CENTER OF EXCELLENCE FOR AIRPORT TECHNOLOGY

TECHNICAL NOTE

TECH NOTE NO: 34
TITLE: Fracture and Drying Shrinkage Properties of Concrete Containing Recycled Concrete Aggregate

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1. EXECUTIVE SUMMARY

The objective of this study was to show that using recycled concrete as a coarse aggregate with and without the addition of synthetic fibers can produce a paving concrete with similar fracture properties as those made with virgin coarse aggregate. Six different concrete mixtures were produced. Two mixtures were made completely with virgin coarse aggregate, two mixtures only used recycled coarse aggregate (RCA), and the last two were a blend of virgin and recycled coarse aggregate. For each of the mixtures three point bending, shrinkage, compression, and tensile splitting tests were conducted.

Testing results demonstrated that the use of RCA alone reduced the peak load capacity of the concrete beam specimen, the total fracture energy of the concrete, and created greater drying shrinkage. However, when 0.2% volume fraction of fibers were added the total fracture energy of all the mixtures became similar. The blending of RCA and virgin coarse aggregate at a 50-50 volume percentage also produced a pavement concrete with similar fracture and shrinkage properties to that of the virgin coarse aggregate concrete.

2. INTRODUCTION

Recycling concrete is a viable option to decrease the demand on high quality natural resources and to limit the amount of waste that is disposed in landfills. Recycled concrete has been primarily used as a unbound material in embankments, bases, and sub-bases. Engineers have also used recycled concrete as an aggregate in the construction of new structures such as concrete pavements but with limited frequency. The use of recycled concrete in load bearing structures has not gained wide acceptance probably because of the lack of accessible information on the subject, such as expected fresh and hardened material properties.

Concrete is not the only recycled material that has been used in previous construction applications. Recycled asphalt, fly ash, and slag have been used in past projects [9]. Recycled materials contribute to material sustainability, reduce environmental impact of demolished materials, and can have positive financial implications for certain projects. The cost of a project could decrease if concrete does not have to be hauled and dumped, and instead be used to replace a portion of virgin aggregate in the new concrete structure. The main objective of this study is to quantify the fracture and shrinkage properties of one type of recycled coarse aggregate concrete (RCAC) for rigid pavements. Secondly, increase the fracture properties of the specific RCAC to obtain equal or greater fracture properties than virgin aggregate concrete (VAC) containing similar virgin materials.

3. BACKGROUND

3.1 General Information

There is a common reluctance to use recycled concrete as an aggregate in new concrete due to the limited information on the topic. One of the major issues with the use of recycled concrete has been the loss of strength which may be attributed to concrete mixture constituents, RCA blending percentage, water-cement ratios, and aggregate gradation [6]. A number of different studies have been conducted to analyze each of these factors and in general the results show a decrease in compression and tensile strength is expected with RCAC. Other studies have also documented that RCA has a higher water absorption capacity which causes a higher water demand and leads to issues like greater drying shrinkage values [15].

A 2006 study focused on the chemical-mineralogical characteristics of RCAC on the cement hydration for several sources of RCA [10]. A 30% direct replacement of virgin aggregate with recycled aggregate had no influence on SiO_2, Al_2O_3, or CaO content. Once the replacement level was above 30%, a marginal decrease in SiO_2 and a marginal increase in Al_2O_3 and CaO levels were realized.

Another recent study [18] addressed the surface permeability of recycled concrete, which used both fine and coarse recycled aggregates. The concrete made with the recycled aggregate had an increased porosity resulting in lower densities and reduced mechanical properties. Results showed that both the water and air permeability were two times greater for the concrete made with recycled aggregates as opposed to the virgin aggregate. This study reported that the main problems of durability come from the use of recycled fine aggregate.

3.2 Application of RCA Concrete

The use of recycled concrete can be traced back to post-World War II Europe. At that time, there was a great need for the Europeans to rebuild their countries. Rubble from damaged buildings and structures was used as an aggregate in new concrete structures [17]. Once the demand for materials no longer existed, conventional materials for new construction were utilized for a period of time. In modern day Europe, there has been an increase in the use of recycled concrete. The government has taken an active role in the disposal of building materials and has created incentives that encourage the use of materials like recycled concrete [5].

The state of Illinois also has used recycled concrete in several transportation projects. In 1986 and 1987, two interstate projects, sponsored by the Illinois Department of Transportation (IDOT), were constructed with recycled concrete. Each of the projects was approximately eight centerline miles long and involved rehabilitating an existing stretch of the interstate. The first project was a continuously reinforced concrete pavement (CRCP) inlay on I-57 near Effingham, Illinois and the second project was an asphalt concrete pavement inlay south of Ullin, Illinois also on I-57.

The CRCP project was done to replace a faulted jointed reinforced concrete pavement that contained high quality aggregates. The concrete was crushed using a jaw and roll crusher. The new CRCP required a 10-inch concrete surface and a 7-inch cement stabilized base. The slab geometry also included an 18 inch widened lane. In this project, both recycled coarse and fine aggregates were used in the concrete mixture. Fly ash and natural sands were also utilized in order to improve the concrete workability. Periodic friction tests, ride quality tests, and condition surveys were conducted. A six year evaluation of the I-57 CRCP inlay found no major problems [13]. The CRCP inlay is currently 20 years old and still provides a very smooth riding surface. However, this project is beginning to show some signs of deterioration due to settlement cracking which has been attributed to the tube feeding process used during construction [12].

3.3 Economy

Approximately 1 million tons of concrete were disposed of in California landfills in 2003 [3]. Some part of that concrete had the potential of becoming RCA and being used in new construction projects. The state and federal government and construction companies would have saved money on hauling and dumping costs. Cost saving would also have occurred in not having to purchase virgin coarse aggregate for new concrete construction.

4. RESEARCH OBJECTIVES

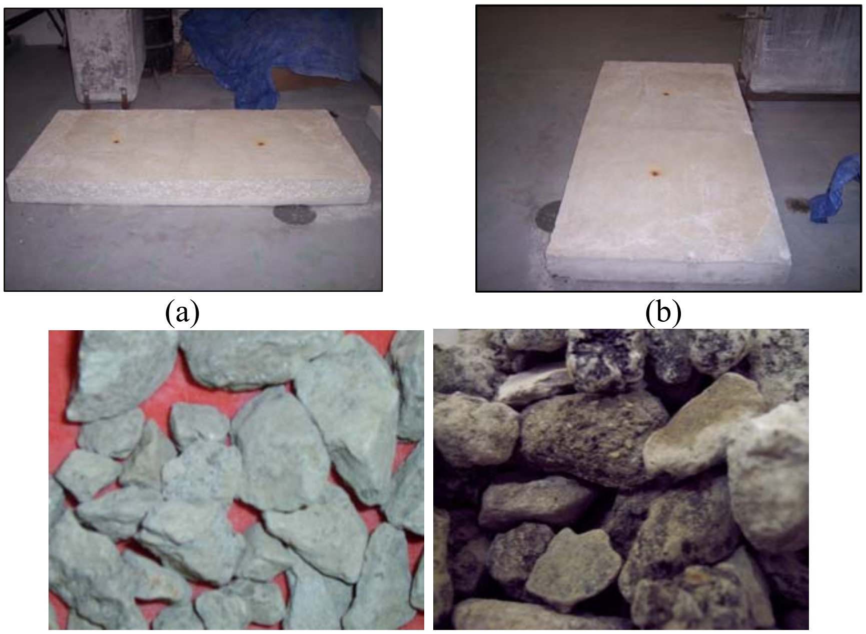
The purpose of this research was to determine the fracture properties of a specific recycled concrete aggregate concrete (RCAC) as compared to concrete with virgin aggregate concrete (VAC) with similar mixture constituents and properties. The second objective of the research was to develop a RCAC that had similar or greater fracture properties than the VAC. Finally, the drying shrinkage characteristics of RCAC were also measured and documented relative to the plain concrete mixture.

