coarse aggregates, which were classified as CA-7 and CA-16 according to the Illinois Department of Transportation (IDOT, 2012). These two virgin coarse aggregates were blended to achieve a more optimized gradation, and the coarse RCA was sieved and recombined to match the virgin coarse aggregate gradation (see Table 1). The virgin fine aggregate (natural sand) was classified as FA-02 and the RFA could be best classified as FA-05 or FA-06 (IDOT, 2012). The aggregate gradation, specific gravity (relative to saturated surface dry [SSD]), and absorption capacity are shown in Table 1. As expected, the coarse RCA and RFA had a lower specific gravity and significantly greater absorption capacities relative to the virgin aggregates.

Table 1. Aggregate Gradations and Properties

Gradation (Percent Cumulative Passing)						
Sieve		Natural Coarse 1	Natural Coarse 2	Combined Grading of CA-7 and CA-16 for RCA	Natural Sand Fine Aggregate	RCA Fine Aggregate (RFA)
U.S.	mm	CA-16	CA-7		FA-02	FA-06
3/4 in	19	100%	83%	93%	100%	100%
1/2 in	12.5	100%	20%	66%	100%	100%
3/8 in	9.5	95%	6%	59%	100%	100%
#4	4.75	41%	1%	47%	92%	87%
#8	2.36	6%	0%	31%	68%	65%
#16	1.18	2%	0%	19%	42%	44%
#30	0.6	1%	0%	10%	21%	30%
#50	0.3	1%	0%	1%	2%	19%
#100	0.15	1%	0%	0%	0%	12%
#200	0.075	--	--	--	0%	9%
Aggregate Properties						
Specific Gravity		2.68	2.67	2.41	2.57	2.20
Absorption Capacity		2.73%	1.90%	5.51%	2.43%	9.85%

The RCA and RFA source was the same as the previous study by the authors (Brand *et al.*, 2015), which was a single stockpile from O'Hare International Airport. Given the stricter protocols for concrete used in airfield rigid pavements, this particular RCA was of higher quality and less variability relative to other RCA or construction and demolition waste sources.

The residual mortar content (RMC) of the coarse RCA was evaluated using a method described by Abbas *et al.* (2009), where a sample of the coarse RCA underwent freezing and thawing cycles in a sodium sulfate solution. For this study, the RCA aggregates retained on the #4 (4.75 mm) sieve resulted in an RMC of 26%, while the particles larger than 1 inch (25 mm) resulted in an RMC of 13%.

Based on the previous results by the authors (Brand *et al.*, 2015), it was found that an ~80% SSD moisture condition was optimal for coarse RCA in concrete. Therefore, in this study, the virgin coarse aggregate and coarse RCA were mixed into the concrete at an 80% SSD moisture content. This condition was achieved by soaking the aggregates in water for at least 24 hours prior to batching and then allowing the excess moisture to evaporate by exposing the aggregates to laboratory conditions. Prior to batching the concrete, the aggregate moisture content was verified by drying a sample in the oven. The RFA was similarly soaked in water and mixed in the concrete while in a partially saturated condition (less than SSD). The virgin fine aggregate was in an air dry moisture condition (i.e., near oven dry but with some measurable moisture). The water was adjusted for each mixture based on the measured moisture content of all aggregates to ensure that there was sufficient water to bring all aggregates to the SSD condition.

Batching Methodology. The modified TSMA procedure outlined by Tam and Tam (2008) was utilized in this study for all concrete mixtures. The TSMA adds water to the concrete mixture in two steps. Initially, the coarse aggregates (virgin or RCA), the RFA, and the cementitious materials were mixed for one minute after which half of the water was added and then mixed for one more minute. Finally, the virgin fine aggregate and remaining water was added with the chemical admixtures and then mixed for two minutes.

