Coarse Recycled Aggregate Concrete Pavements – Design, Instrumentation, and Performance

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ABSTRACT

Although there is a critical shortage of virgin aggregate, the availability of demolished concrete for use as recycled concrete aggregate (RCA) is increasing. Using the waste concrete as RCA conserves virgin aggregate, reduces the impact on landfills, decreases energy consumption and can provide cost savings. However, there are still many unanswered questions on the beneficial use of RCA in concrete pavements. This paper identifies several mix designs containing RCA that show encouraging results in both the laboratory and field testing.

The coarse RCA used in the mix designs was selected to minimize impurities and limit the amount of interfacial transition zones. Waste curb and gutter and sidewalks were used to provide consistency in the RCA properties. Fine RCA was not used since it may contain large amounts of impurities that result in concrete strength loss. Twelve mix designs were laboratory tested using coarse RCA amounts of 0% (control), 15%, 30% and 50%, and cement contents of 315 kg, 330 kg, and 345 kg. Since all test mixes exceeded 30 MPa at 28-days, the lowest cement content mixes were selected for field testing

Performance of four test sections is monitored through ongoing pavement evaluations using the Ontario Ministry of Transportation's Manual for Condition Rating of Rigid Pavements. Additionally, the pavement was instrumented with sensors to monitor pavement performance in relation to long-term environmental conditions. Preliminary laboratory testing and field results support a mix design containing quality coarse RCA of a specific size to result in concrete that exhibits similar or improved performance compared to non-RCA containing concrete.

INTRODUCTION

There is a dramatic decline in good quality aggregate available for construction use. World wide, approximately eight to eleven billion tonnes of aggregate (sand, gravel, and crushed rock) is being used for concrete production every year *(1,2)*. In Canada, fourteen tonnes of aggregate are consumed per person each year. However, for every three tonnes of aggregate that is produced only one tonne is replaced by opening new aggregate sources or through recycling *(3)*. Ontario is currently using aggregate faster than it is being made available resulting in an aggregate shortage *(4)*.

The current state of aggregate resources in Ontario is not fully known since the last detailed study was done in 1992 by the Ministry of Natural Resources (MNR) in "State of the Resource Report" *(5)*. From 1992 to 2003 Ontario's yearly consumption of aggregate was approximately 170 million tonnes. More than sixteen tonnes of aggregate are used per person in Ontario each year *(4)*. To construct one kilometre of 6-lane expressway, 51,800 tonnes of aggregate are used. 2800 licensed pits and quarries in Ontario produced over 160 million tonnes in 2001 *(5)*. Aggregate consumption in Ontario over the next 25 years is estimated at four billion tones *(4)*. Ontario is facing an aggregate shortage. It is estimated that some urban areas will run out of aggregate by 2010 *(5)*.

Although there is a critical shortage of natural aggregate, there is an increasing amount of demolished concrete *(6)*. The environmental impact of waste concrete is significant. Not only is there the environmental impact of transporting the waste concrete away from the site but the waste concrete also fills up valuable space in landfills. There is a huge potential to reuse this material as source of new aggregate *(7)*. Recycling concrete, from deteriorated concrete structures, would reduce the negative impact on the environment and increase sustainability of aggregate resources *(6,8)*. There are both environmental and economic benefits to using recycled concrete aggregate (RCA). Using RCA conserves virgin aggregate, reduces the impact on landfills and decreases energy consumption *(9)*. Using RCA, creates cost savings in the transportation of aggregate and waste products, and in waste disposal *(9,10)*. It is estimated that using RCA can save up to $11 per 1000 kg ($10 per ton) of aggregate *(10)*.

RESEARCH SIGNIFICANCE

The objective of this research was to identify several mix designs containing RCA that would be suitable for usage in concrete pavements. The Centre for Pavement and Transportation Technology (CPATT), located at the University of Waterloo, in Southern Ontario, Canada, in partnership with Dufferin Construction and the Cement Association of Canada (CAC) successfully placed high quality concrete test sections containing recycled concrete aggregate. This paper identifies the rationale for using RCA along with the barriers, describes the material used in RCA mix design, gives the laboratory results of nine RCA concrete mix designs compared to three virgin mix designs, and gives the initial results of three concrete containing RCA test sections placed at the CPATT test track along with one virgin mix control test section.