5. METHODOLOGY

5.1 Materials

The first phase of this study looked at the effect recycled coarse aggregate with a high volume fraction of synthetic fibers would have on the fracture properties of paving concrete [6]. In this phase, the recycled concrete was crushed in the University of Illinois laboratory using a jack hammer and a small lab crusher. For this phase only three-point bend (TPB) specimens were cast. The second phase of the study utilized recycled concrete that was crushed by a local construction company, University Construction. The main purpose of the second phase testing was to produce RCAC that was economically feasible while still obtaining fracture properties that exceed the VAC. For the second phase, TPB, compression, splitting tension, and drying shrinkage specimens were cast.

Figures 1a and 1b are photos of the concrete slabs that were crushed. These slabs had been cast and tested for a concrete fatigue study and as such, the fresh and hardened properties of this concrete were known [19]. The concrete had a compressive strength of 58.3 MPa, a split tensile strength of 4.5 MPa, and a modulus of elasticity of 32.0 GPa at an age of one year. Figure 1c is an image of the recycled coarse aggregate that was produced after crushing the concrete slabs with the Hazemag 1515 Impact crusher at University Construction. The RCA was not completely free of debris as seen in Figure 1d. The RCA contained small amounts of asphalt, brick, and wood. Since this company accepts and crushes all types of urban building materials, some contamination was expected.



(a) (b)

(c) (d)

Figure 1: (a) and (b) photos of the concrete slabs prior to being crushed;
(c) Image of the crushed RCA; (d) debris in the RCA

5.2 Coarse Aggregate Gradation

Prior to the mix design being generated, the recycled coarse aggregate had to be sieved and graded to ensure a quality mixture. The grading process took place during each of the project phases after the old concrete slabs were crushed. Previous publications suggest that the gradation of RCA be the same as that of the virgin aggregate [16]. During the first phase, the grading curve that was achieved with the laboratory crusher is seen in Figure 2. In order to reduce the RCA's water demand, all particles less than the #4 sieve were not used. For the second phase, the RCA was sieved so that it would be within the minimum and maximum limits described in two specifications pertinent to the study, the FAA 25mm Coarse Aggregate requirement (P-501) and the IDOT CA-7 requirement (see Figures 3a and 3b respectively). The construction company's operation produced a coarser aggregate gradation for the RCA that was not ideal for coarse aggregate to be used in concrete mixtures. However, in future work a more optimal combined aggregate (RCA and virgin aggregate) gradation could be developed and produced by the same crusher, if necessary.

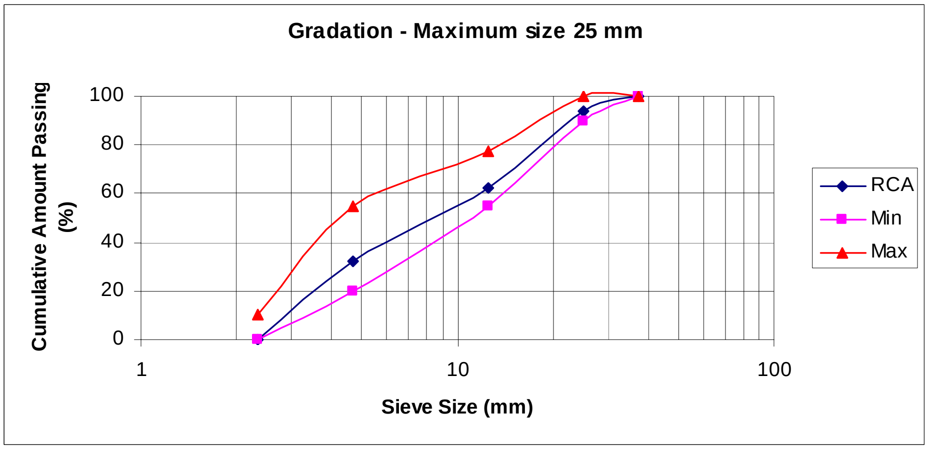


Figure 2: Recycled coarse aggregate gradation curve for Phase 1 testing

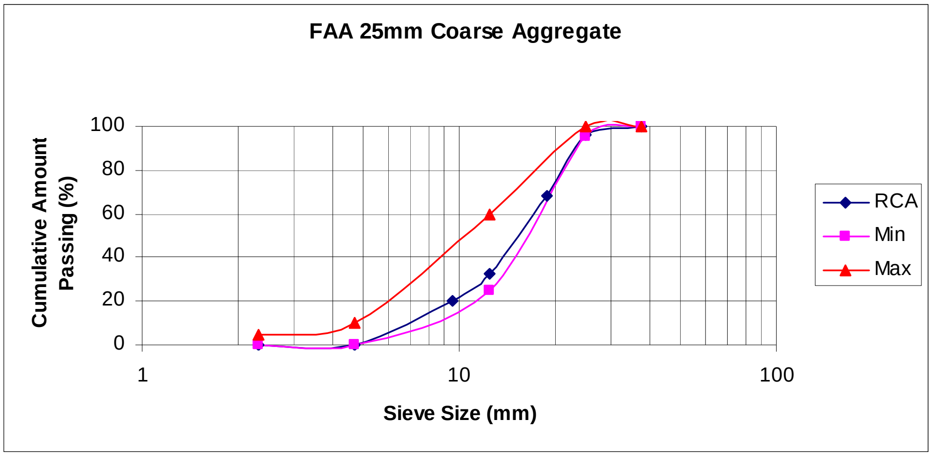


Figure 3a: Recycled coarse aggregate gradation curve for Phase 2 (FAA limits for 25mm nominal maximum size aggregate)

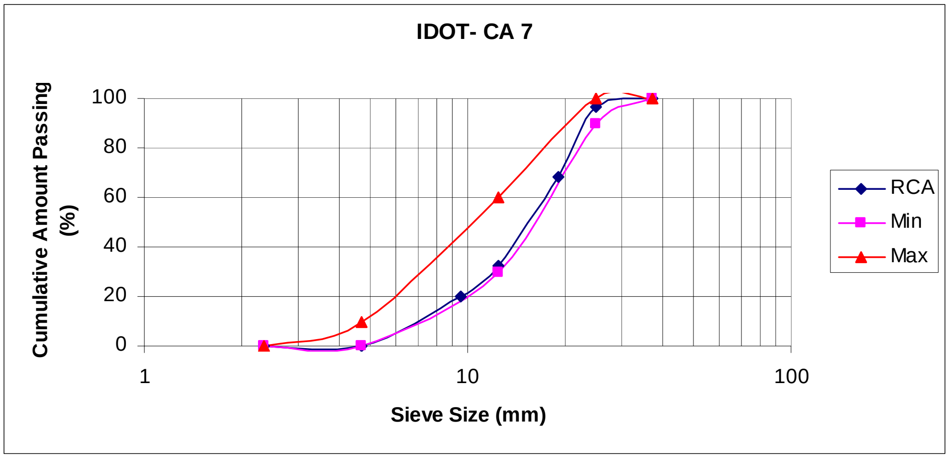


Figure 3b: Recycled coarse aggregate gradation curve for Phase 2 (IDOT CA-7 limits for 25mm nominal maximum size aggregate)