Concrete Testing. Upon the completion of the concrete mixing, the fresh concrete was tested for initial slump (ASTM C 143, 2012) prior to casting the laboratory specimens (ASTM C 192, 2007). After casting, all specimens were covered with a plastic sheet to prevent moisture loss for the first 24 hours of hydration, after which the specimens were removed from the molds and placed in a moist curing room until testing. The concrete was tested for compressive (ASTM C 39, 2010) and split tensile (ASTM C 496, 2004) strengths using cylindrical specimens what were 4 inches (100 mm) in diameter and 8 inches (200 mm) in height. The flexural strength (ASTM C 78, 2010) was also measured under third-point (four point) loading with beams that measured 6 by 6 by 21 inches (150 by 150 by 530 mm). A slightly modified ASTM C 157 (2008) test was used to measure the free drying shrinkage of the concrete: immediately after removing the molds (rather than initially curing the specimens), the shrinkage prisms, which measured 3 by 3 by 11.25-inch (75 by 75 by 285 mm), were placed in an environmentally-controlled room at 50% relative humidity and 23°C. This modified shrinkage test was conducted to study the early-age shrinkage properties of the concrete.

Concrete Mix Designs. The total cementitious content of all mixes was 517 lb/yd^3 (307 kg/m^3) with a water-to-cementitious ratio of 0.42. The concrete mix designs are shown in Table 2, and each mix is labelled based on the cementitious material and RFA content. In order to maintain a constant volume of concrete constituents, it can be seen that the total coarse and fine aggregates vary due to the change in specific gravity for the recycled versus virgin aggregates. The only chemical admixture used in all mixtures was a polycarboxylate-based high range water reducer, the dosages of which can be seen in Table 3 with the slump values. The two control mixes in Table 2 were from the previous study with similar constituent materials and volumetric proportions (Brand *et al.*, 2015).

Table 2. Concrete Mixture Designs in lb/yd^3 (kg/m^3)

Mixture*	Cement	Fly Ash	GGBFS	Water	Coarse Aggregate			Fine Aggregate	
					Virgin CA-7	Virgin CA-16	RCA	Virgin Sand	RFA
Control (Virgin)	414 (246)	103 (61)	0	217 (129)	1495 (887)	500 (297)	0	1279 (758)	0
Control (RCA)	414 (246)	103 (61)	0	217 (129)	0	0	1799 (1067)	1279 (758)	0
20FA-30RFA	414 (246)	103 (61)	0	217 (129)	0	0	1799 (1067)	895 (531)	328 (195)
20FA-50RFA	414 (246)	103 (61)	0	217 (129)	0	0	1799 (1067)	640 (380)	547 (324)
35FA-30RFA	336 (199)	181 (107)	0	217 (129)	0	0	1790 (1061)	891 (528)	327 (194)
50FA-20RFA	259 (154)	259 (154)	0	217 (129)	0	0	1781 (1056)	1013 (601)	217 (129)
50FA-50RFA	259 (154)	259 (154)	0	217 (129)	0	0	1781 (1056)	633 (375)	542 (321)
50FA-0RFA	259 (154)	259 (154)	0	217 (129)	0	0	1781 (1056)	1266 (751)	0
60FA-20RFA	207 (123)	310 (184)	0	217 (129)	0	0	1775 (1053)	1009 (598)	216 (128)
35S-30RFA	336 (199)	0	181 (107)	217 (129)	0	0	1805 (1070)	898 (533)	329 (195)
30S-30FA-30RFA	207 (123)	155 (92)	155 (92)	217 (129)	0	0	1787 (1060)	890 (528)	326 (193)
30S-30FA-50RFA	207 (123)	155 (92)	155 (92)	217 (129)	0	0	1787 (1060)	635 (377)	544 (323)

*Mixture labels are abbreviated. For example, 30S-30FA-50RFA refers to a mixture with 30% GGBFS, 30% fly ash, and 30% RFA. The abbreviations are: FA=Fly Ash, RFA=RCA Fine Aggregate, S=GGBFS

Results and Discussion

Initial Slump. The fresh concrete initial slump can be found in Table 3. The angularity of the RFA required that additional chemical admixture be added to sustain the workability. As expected, increasing the amount of fly ash did not require as much chemical admixture due to the spherical shape of the fly ash particles that improved the workability. Overall, a workable concrete can be produced when using both coarse RCA and RFA, especially if fly ash and a high range water reducer are utilized.

