Recycled Aggregates in Roller-Compacted Concrete

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Abstract

With increasing demand for more sustainable pavement options, roller-compacted concrete (RCC) is attractive because of its lower cement contents, construction expediency, and early opening to traffic. Addition of recycled aggregates to RCC can further economize this pavement type. The objective of this study was to determine the effects of the following recycled aggregates on RCC mixture design and hardened properties: recycled concrete aggregate (RCA), electric arc furnace (EAF) slag aggregates, reclaimed asphalt pavement (RAP), and steel furnace slag fractionated reclaimed asphalt pavement (SFSFRAP). For each mixture, compressive, split tensile, and flexural strengths and fracture properties were tested at multiple ages. The strength of the RCC containing recycled aggregates was similar to or lower than the RCC with virgin except for the RCC mixture with EAF, which produced statistically greater compressive strength. As expected, RAP and SFSFRAP resulted in lower compressive strengths compared to the virgin aggregate RCC. All RCC mixes with recycled aggregates had statistically lower flexural strength to RCC with virgin aggregates except the EAF aggregates. Disk compact tension fracture testing demonstrated that all recycled aggregate mixes had similar or greater values of critical stress intensity factor and total fracture energy relative to the virgin RCC. Based on past slab testing of concrete with recycled aggregates that had similar or greater fracture parameters relative to virgin aggregate concrete, slab flexural capacities are anticipated to be similar for RCC with and without recycled aggregates despite the lower strength properties for RCC containing recycled aggregates except the EAF aggregates.

Introduction

The use of recycled materials, such as recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP), as aggregate in concrete has been gaining interest as a result of growing interest in more sustainable pavement options. Many studies have shown the effects of such recycled materials on the fresh and hardened properties of conventional paving concrete (Van Dam et al. 2011; Gardiner and Komas 2013). However, there have been fewer studies on the use of recycled aggregates in roller-compacted concrete (RCC) with the majority published within the past six years (Haque and Ward 1986; Nanni 1988; Sobhan and Mashnad 2001; Sobhan and Mashnad 2002; Debieb et al. 2009; Courard et al. 2010; Albuquerque et al. 2011; Bilodeau et al. 2011, 2012; Sachet et al. 2011; Villena et al. 2011; Nguyen et al. 2012; Muscalu et al. 2013; Sachet et al. 2013; Ferrebee et al. 2014; Modarres and Hosseini 2014; Angelakopoulos et al. 2015). The most common recycled aggregate

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sources studied for use in RCC have been RAP and RCA, but there has also been some research on using other recycled, co-product, or waste material (RCWM), including rice husk ash (RHA), blast furnace slag sand, limestone tailings, and recycled masonry.

More recently, studies have been published concerning the performance or design of RCC with recycled materials. Accelerated pavement test (APT) sections of RCC with RAP and steel fibers were constructed in France with the material properties summarized by Bilodeau et al. (2011, 2012) and preliminary accelerated pavement testing results presented by Nguyen et al. (2012). Based on the APT results, Nguyen et al. (2012) developed a pavement design for their study and found that, as a base layer for a continuously reinforced concrete pavement, RCC with RAP needed to be 1-2 cm thicker than RCC with limestone (virgin) aggregates.

Replacing virgin coarse aggregate with fractionated reclaimed asphalt pavement (FRAP), either as a partial or full replacement, in RCC was shown to reduce compressive strengths by approximately 40% (Courard et al. 2010; Ferrebee et al. 2014; Modarres and Hosseini 2014), flexural strengths by approximately 35% (Modarres and Hosseini 2014), and split tensile strengths by approximately 20% (Ferrebee et al. 2014). RAP also decreased the RCC elastic modulus by up to 50% (Bilodeau et al. 2011). The use of fine FRAP in RCC has proved to be more detrimental to the strength properties compared to the use of coarse FRAP (Modarres and Hosseini 2014). Fracture properties of RCC with 16% FRAP (by weight of total aggregate) were shown to be statistically similar to virgin RCC (Ferrebee et al. 2014), although Sachet et al. (2011) found that the use of RAP (50% by total aggregate volume) reduced the stress intensity factor of RCC. Modarres and Hosseini (2014) also demonstrated that RCC with 100% RAP aggregates had a lower fatigue life compared with virgin RCC at stress ratios less than 0.70.