5.3 Design Mixtures

In the first phase of the research, four different concrete mixtures were cast. The first concrete mixture had 100% virgin coarse aggregate. The second mixture included the 100% virgin coarse aggregate with the addition of 12.1 lb/yd^3 of synthetic fibers. The third mixture replaced the virgin coarse aggregate with 100% recycled coarse aggregate. The final mixture had 100% recycled coarse aggregate and 12.1 lb/yd^3 of synthetic fibers. Table 1 lists the mix proportions for the Phase 1 mixtures [6]. Note, the mixture proportions in Phase 1 were not adjusted for the different coarse aggregate specific gravities. Table 2 shows the physical properties of the fine and coarse aggregates. The bulk specific gravity at SSD for the recycled coarse aggregate was lower than that of the virgin aggregate. The absorption capacity for the RCA was approximately 2.5 times greater than that of the virgin aggregate.

Table 1: Concrete mixture design for Phase 1 testing

	Plain Concrete		**Synthetic Fiber Reinforced Concrete**	
Mix ID	**PCC**		**FRC**	
Material	kg/m^3	lb/yd^3	kg/m^3	Lb/yd^3
Water	183	308	183	308
Type I Cement	360	607	360	607
Coarse aggregate	976	1645	976	1645
Fine aggregate	807	1360	80	1360
Synthetic Fibers	---	---	7.2	12.1

Table 2: Fine and coarse aggregate properties

	BSG_{ssd}	Absorption Capacity
RCA - coarse	2.42	5.27%
Virgin Coarse Aggregate	2.64	2.01%
Virgin Fine Aggregate	2.51	1.79%

The second phase of testing focused on creating a cost effective RCAC mixture that would achieve similar fracture properties to concrete with virgin aggregate. Table 3 shows all six concrete mixtures. The first two mixtures are with virgin aggregate. These mixtures remained the same as in Phase 1 except that 3 lbs/yd^3 of synthetic fibers were used instead of 12.1 lbs/yd^3 in the FRC mixture, which equals to a fiber amount of 0.19% and 0.80% by volume respectively. For the third and fourth mixtures, RCA proportions were adjusted to account for the lower bulk specific gravity of the RCA relative to the virgin aggregate mixtures. The fiber content was also 3 lbs/yd^3, which is the minimum manufacturer recommendation for this fiber type. The last two mixtures are with a blended coarse aggregate mixture (by volume), i.e. 50% virgin coarse aggregate and 50% RCA with fibers (50-50 Blend FRC), and without fibers (50-50 Blend). In order to reduce variability in water demand and concrete workability, all mixtures containing RCA were presoaked over night to ensure saturation during batching [4]. Excess water above SSD condition, typically 1 to 2 percent, was measured and accounted for in the batch weights.

Table 3: Concrete mixture designs for Phase 2 testing (lb/yd^3)

Mixture	VAC	VAC FRC	RCAC	RCAC FRC	50-50	50-50 FRC
Water	308	308	308	308	308	308
Type I Cement	607	607	607	607	607	607
RCA	0	0	1508	1508	754	754
Coarse aggregate (Virgin)	1645	1645	0	0	823	823
Fine aggregate	1360	1360	1360	1360	1360	1360
Synthetic Macrofibers	0	3	0	3	0	3

Two concrete beams, six cylinders and three shrinkage prisms were cast for each mix designs to determine the concrete's fracture properties, split tensile strength, compressive strength, and free shrinkage. After 24 hours, the specimens were de-molded. Cylinders and beams were placed in a lime water bath for seven days before they were tested. Shrinkage samples, 75mm x 75mm x 285mm, were measured and held in a climate controlled room with 23ºC and 50% relative humidity. The free shrinkage tests were measured using a modified ASTM C157 [22] procedure where specimens are only cured one day prior to drying. The compression and tensile splitting tests were conducted in accordance to ASTM C 39 [1] and ASTM C 496 [2], respectively, using cylindrical samples with a four inch diameter and a height of eight inches.

5.4 Fracture Properties

The strength of concrete can be a good indicator of the concrete's quality and potential performance. However, measuring only the compressive and tensile strength of concrete will not guarantee the performance of the concrete structure due to the interaction of the material behavior with the geometry of the structure. For example, concrete of various qualities can be made to have a similar tensile strength but produce varying degrees of structural performance. The fracture properties of the concrete can provide more description of the maximum load capacity of the material and the crack propagation resistance or toughness of the material. The critical stress intensity factor (K_{IC}) and critical crack tip opening displacement ($CTOD_c$) describe the initial cracking properties of the concrete while the total fracture energy (G_F) characterizes the crack propagation and load carrying capacity of the partial cracked concrete.

The three-point bend (TPB) samples were used in conjunction with the two parameter fracture model [8] to obtain the concretes' initial fracture properties. Figure 4 presents the TPB sample geometry and loading configuration that was used for calculating the two parameter fracture model parameters.

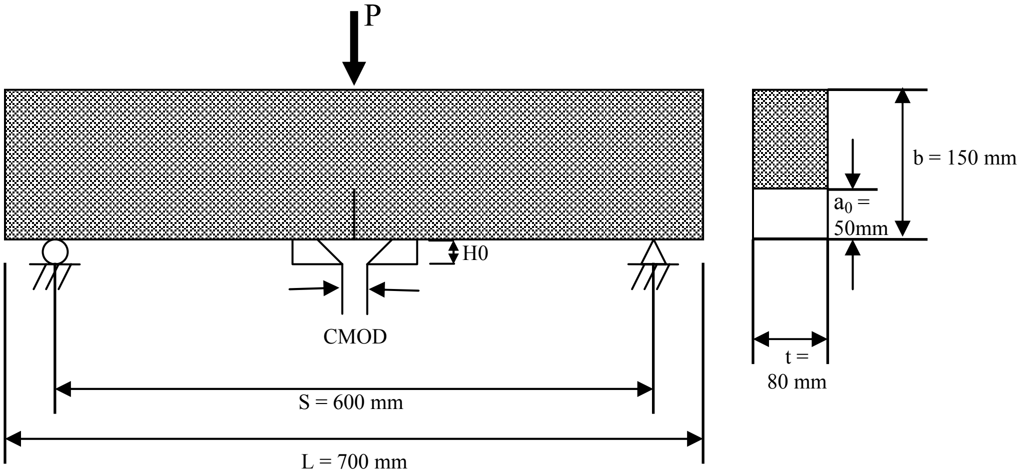


Figure 4: Schematic representation of the three-point bend experiment

In order to calculate the fracture properties of the concrete, the load (P) versus crack mouth open displacement (CMOD) must be measured and plotted. Details on the testing procedure can be found in [8]. The specims were loaded and unloaded to propagate the crack and to determine the fracture properties. Figure 5 is a schematic representation of a P versus CMOD for one load-unload curve.