Table 3. Initial Slump and Chemical Admixture Dosage

Mixture*	Slump, inches (mm)	High Range Water Reducer Dosage**
Control (Virgin)	7 (160)	3.8 (250)
Control (RCA)	8 (205)	4.0 (260)
20FA-30RFA	6 (150)	4.3 (280)
20FA-50RFA	4 (100)	4.6 (300)
35FA-30RFA	6 (150)	3.8 (250)
50FA-20RFA	6-3/4 (170)	3.2 (210)
50FA-50RFA	4-1/2 (115)	4.6 (300)
50FA-0RFA	5-1/4 (135)	3.1 (200)
60FA-20RFA	7 (180)	3.1 (200)
35S-30RFA	3-1/2 (90)	4.9 (320)
30S-30FA-30RFA	4 (100)	4.9 (320)
30S-30FA-50RFA	3 (75)	5.0 (350)

*FA=Fly Ash, RFA=RCA Fine Aggregate, S=GGBFS
**In fl. oz. per 100 lbs (mL per 100 kg) cementitious

Compressive Strength. The compressive strength was evaluated as the average of three specimens each at 3, 7, and 28 days (Figure 1). As can be seen, the highest strength achieved at every age was by the control mix with virgin aggregates. The second highest strength was achieved by the other control mix with had 100% coarse RCA and no RFA. The inclusion of RFA clearly decreased the compressive strength relative to the mixtures without RFA, which is consistent with the literature. At a given supplementary cementitious content, however, increasing the RFA content appeared to slightly increase the compressive strength (i.e., compare the mixtures 50FA-0RFA, 50FA-20RFA, and 50FA-50RFA and the mixtures 30S-30FA-30RFA and 30S-30FA-50RFA). The addition of RFA did not appear to influence the magnitude of the standard deviation. In addition, higher volumes of fly ash generally reduced the early age compressive strength because of the slower reaction rate of fly ash. The replacement of cement with GGBFS versus fly ash appears to be beneficial, since the mix with 35% GGBFS achieved the third highest 28-day compressive strength.