BARRIERS TO USING RECYCLED CONCRETE AGGREGATE

There are several barriers to overcome in order for RCA to become widely accepted. Initially, there is a high investment cost to purchase concrete crushers. In addition, maintenance costs of concrete crushers are also significant *(11)*. In Ontario, non-virgin aggregate consumption is estimated at three percent *(5)*. This may be due to the lack of financial incentive. The Ontario government currently places a levy of only six cents per tonne on virgin aggregate. Another barrier relates to the excess amount of fine RCA created during the crushing process. This excess fine aggregate requires disposal or an alternate use. Depending on the source and type of RCA, the absorption, strength, and impurities vary. This can mean that it is unusable or that it might adversely impact the new pavement structure. There is a lack of knowledge on how RCA affects pavement durability since most studies focus only on the properties of RCA concrete *(12)*. Specific standards on how to use RCA in new concrete are not currently available.

IMPACT OF RECYCLED CONCRETE AGGREGATE ON CONCRETE CHARACTERISTICS

The literature on the affects of RCA in concrete is sometimes vague or has mixed results. Since each source of RCA is unique based on its mix design and environment, the test results and performance of RCA containing concrete can vary greatly. RCA has a higher interfacial transition zone (ITZ) due to its higher absorption and porosity *(13)*. It is generally accepted that concrete durability is reduced as the amount of RCA is increased. RCA containing mixes are stiffer and lose workability faster than mixes using virgin aggregates *(14)*. RCA mixes have a decreased slump compared to virgin mixes with the same w/c ratio *(11)*. The air content in RCA containing mixes is higher than virgin mixes *(14,15)*. Some RCA containing mixes have a decreased compressive and flexural strength *(15,16,17)*, while others show an increased compressive and flexural strength *(18)*. The Modulus of Elasticity decreases with the use of RCA *(14,15)*. There are mixed results for freeze-thaw testing with concrete containing RCA *(19,20)*. Concrete containing RCA has a greater amount of dry shrinkage than virgin aggregate concrete *(21,22,23)*.

MATERIALS FOR TEST MIXES

The size of RCA used in concrete can greatly affect the concrete performance. Fine RCA contains many impurities and results in strength loss in the concrete. Natural sand was used as fine aggregate since it provides a greater strength than fine RCA *(10)*. Coarse RCA crushed from air entrained concrete sidewalks, curbs and gutters was chosen since it contained few impurities, and had a maximum aggregate size of 19mm. In order to minimize negative effects on concrete performance from coarse RCA, it is important to limit the amount of interfacial transition zones that are present in the RCA *(13)*. Since the concrete that the RCA was crushed from contained a maximum aggregate size of 19 mm, this was the maximum size of the RCA that was used. Any RCA over 19 mm would contain excess interfacial transition zones that would negatively impact the strength of the concrete. Table 1 shows the properties of the coarse and fine aggregates that were used in the mix design.

The coarse and fine virgin aggregates supplied by the contractor satisfied the Ministry of Transportation of Ontario's standards for concrete pavements. The 19 mm RCA coarse aggregate was selected from decommissioned concrete curb and gutter from the Region of Waterloo. Figure 1 shows the waste concrete prior to being crushed and the resulting coarse aggregate that was used in the study.

The waste concrete had sufficient air-entrainment, had been cured properly, and had a compressive strength in excess of 30 MPa at 28-days, making it an ideal replacement for virgin aggregate. However, if the RCA is measured using the same scale as a virgin aggregate the source would have been rejected due to the Micro-Deval result exceeding the upper allowable limit.

In the test mixes general use (Type 10) cement was used. The cement consisted of 53% tricalcium silicate (C_3S), 18% dicalcium silicate (C_2S), 7% tricalcium aluminate (C_3A), and 8% tetracalcium aluminoferrite (CA_4F). It had a Blaine Fineness of 410 m^2/kg. Type S slag with a Blaine Fineness of 532 m^2/kg was used. Euclid Airex-L, an air entrainment admixture was added at a dose of 55 ml/100 kg of cement to increase the stability of microscopic air bubbles. Euclid Eucon WR, a water reducing admixture was used at a dose of 250 mm/100 kg cement to allow for easier handling and finishing, increased strength and durability, and reduced shrinkage and permeability.