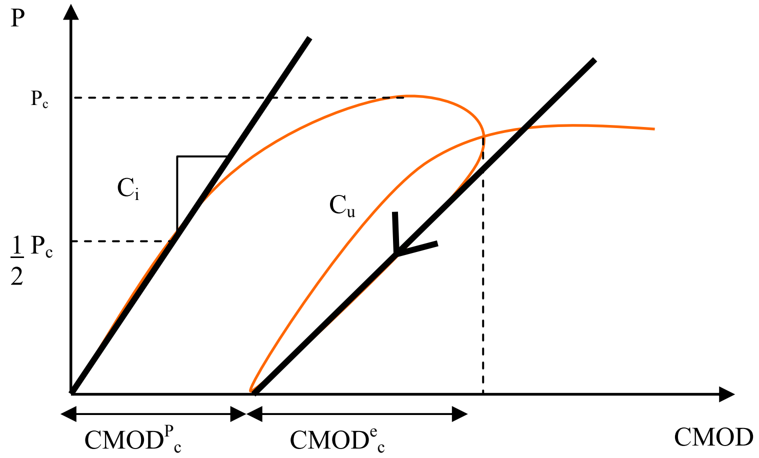


Figure 5**:** Schematic representation of the two-parameter method

The P-CMOD plot was then used to determine the peak load (P_c) as well as computing the loading and unloading compliances (C_i and C_u, respectively). The compliances are can then be used in equations 1 and 2 to estimate the elastic modulus of the material, E_1 and E_2.

$$E_1 = \frac{6Sa_0 g_2(\alpha_0)}{C_i b^2 t} \tag{1}$$

$$E_2 = \frac{6Sa_c g_2(\alpha_c)}{C_U b^2 t} \tag{2}$$

where

$$\alpha_0 = \frac{(a_0 + H0)}{(b + H0)} \tag{3}$$

$$\alpha_c = \frac{(a_c + H0)}{(b + H0)} \tag{4}$$

$$g_2(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2} \tag{5}$$

Since the elastic modulus of the bulk concrete does not change, equations 1 and 2 can be set equal to each other to calculate the critical elastic crack length, a_c. The critical crack length is then used to determine the K_{IC}, from equation 6 below:

$$K_{IC} = 3(P_c \times 0.5W_h)\frac{S\sqrt{\pi a_c}\, g_1(a_c / b)}{2b^2 t} \tag{6}$$

where S, b, HO, a_0 and t are shown in Figure 4, P_c is the peak load, W_h is equal to the beam weight multiplied by S/L, and $g_1(a_c/b)$ is the geometric correction factor determined by equation 7.

$$g_1\left(\frac{a_c}{b}\right)=\frac{1.99-(a_C/b)(1-a_c/b)\left[2.15-3.93a_c/b+2.70(a_c/b)^2\right]}{\sqrt{\pi}(1+2a\ \ /b)(1-a_c/b)^{3/2}} \qquad (7)$$

The $CTOD_c$ was calculated using equation 8, where β_0 is equal to a_0/a_c [13].

$$CTOD_C=\frac{6(P_c+0.5W_h)Sa_c g_2(a_c/b)}{Eb^2t}\cdot\sqrt{\left[(1-\beta_0)^2+\left(1.081-1.49\frac{a_c}{b}\right)(\beta_0-\beta_0^2)\right]} \qquad (8)$$

The initial fracture energy release rate G_{IC} was calculated using equation 9, where E is concrete's elastic modulus, which was determined by the beam's geometry and the compliance in equations 1 and 2.

$$G_{IC}=\frac{(K_{IC})^2}{E} \qquad (9)$$

The total fracture energy, G_F, was calculated using equation 10.

$$G_F=\frac{W_0+mg\delta_0}{(b-a_0)t} \qquad (10)$$

where W_0 is the area under the P versus CMOD curve, mg is the self weight of the beam, δ_0 is the value of deflection when the descending branch of the softening curve goes to zero [8].

6. RESULTS AND DISCUSSION

6.1 Phase 1

Three beams for each mixture were cast. Figure 6 is the comparison of the average softening curves for the concrete containing virgin coarse aggregate relative to the RCA. Table 4 shows the fracture parameters collected for this case. The peak load of the virgin aggregate mixture was 38 percent greater than the RCA mixture. The $CTOD_c$ at failure for the virgin aggregate mixture was less than the RCA mixture. The total fracture energy (G_F) for the virgin aggregate beams was approximately two times greater than the RCA beams while the fracture toughness was only 20 percent greater. The elastic modulus of the RCA mixture was lower than the virgin aggregate mixture.

Table 4: Fracture properties plain concrete with virgin or RCA (Phase 1)

		Peak Load (kN)	E (GPa)	K_{IC} (MPa-m$^{1/2}$)	CTOD$_c$ (mm)	G_F (N/m)
VAC	Beam 1	3.76	27.6	1.17	0.0152	127
	Beam 2	3.95	32.1	1.52	0.0267	113
	Beam 3	3.42	27.4	1.07	0.0138	115
	Average	3.71	29.0	1.25	0.0186	119
RCAC	Beam 1	3.05	26.6	1.13	0.0212	64
	Beam 2	2.75	22.0	1.13	0.0289	46
	Beam 3	2.91	11.0	0.94	0.0300	74
	Average	2.90	19.9	1.07	0.0267	61

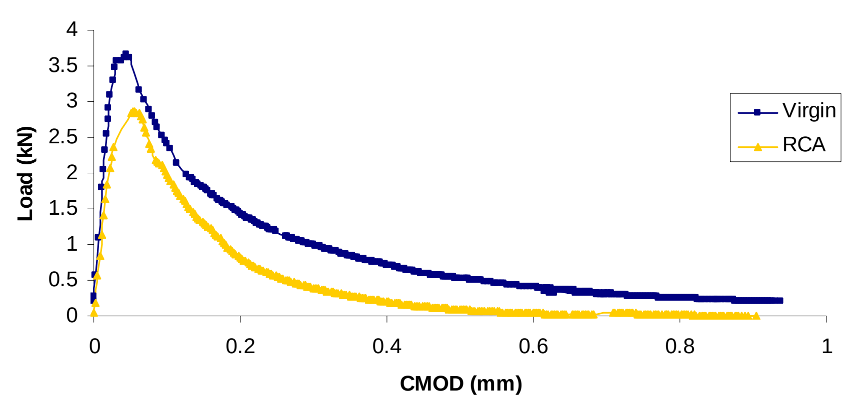


Figure 6: Comparison of TPB softening curves for concrete mixtures containing virgin or RCA (Phase 1)

As part of the first phase, 12.1 lb/yd^3 were added to each of the concrete mixtures. Figure 7 shows the P versus CMOD curves of the virgin aggregate and the RCA mixtures with fibers. Table 5 presents the fracture parameters based on the FRC mixtures of Phase 1. As expected, the addition of fibers increased the total fracture energy for both the virgin aggregate and RCA mixtures. The virgin aggregate mixture with fibers had a total fracture energy up to 2mm CMOD that was approximately 36 percent larger than the RCA mixture with fibers. The peak load was 38 percent greater for the virgin aggregate mixture with fibers, which was the main contributor in the total fracture energy difference between the two mixtures. The residual load capacity, defined as the load when the CMOD equals 2mm, was almost the same for the VAC with fibers and RCAC with fibers. The fracture toughness for the two mixtures with fibers was also very similar. The calculated elastic modulus for the recycled coarse aggregate FRC is lower and the CTOD$_c$ is higher than the virgin aggregate FRC mixture.