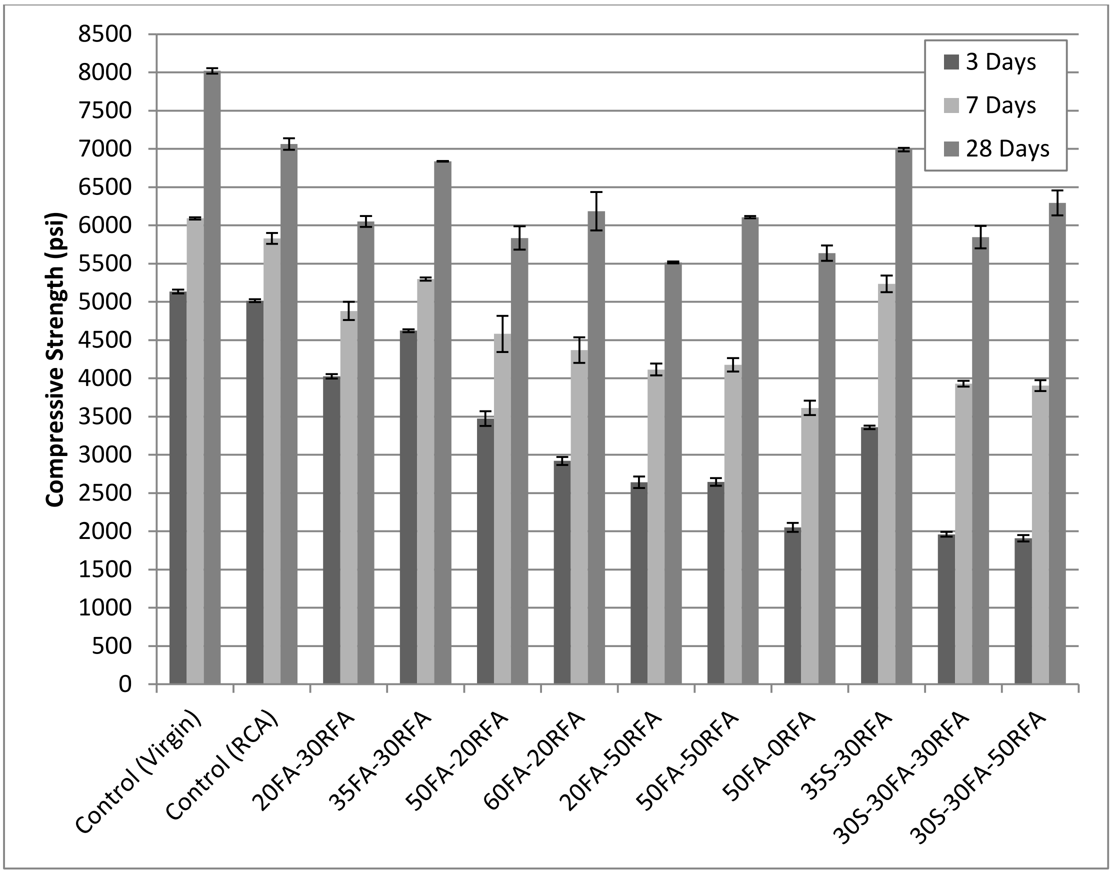

Figure 1. Compressive strength at 3, 7, and 28 days for each mixture (error bars indicate one standard deviation). Note: 1 psi = 6.9 kPa.

Split Tensile and Flexural Strengths. The split tensile strength was evaluated at 28 days as the average of two or three specimens (Figure 2), and the flexural strength (by third-point loading) was evaluated at 28 days as the average of three specimens (Figure 2). A similar trend to the compressive strength can be seen, where the concrete strength decreases with the inclusion of RFA and higher volumes of fly ash. The negative impact of high volumes of fly ash on the 28-day strength is more pronounced with the flexural strength than with the split tensile strength. However, at a given supplementary cementitious content, increasing the RFA content did not appear to increase the split tensile or flexural strength (i.e., compare the mixtures 50FA-0RFA, 50FA-20RFA, and 50FA-50RFA and the mixtures 30S-30FA-30RFA and 30S-30FA-50RFA). Therefore, it may be concluded that the angularity of the RFA may assist in increasing the compressive strength but not the tensile strength of concrete.

Assuming a minimum 28-day flexural strength requirement of 600 psi (4.1 MPa) for rigid pavements, it is evident that the two control mixes (with no RFA) would pass along with the mix with 35% GGBFS and 30% RFA. Therefore, in order to meet the strength requirements for a concrete pavement, high replacements of RFA and this source of fly ash may be less suitable with more evidence in support of using GGBFS with RFA.