The addition of RCA to RCC has been shown to reduce its strength and elastic modulus (Debieb et al. 2009; Muscalu et al. 2013) with the magnitude of reduction dependent on the quality and source of the RCA. Angelakopoulos et al. (2015) showed that recycled masonry aggregates in RCC reduced strength by approximately 40% while high-quality RCA yielded similar strengths to a virgin aggregate RCC. Albuquerque et al. (2011) reported blast furnace slag sand reduced RCC strength and elastic modulus while having little effect on its fracture properties. The use of RHA (Villena et al. 2011) and limestone tailings (Nanni 1988) as aggregate replacements in RCC have yielded greater strengths than similar virgin RCC mixtures.

The literature for RCC containing recycled materials as aggregate have generally shown reductions in strength and modulus relative to virgin RCC with a few exceptions. None of the studies used a fixed gradation to compare the RCC properties produced by virgin or recycled aggregates even though aggregate gradation is known to affect the RCC properties (ACI 1995; LaHucik and Roesler 2015). Therefore, this study aims to compare the effects of various recycled materials on RCC properties, while maintaining the aggregate gradation and cement content, in order to better determine their feasibility for use in RCC pavements. For both recycled and virgin aggregate RCC mixtures, moisture-density relationship, strength (compression, split tension, and flexure), and fracture properties were measured in order to compare the various recycled material types and replacement amounts with the virgin RCC mixture.

Mixture Design

Four types of recycled aggregates were included in this study: RAP, a fractionated reclaimed asphalt pavement that contained steel furnace slag aggregates (SFSFRAP), electric arc furnace slag aggregates (EAF), and RCA. A control mixture was also created using virgin dolomite and natural sand. Extensive characterization of the EAF and SFSFRAP aggregates was performed by Brand and Roesler (2015a, 2015b). For one mix design of each recycled aggregate, the combined gradation was made equivalent to that of the virgin mix to make a direct comparison between all mixtures. For the fixed combined gradation mixtures, only the recycled aggregates coarse fraction (i.e., retained on 4.76 mm, #4, sieve) was used. In order to ensure that the combined gradations were equivalent between these mixtures, each aggregate was individually sieved and recombined. These mixtures are labeled by their type of recycled aggregate (RCA, EAF, RAP, and SFSFRAP) with all mixtures replacing 40% of total aggregate weight with recycled aggregate. Each recycled aggregate type also has at least one additional mix design where the recycled aggregate was used at its natural gradation and blended with the natural gradations of the virgin aggregates to minimize deviation from the 0.45-power curve. These mixes are labelled by their type of recycled aggregate followed by the percent replacement (by total aggregate weight) of virgin aggregate with recycled aggregate (i.e., RCA-25, RCA-40, etc.). For these mixes, the recycled aggregate gradation was used in its entirety, which includes any material passing the 4.76 mm (#4) sieve. The cement content was fixed at 282 kg/m^3 for all mixes, using a Type I portland cement.

Three virgin aggregates (coarse dolomite, intermediate dolomite, and natural sand) were used in this study to obtain a dense gradation, following the recommended gradation for RCC by ACI (1995). The aggregate gradations, specific gravity, and absorption capacity for each virgin and recycled aggregate are shown in Table 1. The combined gradations for each mix design are shown in Figure 1 along with the maximum density line (0.45-power curve) and gradation limits suggested by the American Concrete Pavement Association (ACPA 2014). All of the RCC mixtures using recycled aggregates (RCA, RAP, SFSFRAP) in their stock gradations have similar combined gradations, which are also quite similar to the mixtures where the gradation was held constant by sieving and recombining, at least until the 0.3 mm (#50) sieve. Modified Proctor testing according to ASTM D1557 (2012) was performed to determine the optimum moisture content (OMC) and maximum dry density (MDD) of each mixture. The final mixture proportions (Table 2) were determined by knowing the MDD, OMC, aggregate blends, and cement content for each mix. The EAF mixes yielded greater values of MDD (relative to the control) as a result of the higher specific gravity of the EAF aggregates while the RCA mixes yielded greater values of OMC (relative to the control) because of the high absorption capacity of the RCA as noted in Tables 1 and 2.