Table 5: Fracture properties of Phase 1 virgin aggregate beams

		Peak Load (kN)	E (GPa)	K_{IC} (MPa-m$^{1/2}$)	CTOD$_c$ (mm)	[1]G_F (N/m)
VAC FRC	Beam 1	3.79	28.6	1.33	0.0223	357
	Beam 2	4.42	28.4	1.38	0.0188	460
	Beam 3	3.28	27.7	1.05	0.0140	385
	Average	3.83	28.3	1.25	0.0184	401
RCAC FRC	Beam 1	2.63	27.2	1.23	0.0405	236
	Beam 2	2.63	24.7	1.33	0.0501	303
	Beam 3	3.01	22.3	1.33	0.0434	345
	Average	2.76	24.7	1.30	0.0447	295

[1] up to 2mm CMOD

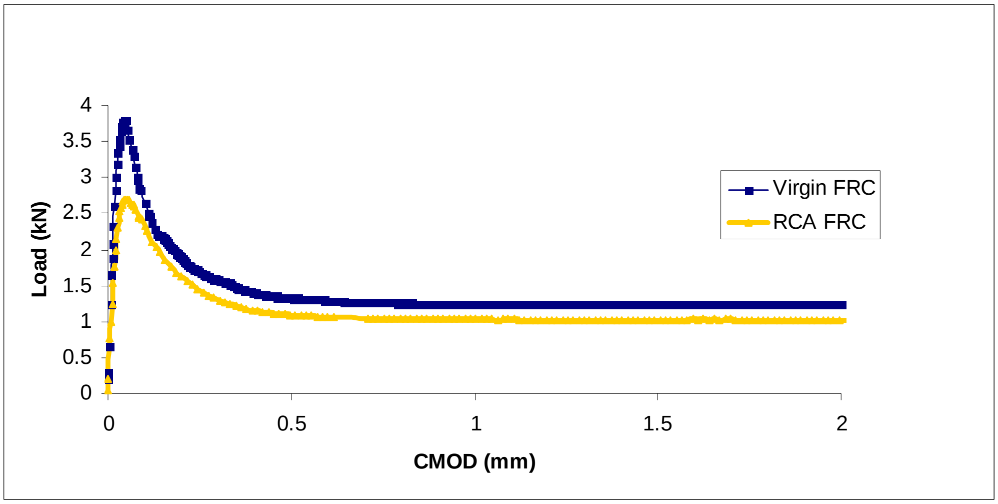


Figure 7: Load versus CMOD curves of virgin aggregate and RCA mixtures with fibers (Phase 1)

6.2 Phase 2

6.2.1 Compressive and Tensile Splitting Results

Compressive and splitting tensile tests were conducted for all mixtures in Phase 2. Three compression and three tensile splitting samples were cast for each of the six mixtures. The average 7-day strengths are reported in Table 6. The compressive strengths ranged from 22.9 MPa for the 50-50 Blend to 31.2 MPa for the virgin coarse aggregate concrete. There were no consistent trends between the split tensile and compressive strength for the virgin aggregate, RCA, and blended aggregate concrete mixtures with or without fibers.

Table 6: Average strength results of Phase 2 samples

Mixture Type	Compressive Strength		Tensile Strength	
	(MPa)	(psi)	(MPa)	(psi)
VAC	31.2	4528	2.61	378
VAC FRC	30.3	4396	2.93	425
RCA	27.8	4030	2.45	356
RCA FRC	23.8	3450	2.86	415
50-50 Blend	22.9	3328	2.84	412
50-50 Blend FRC	24.4	3539	2.63	382

6.2.2 Fracture Properties Results

The Phase 2 fracture testing used the TPB specimen to determine the initial fracture parameters and the total fracture energy. Figure 8a shows the experimental set up of TPB specimen for Phase 2 tests. Figure 8b shows how the synthetic fibers bridge the crack at high levels of deformation. Two beams were cast for each mixture. Figure 9 shows the average load-deformation curve between the virgin aggregate samples with 3 lbs/yd^3 of fibers and without fiber reinforcement.

Figure 8a and 8b: Experimental set up of three point bending test and synthetic fibers bridging the crack

As expected, the peak load between the VAC with and without fibers are very similar. Table 7 lists the fracture properties of the virgin aggregate beams. The total fracture energy up to 4mm for the beams with the fibers is about 3.2 times greater that that of the beams without fibers for at a CMOD of 4mm. The G_F at a CMOD of 2mm of the VAC beams with 3 lbs/yd^3 is 64% less than the beams with 12.1 lbs/yd^3 of fibers. Even with 3 lbs/yd^3, the fiber-reinforced VAC was able to support loads at crack mouth openings greater than 1mm.

Table 7: Fracture properties of virgin coarse aggregate beams (Phase 2)

Mixture Type		Peak Load (kN)	E (GPa)	K_{IC} (MPa-m$^{1/2}$)	CTOD$_c$ (mm)	[1]G_F (N/m)	[2]G_F (N/m)
VAC	Beam 1	2.92	27.2	1.06	0.0182	-	63
	Beam 2	3.57	24.7	1.18	0.0195	-	83
	Average	3.25	26.0	1.12	0.0189	-	73
VAC FRC	Beam 1	3.68	26.81	1.35	0.0262	153	254
	Beam 2	3.00	25.25	1.24	0.0292	133	217
	Average	3.34	26.03	1.30	0.0277	143	236

[1]up to 2mm CMOD; [2]up to 4mm CMOD

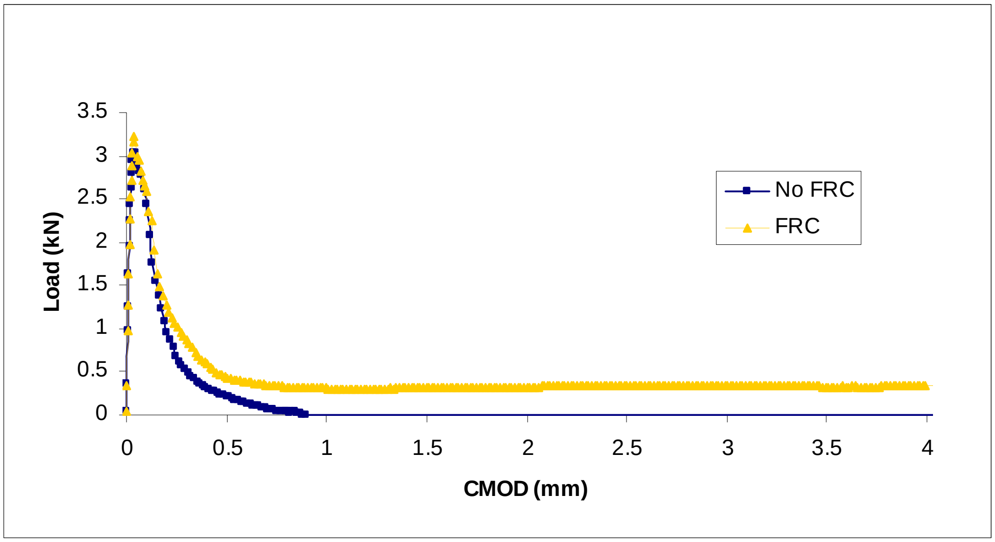


Figure 9: Load versus CMOD curves for virgin coarse aggregate concrete with 3 lbs/yd^3 of fibers and without fibers (Phase 2).