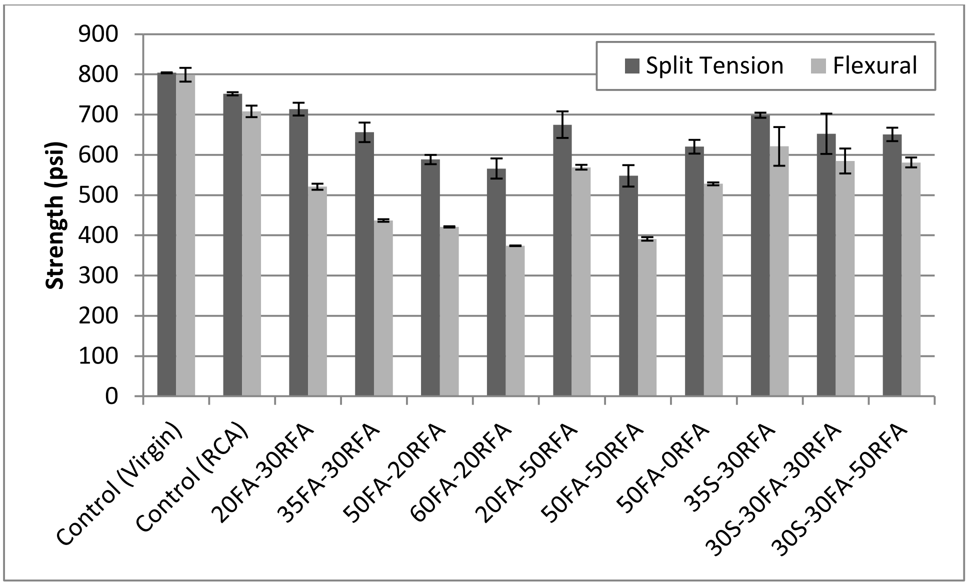

Figure 2. Split tensile and flexural strengths at 28 days for each mixture (error bars indicate one standard deviation). Note: 1 psi = 6.9 kPa.

Drying Shrinkage. The free drying shrinkage is shown in Figure 3 and Figure 4 as the average of three prism specimens for all mixes except for the mix with 50% fly ash and no RFA, which only had one measureable specimen. The shrinkage was measured at 4, 7, 14, 28, and 56 days. The shrinkage strains are plotted in Figure 3 and Figure 4 relative to the control mixes. After 56 days of drying, both control mixes have similar shrinkage strains while it is evident that most of the mixes with RFA have higher shrinkage strains. In particular, the two ternary blend mixes (with both fly ash and GGBFS) experienced the greatest amount of shrinkage. Otherwise there does not appear to be a significant trend in the effect of higher replacements with fly ash or RFA on the shrinkage. It has been proposed that concrete with RFA experiences greater shrinkage because of the lower modulus of the aggregates and/or the adhered mortar on the RCA (Sri Ravindrarajah *et al.*, 1987; Yang *et al.*, 2008; Kou and Poon, 2009a). Additionally, the mixtures with high supplementary cementitious material contents may have experienced greater shrinkage because of the slower pozzolanic reaction, thus perhaps resulting in more permeable microstructure at early ages.