Table 1: Stock aggregate gradations and physical properties

	Coarse Dolomite	Intermediate Dolomite	Natural Sand	RAP	SFSFRAP	EAF	RCA
Sieve Size (mm)	Cumulative Percent Passing (%)						
25.4	100.0	100.0	100.0	98.3	100.0	100.0	91.0
19	76.8	100.0	100.0	95.0	100.0	100.0	74.4
12.7	30.9	99.8	100.0	88.2	99.9	99.9	53.3
9.51	13.5	93.8	100.0	81.9	83.7	83.3	43.9
4.76	2.1	33.6	96.0	53.2	13.3	24.1	28.8
2.38	0.5	3.6	83.2	30.1	3.9	4.7	20.4
1.19	0.4	1.2	66.6	15.3	2.8	2.2	14.6

0.595	0.4	0.9	46.3	2.0	2.5	1.9	4.0
0.297	0.4	0.8	12.4	0.2	2.2	1.6	1.2
0.149	0.3	0.7	1.3	0.0	1.7	1.3	0.2
0.074	0.3	0.6	0.4	0.0	0.8	0.9	0.1
Absorption Capacity (%)	2.95	3.00	1.38	2.12	2.00	1.75	7.34
Oven-Dry Specific Gravity	2.49	2.45	2.50	2.40	2.63	3.64	2.42