Figure 10 shows the load versus CMOD of the RCAC mixtures with and without fibers. Similar to the virgin coarse aggregate mixtures, there was little difference in the peak load capacity of RCAC with and without fibers. There was an even larger difference in the total fracture energy between the beams with and without fiber reinforcement as seen in Table 8. The RCAC with fibers had 5 times greater total fracture energy at 4mm than RCAC without fibers. Furthermore, the total fracture energy between the RCAC and VAC with fibers was approximately despite a 38% reduction in the fracture energy from the VAC to RCAC without fibers (73 to 45 N/m).

Table 8: Fracture properties of RCAC (Phase 2)

Mixture Type		Peak Load (kN)	E (GPa)	K_{IC} (MPa-m$^{1/2}$)	$CTOD_c$ (mm)	^1G_F (N/m)	^2G_F (N/m)
RCAC	Beam 1	2.95	30.1	1.13	0.0196	-	40
	Beam 2	3.01	25.8	1.06	0.0186	-	49
	Average	2.98	28.0	1.09	0.0191	-	45
RCAC FRC	Beam 1	3.06	28.4	1.12	0.0193	165	278
	Beam 2	3.20	28.0	1.13	0.0192	118	165
	Average	3.13	28.2	1.12	0.0192	142	222

^{1}up to 2mm CMOD; ^{2}up to 4mm CMOD

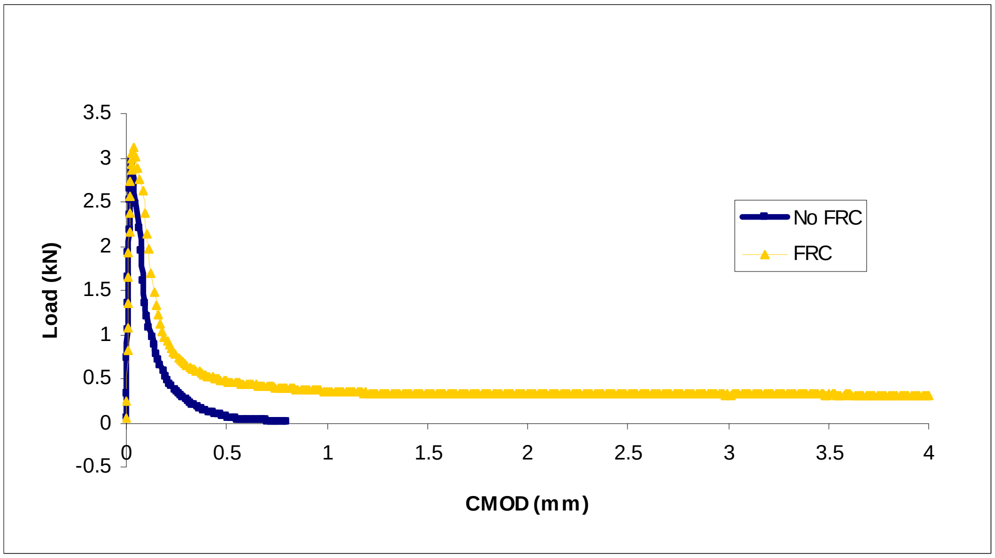


Figure 10: RCAC beams fracture behavior with and without 3 lbs/yd^3 of fiber reinforcement (Phase 2)

The third case in Phase 2 involved concrete mixtures with blended coarse aggregate, i.e., 50% virgin coarse aggregate and 50% RCA, with and without fibers. Two beams of each mixture were cast. As seen in Figure 11, the peak load was approximately the same for the plain and FRC blended mixtures. Table 9 shows the fracture properties for the blended concrete specimens. The blended FRC beams had a total fracture energy at 4 mm that was 3.3 times greater than plain 50-50 blended aggregate beams. The blended coarse aggregate mixture without fibers had a similar fracture energy to the VAC without fibers. The total fracture energy at 4 mm CMOD of the blended FRC was approximately the same as the RCAC and VAC with fibers (3 lbs/yd^3).

Table 9: Fracture properties of the 50-50 blend of virgin coarse aggregate and RCA

		Peak Load (kN)	E (GPa)	K_{IC} (MPa-$m^{1/2}$)	$CTOD_c$ (mm)	[1]G_F (N/m)	[2]G_F (N/m)
50-50 Blend	Beam 1	2.68	27.2	0.97	0.0162	-	76
	Beam 2	3.09	22.3	1.09	0.0226	-	63
	Average	2.89	24.7	1.03	0.0194	-	69
50-50 Blend FRC	Beam 1	2.78	27.2	0.84	0.0093	109	154
	Beam 2	2.84	24.7	0.95	0.0179	119	302
	Average	2.81	26.0	0.90	0.0136	114	228

[1]up to 2mm CMOD; [2]up to 4mm CMOD

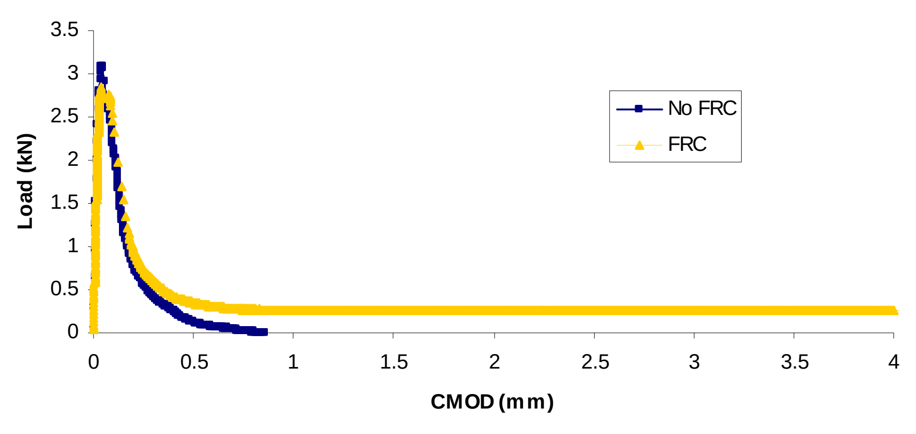


Figure 11: Load-deformation of concrete mixture with blended coarse aggregate, 50-50 blend, with 3lbs/yd^3 and without fibers.

6.2.3 Discussion of Fracture Property Results

The results of Phase 2 testing are summarized in Table 10 to allow for fracture property comparison in terms of coarse aggregate type and use of fiber reinforcement. Figure 12 is a summary of Load-CMOD results for the virgin aggregate, RCA, and blended coarse aggregate mixtures. For the plain concrete (unreinforced), the virgin coarse aggregate produced the highest peak loads. (Note, when averaging Load-CMOD curves between specimens, the average plot does not show the average peak load calculated from Table 10 since the peak loads from different specimens occur at different CMOD levels.) The total fracture energy is higher for the concretes containing virgin coarse aggregate and the blended coarse aggregate relative to the RCA. This behavioral difference can also be visualized in Figure 12 as the RCAC has a lower post-peak curve. For this coarse aggregate type and RCA properties, the fracture properties of a concrete mixture with RCA and no fibers can be significantly improved by blending RCA with a virgin aggregate (e.g. 50-50 blend per this study).