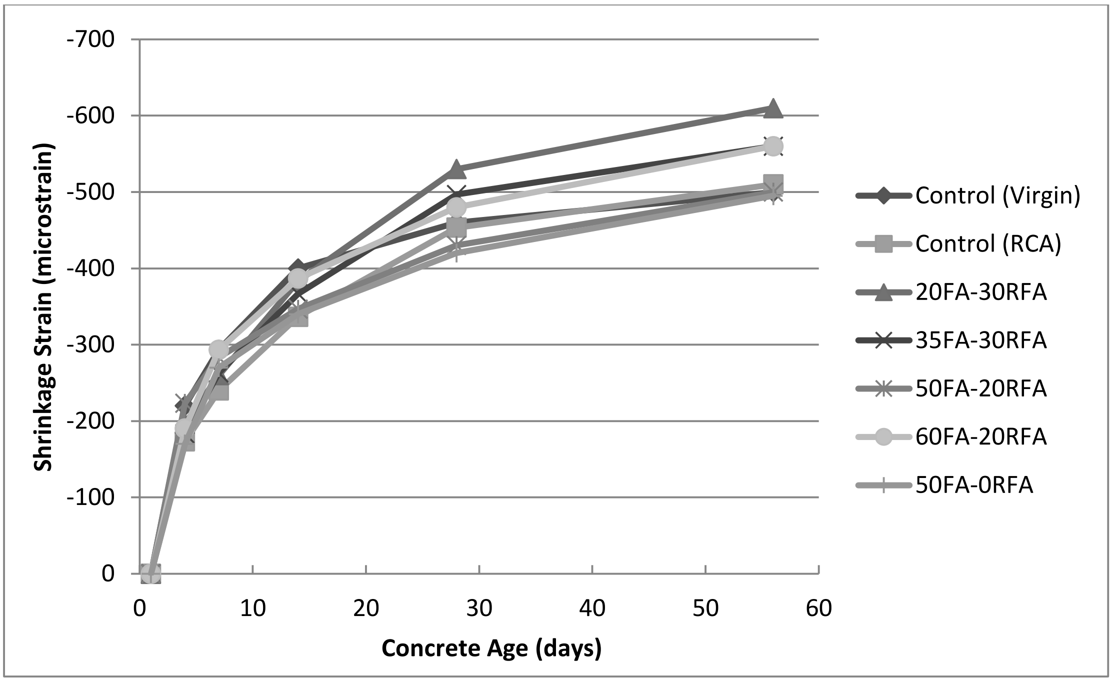

Figure 3. Free drying shrinkage for the mixes with fly ash and RFA compared to the control.

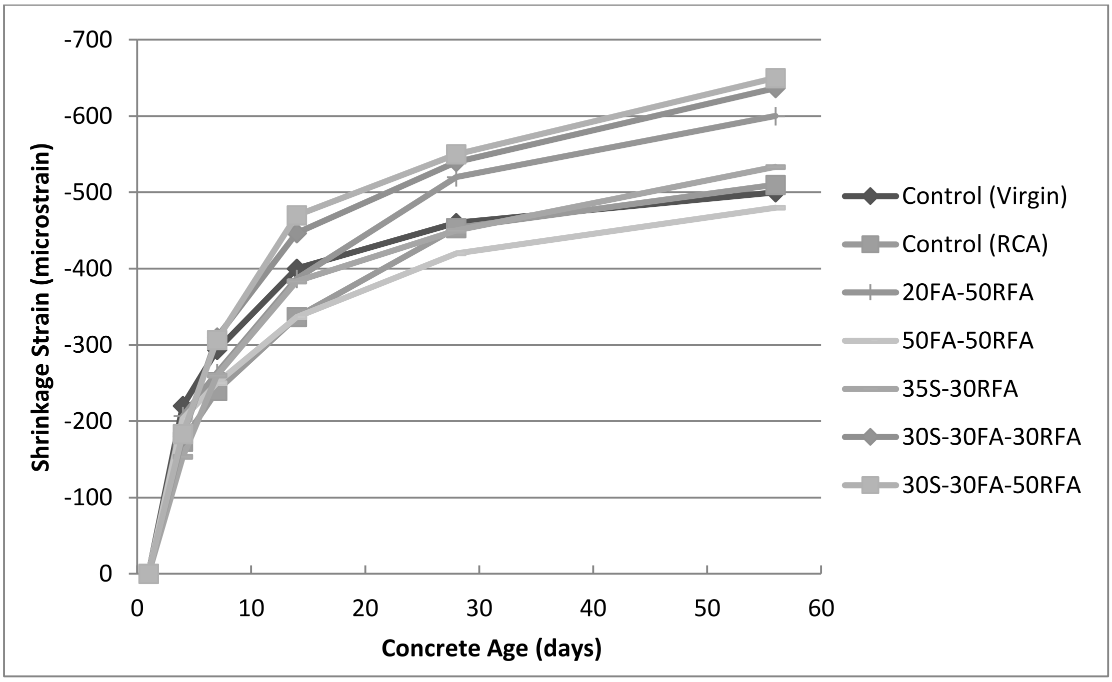

Figure 4. Free drying shrinkage for the mixes with fly ash and/or GGBFS with higher RFA contents compared to the control.

Statistical Analysis of Mechanical Properties. The results for strength and shrinkage were compared using a one-way analysis of variance (ANOVA) test, which revealed that the means were statistically different with 95% confidence. Thus, in order to gain more information on the results, Tukey's significant difference (TSD) test was used, which is based on a studentized distribution and uses the mean squared error from the

ANOVA test (Mason *et al.*, 2003). A piecewise comparison was performed on the results using TSD, so the different mixes with statistically similar means can be grouped together.