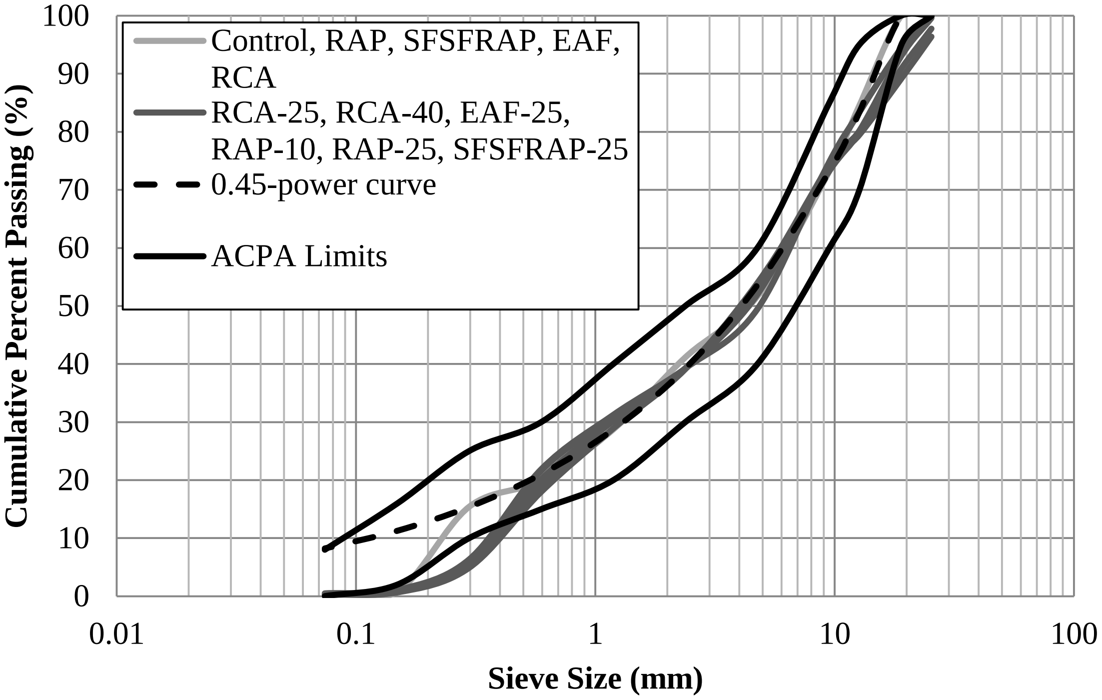

Figure 1: Combined aggregate gradations

Table 2: Mixture proportions and modified Proctor results

Mixture	Modified Proctor Results		Mixture Proportions (kg/m³)		
	MDD (kg/m³)	OMC (%)	Total Aggregate	Cement	Water
Control	2351	6.43	2070	282	151.2
RCA	2262	8.52	1980	282	192.7
RCA-25	2375	7.06	2094	282	167.7
RCA-40	2342	7.94	2060	282	185.9
EAF	2641	6.80	2360	282	179.6
EAF-25	2540	5.99	2259	282	152.2
RAP	2311	6.75	2030	282	156.0
RAP-10	2382	6.06	2100	282	144.3
RAP-25	2375	6.20	2094	282	147.3
SFSFRAP	2404	5.90	2123	282	141.9
SFSFRAP-25	2382	6.14	2100	282	146.3

Specimen Preparation

All specimens were mixed in a pan mixer according to ASTM C192 (2013) using the mixture proportions from Table 2. Virgin aggregates were mixed in an oven dry condition while RAP, SFSFRAP, and EAF were mixed in an air dry condition to avoid altering aggregate characteristics via oven drying. The RCA was mixed at approximately 80% of its saturated surface dry condition according to recommendations by Brand et al. (2015). For fracture testing via the disk-shaped compact tension (DCT) geometry, 150x300 mm cylinders were cast according to ASTM C1435 (2008). For strength testing (compression and split tension), 100x200 mm cylinders were cast in a similar manner to ASTM C1435 (2008) with the differences being the size of the tamping plate (88 mm diameter), number of lifts (three), and cylinder size (100 by 200 mm vs. 150 by 300 mm). Flexural strength beams measuring 100x100x400 mm were cast in two layers using a vibrating hammer with an 88x88 mm tamping plate attached to a vibrating hammer. Each layer was compacted for 5 seconds at the following locations: the ends, the middle, and between each end and the middle for a total of 25 seconds per layer. All specimens were cured in a fog room at 100% relative humidity and 20°C until the time of testing.

Results

Compressive Strength

Compressive strength testing was conducted according to ASTM C39 (2012) at ages of 7, 14, and 28 days. Triplicate specimens were tested at each age for all mixes. Results of compressive strength testing are shown in Figure 2. In order to analyze the statistical significance of these results, Tukey’s significant difference (TSD) test was performed piecewise with 95% confidence to compare which mean values were statistically similar (Mason et al. 2003). Results of the TSD test for only the 28-day compressive strength are shown in Table 3. The EAF-25 mixture yielded statistically greater 28-day compressive strength relative to the RCC control while the EAF and RCA coarse aggregate replacement mixes had statistically similar strength to the virgin RCC. The two RCA mixtures that contained the entire RCA gradation (i.e., RCA-25 and RCA-40) as well as all mixtures containing RAP and SFSFRAP yielded statistically lower 28-day compressive strengths than the control. Comparing the RCA mix (which has 40% replacement of virgin aggregate with coarse RCA) with RCA-40, it can be seen that the inclusion of the fine fraction of the RCA led to a significant reduction in strength (ignoring slight differences between the two combined gradations). Compressive strength was also shown to decrease with increasing RAP content, which agreed with the findings by Brand and Roesler (2015c) for slip-form paving concrete. Mixtures with SFSFRAP and RAP yielded statistically similar 28-day compressive strengths, for the same replacement levels, which was also reported by Brand and Roesler (2014, 2015b) for slip-form paving concrete. Overall, the recycled aggregate gradations for EAF, RAP, and RCA were shown to impact the RCC compressive strength like it was shown for virgin aggregates (LaHucik and Roesler 2015)

The ACPA (2014) suggests minimum 28-day compressive strengths of 31 and 28 MPa for RCC in areas with and without freeze-thaw conditions, respectively. Thus, in a freeze-thaw susceptible climate, the only mixture containing RAP or SFSFRAP that meets this requirement is RAP-10, and all mixtures containing RCA or EAF, as well as the control, would be acceptable for this strength requirement. The guidelines set forth by ACPA (2014) are for RCC when used as a wearing course. If RCC were to be used lower in the pavement structure, such as a base material, compressive strength requirements would likely be reduced and mixtures such as RAP-25, RAP, SFSFRAP-25, and SFSFRAP could have acceptable strengths.