Table 10: Summary of concrete fracture properties of virgin, RCA, and blended coarse aggregate mixtures without fibers

		Peak Load (kN)	E (GPa)	K_{IC} (MPa-$m^{1/2}$)	$CTOD_c$ (mm)	[2]G_F (N/m)
VAC	Beam 1	2.92	27.2	1.06	0.0182	63
	Beam 2	3.57	24.7	1.18	0.0195	83
	Average	3.25	26.0	1.12	0.0189	73
RCAC	Beam 1	2.95	30.1	1.13	0.0196	40
	Beam 2	3.01	25.8	1.06	0.0186	49
	Average	2.98	28.0	1.09	0.0191	45
50-50 Blend	Beam 1	2.68	27.2	0.97	0.0162	76
	Beam 2	3.09	22.3	1.09	0.0226	63
	Average	2.89	24.7	1.03	0.0194	69

[2] up to 4mm CMOD

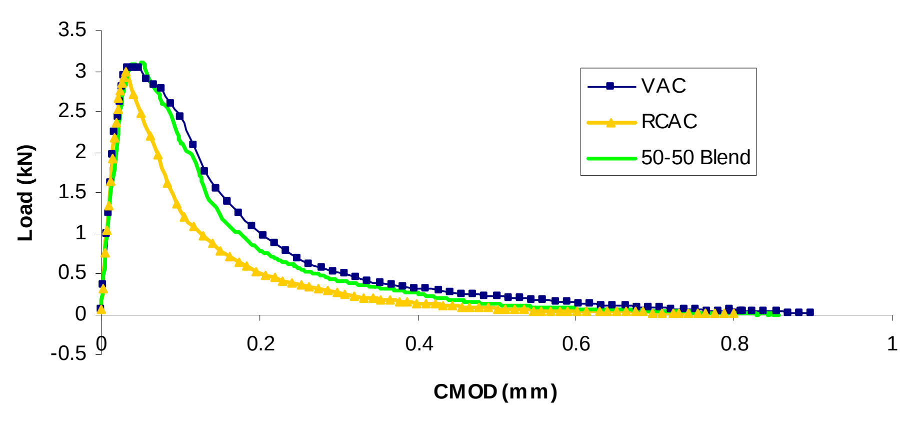


Figure 12: Average load-deformation curves for plain concrete mixtures containing virgin aggregate, RCA, and blended RCA-virgin coarse aggregates

Phases 1 and 2 testing results for 12 lb/yd^3 and 3 lb/yd^3 respectively are displayed in Table 11 for comparison of fiber volume and coarse aggregate type. As seen in Table 11 and Figure 13, the fracture behavior of RCAC can be made similar to virgin coarse aggregate or a 50-50 blended mixture if only 3 lbs/yd^3 of synthetic fibers are added. The peak load capacity of the virgin concrete and blended aggregate mixtures were higher than the RCA with fibers but all show similar post-peak softening curves. One other point is that the fracture properties of RCAC with fibers exceed the fracture properties of non-reinforced concrete with virgin aggregate, RCA, or blended coarse aggregate mixtures.

Table 11: Summary of fracture properties of virgin and RCAC with 12 lbs/yd^3 (Phase 1) and 3 lbs/yd^3 (Phase 2) of fiber reinforcement

		Peak Load (kN)	E (GPa)	K_{IC} (MPa-m^e)	CTOD$_c$ (mm)	Phase 1 ^1G_F (N/m)	Phase 2 ^1G_F (N/m)	Phase 2 ^2G_F (N/m)
VAC FRC	Beam 1	3.68	26.8	1.35	0.0262	357	153	254
	Beam 2	3.00	25.2	1.24	0.0292	460	133	217
	Beam3	-	-	-	-	385	-	-
	Ave.	3.34	26.0	1.30	0.0277	401	143	236
RCAC FRC	Beam 1	3.06	28.4	1.12	0.0193	236	165	278
	Beam 2	3.20	28.0	1.13	0.0192	303	118	165
	Beam 3	-	-	-	-	345	-	-
	Ave.	3.13	28.2	1.12	0.0192	295	142	222
50-50 Blend FRC	Beam 1	2.78	27.2	0.84	0.0093	-	109	154
	Beam 2	2.84	24.7	0.95	0.0179	-	119	302
	Ave	2.81	26.0	0.90	0.0136	-	114	228

[1]up to 2mm CMOD; [2]up to 4mm CMOD

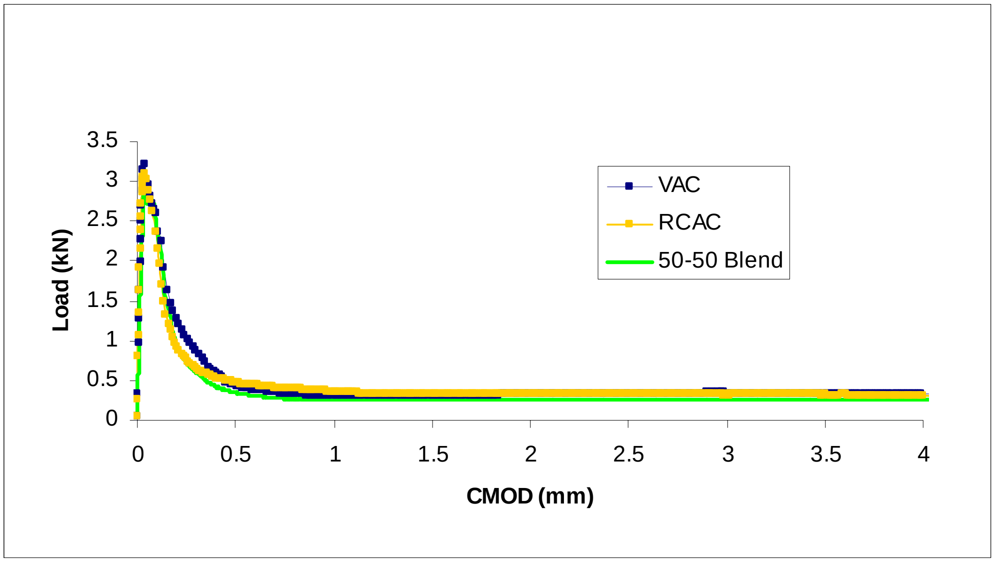


Figure 13: Effect of RCA, virgin, and blended coarse aggregate on the fracture behavior of 3 lb/yd^3 fiber reinforced concrete mixtures

Due to the ductility and bridging capabilities of fibers, the 4 mm range of the extensometer used for the CMOD measurement required modification. A second device to measure the CMOD to larger openings, called a yoyo gauge, is shown in Figure 8. This gage allowed calculation of the concrete fracture energy up to 20 mm range. This was able to capture the total energy of the FRC mixtures when the post-peak curve was close to zero load capacity. Figure 14 shows the softening curve of one of the 50-50 Blend FRC beams. This particular beam was able to hold load of 0.15 kN at a 16 mm CMOD. This increased the total fracture energy of the concrete beam from 228 N/m at 4mm CMOD to 517 N/m at 16 mm CMOD.