The groupings based on the TSD test for the strength results are shown in Table 4. The two control mixes (virgin and coarse RCA) had similar compressive strength at 7-day age but statistically different than mixes containing RFA. For the 28-day compressive strength, the virgin concrete is statistically greater than all mixes, while mixes 35% GGBFS with 20% RFA and 20% fly ash with 50% RFA have statistically similar compressive strengths to the control RCA mix. Those same two mixes are also statistically similar to the control RCA mix for the split tensile strength along with the 20% fly ash with 30% RFA mix. No mixes containing RFA are statistically similar to the control mixes for the flexural strength tests. The mixes with the lowest statistical strengths contained high contents of pozzolans and/or RFA. Therefore, mixes with RFA cannot achieve the same strength as virgin aggregates but it is possible to achieve similar strengths to 100% coarse RCA mixes when using RFA, particularly with lower amounts of fly ash or GGBFS.

The Tukey statistical groupings for the shrinkage results are shown in Table 6. At early ages (7 days), the shrinkage of nearly all of the mixes is statistically similar, but at later ages (56 days), the shrinkage magnitude is more varied with many mixes being statistically different. It is clear that some mixes with and without RFA had statistically similar shrinkage strains to virgin aggregate concrete. Overall it appears that the ternary blended mixes with higher supplementary cementitious material contents had the greatest amount of shrinkage. Otherwise, mixtures in the same Tukey grouping did not display a discernible trend in shrinkage magnitude.

Table 4. Grouping Based on the TSD Test for the Compressive Strengths at 7 and 28 Days

7-Day Compressive Strength					28-Day Compressive Strength				
Tukey Grouping*		**Mean (psi)**	**Standard Deviation (psi)**	**Mix**	**Tukey Grouping***		**Mean (psi)**	**Standard Deviation (psi)**	**Mix**
	A	6091	16.1	Control (Virgin)	H		8020	36.5	Control (Virgin)
	A	5828	71.7	Control (RCA)	I		7064	74.7	Control (RCA)
	B	5297	21.4	20%FA-50%RFA	I		6991	23.0	35%SLAG-30%RFA
	B	5233	108.6	35%SLAG-30%RFA	I		6837	5.4	20%FA-50%RFA
	C	4880	118.7	20%FA-30%RFA	J		6294	161.9	30%SLAG-30%FA-50%RFA
D	C	4581	235.7	35%FA-30%RFA	J		6184	252.6	50%FA-20%RFA
D	E	4369	166.9	50%FA-20%RFA	J	K	6106	15.5	50%FA-0%RFA
F	E	4176	87.5	50%FA-0%RFA	J	K	6052	71.3	20%FA-30%RFA
F	E	4116	77.2	50%FA-50%RFA	L	K	5845	146.4	30%SLAG-30%FA-30%RFA
F	G	3929	38.1	30%SLAG-30%FA-30%RFA	L	K	5835	154.3	35%FA-30%RFA
F	G	3904	70.8	30%SLAG-30%FA50%RFA	L		5638	100.0	60%FA-20%RFA
	G	3613	94.8	60%FA-20%RFA	L		5514	12.8	50%FA-50%RFA

*Means with the same letter are not significantly different.

Table 5. Grouping Based on the TSD Test for the Split Tensile and Flexural Strengths at 28 Days

28-Day Split Tensile Strength							**28-Day Flexural Strength**						
Tukey Grouping*				**Mean (psi)**	**Standard Deviation (psi)**	**Mix**	**Tukey Grouping***				**Mean (psi)**	**Standard Deviation (psi)**	**Mix**
M				804	1.1	Control (Virgin)	S				799	17.1	Control (Virgin)
M	N			752	3.9	Control (RCA)		T			708	14.3	Control (RCA)
	N	O		714	15.8	20%FA-30%RFA			U		622	47.9	35%SLAG-30%RFA
	N	O		699	6.5	35%SLAG-30%RFA			U		585	30.9	30%SLAG-30FA-30%RFA
P	N	O		675	32.9	20%FA-50%RFA			U	V	581	12.3	30%SLAG-30%FA-50%RFA
P		O	Q	656	24.3	35%FA-30%RFA		W	U	V	569	5.8	20%FA-50%RFA
P		O	Q	652	49.8	30%SLAG-30%FA-30%RFA		W		V	528	3.4	50%FA-0%RFA
P		O	Q	651	16.9	30%SLAG-30%FA-50%RFA		W			521	7.5	20%FA-30%RFA
P	R		Q	620	17.1	50%FA-0%RFA			X		437	3.0	35%FA-30%RFA
	R		Q	588	11.4	50%FA-20%RFA			X	Y	421	1.3	50%FA-20%RFA
	R			566	25.4	60%FA-20%RFA			X	Y	391	4.4	50%FA-50%RFA
	R			548	26.7	50%FA-50%RFA				Y	374	0.5	60%FA-20%RFA