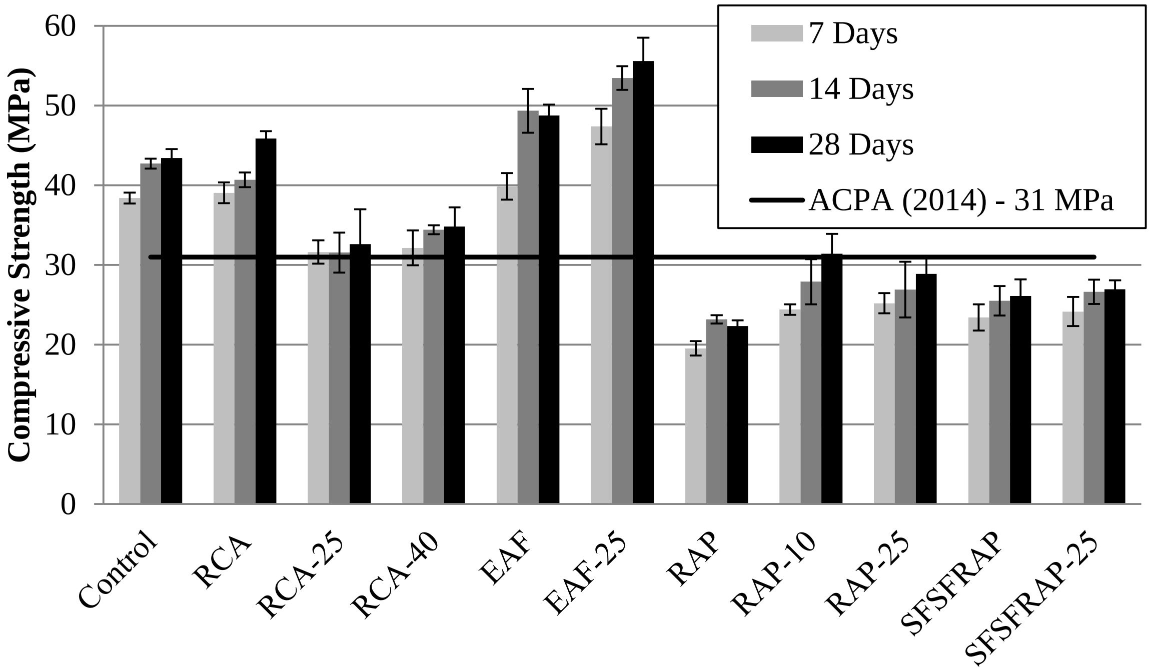

Figure 2: Compressive strength results (error bars indicate +/- one standard deviation)

Table 3: Statistical groupings for 28-day compressive strength based on the TSD test results

Tukey Grouping*						Mean (MPa)	Standard Deviation (MPa)	Mixture
A						55.6	2.9	EAF-25
	B					48.7	1.4	EAF
	B					45.8	1.0	RCA
	B					43.4	1.1	Control
		C				34.8	2.4	RCA-40
		C	D			32.6	4.4	RCA-25
		C	D	E		31.4	2.5	RAP-10
		C	D	E		28.9	2.1	RAP-25
			D	E	F	26.9	1.1	SFSFRAP-25
				E	F	26.1	2.1	SFSFRAP
					F	22.3	0.7	RAP

*Means with the same letter are not significantly different.