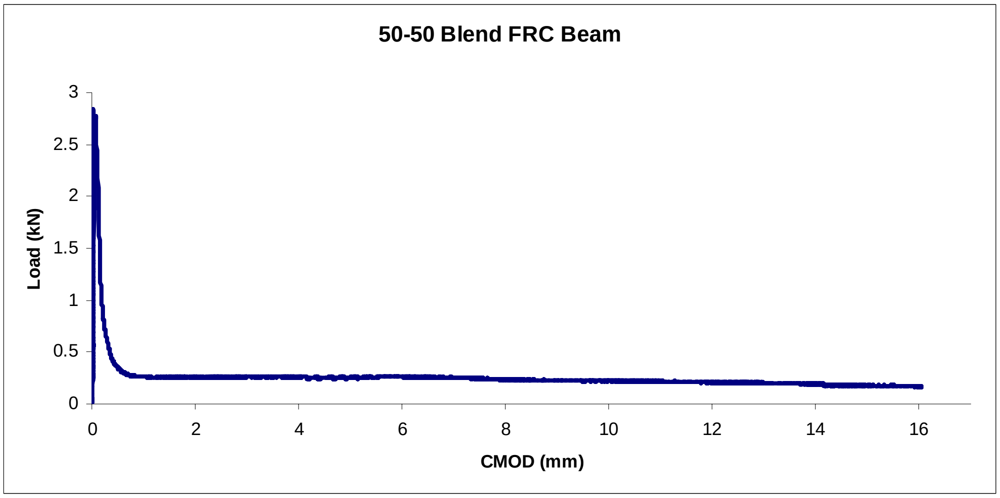


Figure 14: Fracture behavior of concrete mixture with blended RCA-virgin coarse aggregate up to 16mm CMOD.

6.2.4 Drying Shrinkage Results

Drying shrinkage and mass loss of the Phase 2 concrete mixtures was examined according to ASTM C157 [22] in a 23°C and 50% relative humidity chamber. One modification from this test standard was the initial drying began one day after casting. Significantly higher drying shrinkage of RCAC (10 to 50%) has been reported in the literature [7, 11, 14]. Table 12 and Figure 15 present the average free shrinkage strains based on three shrinkage prisms (75x75x285mm). During the first 7 days, the free drying shrinkage was approximately the same for all samples. By 28 days, the RCA samples had the highest shrinkage magnitude. The free shrinkage of the virgin and blended coarse aggregate was very similar at 28 days. The RCAC had approximately 28 percent greater free shrinkage at 28 days than the VAC. The addition of fibers did not significantly alter the shrinkage values found in the plain concrete mixtures. A recent study by Roesler et al. [20] on airport concrete paving mixtures found the drying shrinkage of four different concrete mixtures varied from 335 to 417 microstrain at 28 days. The main difference between this study and the referenced study was the water cement ratio and coarse aggregate types used.

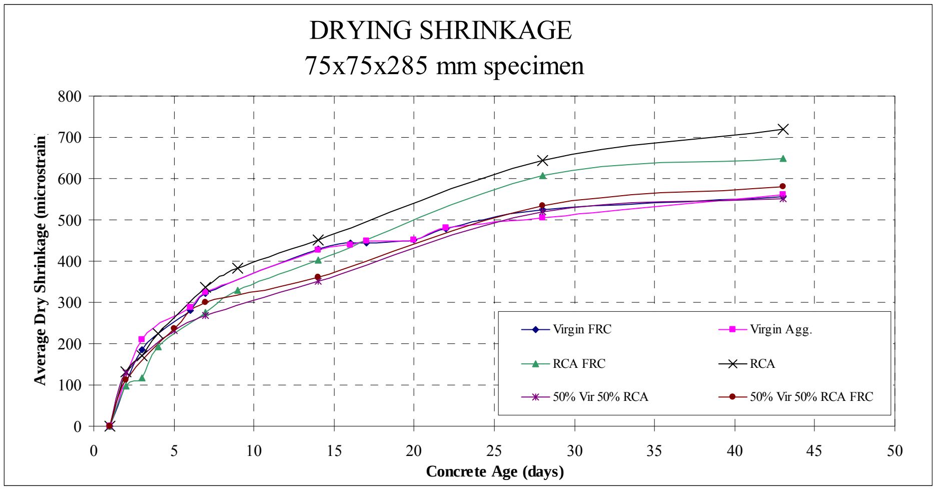


Figure 8: Free drying shrinkage concrete mixtures containing virgin, RCA, and blended coarse aggregate with and without fiber reinforcement

Table 12: Free drying shrinkage of concrete (Phase 2)

Day		**1**	**3**	**7**	**14**	**28**	**43**
VAC	Average Microstrain	0.00	210	325	427	505	562
	Weight loss (%)	0.00	2.25	3.23	3.46	3.68	3.87
	Weight loss (g)	0.00	89.6	128.5	138	147	153
VAC FRC	Average Microstrain	0.00	185	321.7	430	523	555
	Weight loss (%)	0.00	2.35	3.25	3.56	3.79	3.97
	Weight loss (g)	0.00	91.6	126	139	148	155
RCAC	Average Microstrain	0.00	170	337	452	645	720
	Weight loss (%)	0.00	2.41	2.93	3.26	3.73	3.90
	Weight loss (g)	0.00	90.6	110	122	140	147
RCAC FRC	Average Microstrain	0.00	117	277	403	608	648
	Weight loss (%)	0.00	2.75	3.27	3.59	4.05	4.22
	Weight loss (g)	0.00	100	119	131	148	154
50% Virgin 50% RCA	Average Microstrain	0.00	128	268	352	518	552
	Weight loss (%)	0.00	3.17	3.84	4.03	4.42	4.53
	Weight loss (g)	0.00	121	147	154	169	174
50% Virgin 50% RCA FRC	Average Microstrain	0.00	113	300	378	535	580
	Weight loss (%)	0.00	2.86	3.47	3.66	4.03	4.17
	Weight loss (g)	0.00	112	136	143	157	163

7. CONCLUSION

The incorporation of recycled concrete as a coarse aggregate in concrete mixtures has been successfully used in the state of Illinois and can offer economic benefits for new concrete pavement construction. During the first phase of this research, the fracture properties of concrete containing 100% recycled coarse aggregate was shown to be less than virgin aggregate concrete (VAC), but with the addition of a high volume of fibers (0.8%), the fracture properties of recycled concrete aggregate concrete (RCAC) exceeded the plain concrete with virgin aggregates and was similar to the fiber reinforced concrete with virgin aggregates. The second phase of this research demonstrated that a 50-50 blend of virgin and recycled coarse aggregate could give similar fracture properties to 100% virgin coarse aggregate. Furthermore, a cost effective addition of fibers (0.2%) to RCAC could also exceed the fracture properties of virgin and blended coarse aggregate concrete. The peak loads of VAC were always greater than RCAC and blended coarse aggregate concrete even with fibers. Overall, the RCA with fiber-reinforcement showed similar fracture properties as the virgin aggregate and blended aggregate fiber-reinforcement mixtures.

Measurement of the free drying shrinkage of prism samples showed that the RCAC without the fibers had the highest shrinkage strain at 28 and 43 days followed by the RCA concrete with the fibers and finally the virgin aggregate concrete mixtures. The drying shrinkage values obtained from this testing were higher than previous concrete paving mixtures due to the increased cement content, higher water to cement ratio and RCA. The increased shrinkage of the RCA may be compensated in future mixture designs by reducing the water to cement ratio.

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