*Means with the same letter are not significantly different.

Table 6. Grouping Based on the TSD Test for the Free Drying Shrinkage at 7 and 56 Days

7-Day Shrinkage							56-Day Shrinkage					
Tukey Grouping*			Mean (με)	Standard Deviation (με)	Mix		Tukey Grouping*		Mean (με)	Standard Deviation (με)	Mix
	Z		-240	0.0	Control (RCA)			CC	-480	0.0	50%FA-50%RFA
AA	Z		-250	0.0	50%FA-50%RFA		EE	DD	-500	0.0	50%FA-20%RFA
AA	Z	BB	-260	5.8	35%SLAG-30%RFA		EE	DD	-500	0.0	Control (Virgin)
AA	Z	BB	-260	0.0	20%FA-30%RFA		EE		-510	0.0	Control (RCA)
AA	Z	BB	-263	15.3	20%FA-50%RFA			FF	-533	20.0	35%SLAG-30%RFA
AA	Z	BB	-263	15.3	35%FA-30%RFA			GG	-560	0.0	60%FA-20%RFA
AA	Z	BB	-283	5.8	50%FA-20%RFA			GG	-560	0.0	35%FA-30%RFA
AA	Z	BB	-293	5.8	60%FA-20%RFA			HH	-600	0.0	20%FA-50%RFA
AA	Z	BB	-293	5.8	Control (Virgin)			HH	-610	0.0	20%FA-30%RFA
AA		BB	-307	25.2	30%SLAG-30%FA-50%RFA			II	-637	11.5	30%SLAG-30%FA-30%RFA
		BB	-310	43.6	30%SLAG-30%FA-30%RFA			JJ	-650	0.0	30%SLAG-30%FA-50%RFA

*Means with the same letter are not significantly different.
Note: the mix with 50% FA and no RFA was disregarded from this analysis since it only had one measureable specimen

Conclusions

Concrete by-products from reconstruction projects are producing significant stockpiles. This study was undertaken to evaluate the potential to utilize recycled concrete aggregate (RCA) to replace 100% of the coarse aggregate and a significant portion of the fine aggregate in concrete pavement applications. The recycled aggregates were proportioned by volume in order to retain comparable volumetrics in the mix design. The literature suggested that the detrimental effect of using RCA fine aggregate (RFA) could be offset by using supplementary cementitious materials, so fly ash and ground granulated blast furnace slag (GGBFS) were also used as partial replacements of cement. All mixtures were prepared using the two-stage mixing approach with RCA that was in a partially saturated condition, as suggested in the literature.

Overall, the inclusion of RFA in concrete reduced the concrete strength (compression, split tension, flexural), although particularly the mix with GGBFS was found to have statistically similar mean strengths to the control with 100% coarse RCA and no RFA. At a given supplementary cementitious material content, the increasing RFA content appeared to increase the compressive strength but not necessarily the tensile strength. Relative to the control mixes, the shrinkage of the concretes with RFA were variable, although most underwent greater shrinkage than the control. At early ages the shrinkage of all mixes was relatively similar but the concrete with RFA tended to experience greater shrinkage strains at later ages. The usage of RFA with supplementary cementitious materials has potential for concrete pavement applications, even with slight decreases in the concrete mechanical properties.

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