Split Tensile and Flexural Strengths

Split tensile strength testing was performed in accordance with ASTM C496 (2011) at an age of 28 days. Flexural strength testing (third-point loading) was performed on 100x100x400 mm beams in accordance with ASTM C78 (2010) at an age of 28 days. For each test type, triplicate specimens were tested for each mix. Results of split tensile and flexural strength testing are shown in Figure 3 with the results of the TSD tests shown in Table 4. In addition to the TSD tests, t-tests (with a 95% confidence interval) comparing split tensile and flexural strengths for each mixture were conducted. Of the 11 mixtures, four mixtures yielded statistically different split tensile and flexural strengths (control, EAF, RAP, and SFSFRAP). Brand et al. (2014) showed that flexural strength measured on 150x150x530 mm beams yielded consistently greater strengths than split tensile tests conducted on 100x200 mm cylinders for virgin aggregate concrete as well as concrete with FRAP and RCA. As seen from Table 4, all mixtures yielded statistically similar split tensile strengths relative to the control. For RCC flexural strength, only mix EAF was statistically similar to the RCC control mix with all other mixtures statistically lower. Split tensile strength results show similar trends as 28-day compressive strength (i.e., EAF mixes had greater strengths than RCA mixes, which were greater than RAP and SFSFRAP mixes). Mixtures with SFSFRAP and RAP, for the same replacement levels, yielded statistically similar flexural strengths as well as split tensile strengths. Brand and Roesler (2014, 2015b) showed statistically similar split tensile strengths but statistically different flexural strengths when comparing slip-form paving mixtures containing SFSFRAP and RAP.

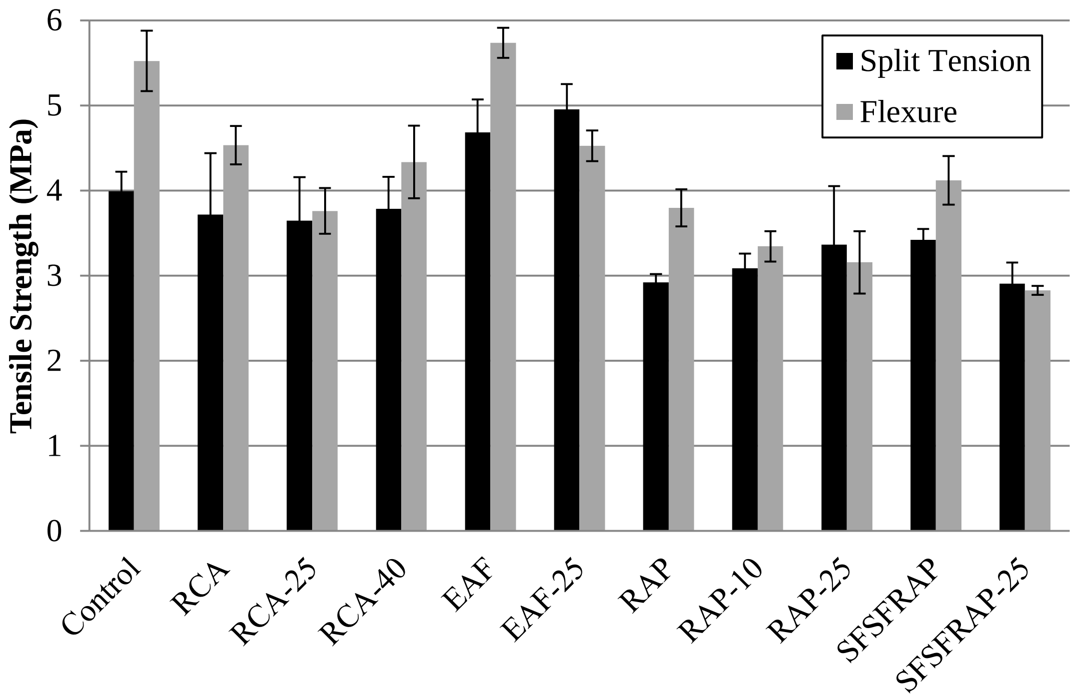

Figure 3: Split tensile and flexural strength results at 28-days age (error bars indicate +/- one standard deviation)

Table 4: Statistical groupings for 28-day split tensile and flexural strength based on the TSD test results

Tukey Grouping*					Mean (MPa)	Standard Deviation (MPa)	Mixture
Split Tensile Strength							
A					4.96	0.29	EAF-25
A	B				4.68	0.39	EAF
A	B	C			3.99	0.23	Control
A	B	C			3.79	0.38	RCA-40
	B	C			3.72	0.72	RCA
	B	C			3.65	0.51	RCA-25
		C			3.42	0.13	SFSFRAP
		C			3.36	0.69	RAP-25
		C			3.09	0.17	RAP-10
		C			2.92	0.10	RAP
		C			2.91	0.25	SFSFRAP-25
Flexural Strength							
A					5.74	0.18	EAF
A					5.52	0.36	Control
	B				4.53	0.23	RCA
	B				4.52	0.18	EAF-25
	B				4.34	0.43	RCA-40
	B	C			4.12	0.29	SFSFRAP
	B	C	D		3.80	0.22	RAP
	B	C	D		3.76	0.27	RCA-25
		C	D	E	3.34	0.18	RAP-10
			D	E	3.16	0.37	RAP-25
				E	2.83	0.05	SFSFRAP-25

*Means with the same letter are not significantly different.

Fracture Properties

RCC fracture testing was conducted on DCT samples fabricated from 150x300 mm cylindrical specimens according to Amirkhanian et al. (2014). The RCC fracture parameters are derived based on the Jenq and Shah (1985) two-parameter fracture model (TPFM) and work of fracture method (Hillerborg 1985), with five replicates tested per mix. The main benefits of fracture testing are provisions for both size dependent (total fracture energy) and size independent properties (critical stress intensity factor and critical crack tip opening displacement) as well as useful parameters for the structural design of concrete pavements (Ioannides et al. 2006; Gaedicke et al. 2012; Brand et al. 2014). These benefits allow for a more in-depth comparison of the performance of the various mixtures presented in this paper. The derived fracture properties are the critical stress intensity factor (K_{IC}), elastic modulus (E), critical crack tip opening displacement ($CTOD_C$), initial fracture energy (G_f), and total fracture energy (G_F). Results of fracture testing are shown in Table 5 along with their coefficients of variation (COV). Table 6 shows results of the TSD tests on critical stress intensity factor and total fracture energy.

According to Table 6, all RCC mixtures had statistically similar or better K_{IC} and G_F relative to the control. Mixture EAF-25 produced statistically greater K_{IC} and G_F than the virgin RCC mix. Previous researchers (Montgomery and Wang 1992; Brand and Roesler 2015a) have reported improved fracture properties for concrete containing steel furnace slag aggregates relative to virgin aggregate concrete. Likewise, the similarity of fracture properties with concrete containing RAP, SFSFRAP, or RCA aggregates relative to virgin aggregate concrete have been previously presented in the literature (Amirkhanian 2012; Brand et al. 2014; Brand and Roesler 2015b, 2015c).

Brand et al. (2014) tested strength and fracture properties of paving concrete with recycled aggregates (RCA and RAP) in addition to conducting slab tests on the same mixtures. They found that the concrete with recycled aggregates resulted in lower strength and elastic modulus values (relative to virgin aggregate concrete) while the fracture parameters and slab testing results demonstrated that the concrete with recycled aggregates performed similarly or slightly better compared to the virgin concrete. Given the strength and fracture properties of RCC mixtures containing virgin or recycled aggregates and previous literature on concrete slab testing, it is likely that RCC slabs containing recycled aggregates would have a similar flexural capacity to RCC with virgin aggregates. Flexural slab capacity testing needs to be conducted to prove or disapprove this hypothesis for RCC materials.

Table 5: Fracture testing results (values in parenthesis indicate COV in percent)

Mixture	K_{IC}, MPa*m$^{1/2}$	E, GPa	$CTOD_C$, mm	G_f, N/m	G_F, N/m
Control	1.07 (6.6)	29.0 (7.2)	0.017 (29.3)	40.0 (18.1)	131.0 (9.7)
RCA	1.04 (9.3)	28.5 (13.9)	0.016 (9.6)	38.3 (9.8)	118.6 (11.3)
RCA-25	0.88 (8.6)	22.5 (8.7)	0.022 (20.8)	34.6 (15.4)	122.1 (17.0)
RCA-40	1.16 (10.5)	35.5 (8.3)	0.016 (18.5)	37.9 (14.1)	149.9 (13.9)
EAF	1.43 (10.5)	42.8 (7.6)	0.017 (18.3)	48.3 (17.8)	170.2 (13.1)
EAF-25	1.40 (8.9)	35.6 (9.5)	0.019 (24.0)	56.5 (25.4)	191.0 (5.7)
RAP	0.86 (17.3)	20.9 (3.1)	0.022 (29.7)	36.5 (32.5)	158.1 (22.3)
RAP-10	0.87 (13.8)	24.7 (15.0)	0.019 (31.2)	31.3 (24.9)	140.3 (6.8)
RAP-25	0.97 (4.1)	21.6 (11.1)	0.021 (10.6)	43.7 (9.3)	157.9 (5.9)
SFSFRAP	1.03 (10.8)	29.0 (6.8)	0.016 (20.9)	37.0 (23.9)	261.1 (12.2)
SFSFRAP-25	1.14 (6.2)	31.4 (6.6)	0.018 (11.6)	41.2 (7.5)	195.3 (16.1)

Table 6: Statistical groupings for 28-day critical stress intensity factor and total fracture energy based on the TSD test results

Tukey Grouping			Mean	Standard Deviation	Mixture
K_{IC}			MPa*m$^{1/2}$	MPa*m$^{1/2}$	
A			1.43	0.151	EAF
A			1.40	0.124	EAF-25
	B		1.16	0.122	RCA-40
	B		1.14	0.070	SFSFRAP-25
	B	C	1.07	0.071	Control
	B	C	1.04	0.097	RCA
	B	C	1.03	0.111	SFSFRAP
	B	C	0.97	0.040	RAP-25
		C	0.88	0.076	RCA-25

		C	0.87	0.120	RAP-10
		C	0.86	0.149	RAP
G_F			N/m	N/m	
A			261.1	31.7	SFSFRAP
	B		195.3	31.4	SFSFRAP-25
	B		191.0	11.0	EAF-25
	B	C	170.2	22.2	EAF
	B	C	158.1	35.2	RAP
	B	C	157.9	9.3	RAP-25
	B	C	149.9	20.8	RCA-40
		C	140.3	9.6	RAP-10
		C	131.0	12.7	Control
		C	122.1	20.8	RCA-25
		C	118.6	13.4	RCA

*Means with the same letter are not statistically different.

Conclusions

The effect of partial replacement of virgin aggregates with recycled aggregates on the moisture-density, strength, and fracture properties of roller-compacted concrete (RCC) was examined. The recycled aggregates utilized for this study were recycled concrete aggregate (RCA), electric arc furnace (EAF) steel slag aggregate, reclaimend asphalt pavement (RAP), and steel furnace slag fractionated reclaimed asphalt pavement (SFSFRAP). All mixes contained the same source of virgin aggregates and cement content. The MDD for the mixes varied with the specific gravity of the blended aggregates while the OMC for all mixtures ranged from 5.9% to 8.5% and depended on the porosity of the recycled aggregate.

The compressive strength of RCC mixes containing RCA, RAP, and EAF aggregates were impacted by their gradations selected, which was similar to previous studies on the effect of gradation on RCC containing virgin aggregates. RCC mixes with EAF aggregates produced similar to greater compressive strengths to the control mix, while RCC mixes with RCA had similar or lower RCC compressive strengths. RCC mixes containing RAP and SFSFRAP led to consistently lower compressive strengths relative to the virgin aggregate, control mix. The split tensile strength of all recycled aggregate RCC mixtures were similar to the control while the flexural strength results produced statistically lower flexural strengths to the control except EAF aggregates.

Fracture properties for RCC mixes were derived from disk-shaped compact tension (DCT) testing. All mixtures containing recycled aggregates yielded similar or greater values of critical stress intensity factor and total fracture energy relative to the RCC control mixture. Previous literature has shown that fracture properties are more indicative of flexural capacity of concrete slabs with recycled aggregates than strength testing of cylinders or beams. Therefore, it is hypothesized that the slab flexural capacity of RCC mixtures containing these recycled aggregates is similar to that of the RCC mixture with virgin aggregates.

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