GUIDELINES FOR MIXTURE DESIGN

The test track is located in Waterloo, Ontario, Canada which is in the Southern part of the province, approximately three hours from the Windsor –Detroit border. It is located in a wet freeze zone with typical annual frost depths of 1.2 m. Figure 2 shows the average daily temperature and the average monthly precipitation from 1998 to 2006. The weather conditions at the test track produce a freeze-thaw environment. The Canadian Standards Association (CSA) recommends that plain concrete in this type of freeze-thaw environment should meet the guidelines for exposure level of C-2. The C-2 exposure level is defined as a plain concrete (no structural reinforcement) that is exposed to both chlorides and freezing/thawing *(24)*.

Based on the exposure level of C-2 the concrete must meet CSA A23.1 standard that includes the follow criteria *(24)*:

- A water cement ratio less than 0.45,
- A 28-day compressive strength greater than 32 MPa,
- A maximum aggregate size of 14 to 20 mm, and
- An air content of 5% to 8%.

The American Concrete Pavement Association further recommends *(10)*:

- A cement content greater than 335 kg/m^3,
- A slump less than 100 mm,
- A well-graded aggregate, and
- Use of a curing compound.

Although the CSA standard recommends a maximum aggregate size of 20 mm, the Ministry of Transportation of Ontario (MTO) specifications allow for aggregate up to 37.5 mm in highway applications. The MTO also allows for 25% of cement content to be replaced with slag by mass *(25)*. Increasing the aggregate size and the slag content reduces the cost of the mix.

TEST MIXES

Laboratory testing was carried out on twelve test mixes in order to determine the best mixes to place on the CPATT test track. A 4x3 factorial design was used consisting of four coarse RCA amounts (0%, 15%, 30% and 50%) and three cement contents (315 kg, 330 kg, and 345 kg). The mixes were made using an absolute volume design method. Table 2 summarizes the quantity of each material used in the test mixes based on an aggregate saturated surface dry condition. Figure 3 shows the combined aggregate gradings for the varying RCA contents, a 65% coarse aggregate to 35% fine aggregate ratio was used.

The concrete was mixed in a portable drum mixer. Each mix combination was batched in two 0.03 m^3 quantities. The first batch was mixed and the fresh properties of unit weight, air content, and slump were measured. Then, the first batch sat while the second batch was mixed. Based on the fresh properties of the first batch, adjustments were made to the amount of water in the second batch. The batches were then combined and mixed for approximately five minutes. The fresh properties of the combined mix were taken and cylinders were cast. For each of the twelve mixes, eight cylinders were cast in order to test for compressive strength and perform an air void analysis.

LABORATORY RESULTS OF TEST MIXES

Unit weight, air content, and slump were measured on the fresh concrete of each mix. Compressive strength was measured initially between four and six days, and then on days seven, fourteen and twenty eight. Table 3 summarizes the results of the laboratory tests.

The compressive strength increased as the cement content increased for all test mixes containing RCA. However, the compressive strength decreased as the cement content increased for test mixtures containing only virgin aggregate. Since all mixes reached the specified 30 MPa at 28-days, the mixes with the smallest amount of cement content were selected for field testing.

Air void analysis was used to confirm the air content of the hardened concrete and to check the spacing factor. Table 4 shows the results of the air void analysis and compares the hardened air content value to the fresh values. The specified maximum spacing factor value is 0.23 mm. The air content and spacing factors were within the specified range for all test mixes. This should provide sufficient freeze-thaw protection.

The mix designs chosen for placement at the CPATT test track were test mixes #1. These mixes have the lowest cement content. Although the cement content is lower than the ACPA recommended 335 kg/m^3, adequate strength was reached and it provides a more cost effective mix design.

TEST TRACK DESIGN AND PLACEMENT

The test track is located at the Region of Waterloo Landfill and Waste Management Facility. It is 180 m in length and 2 lanes or 8.5 m wide. The traffic is almost entirely garbage trucks entering and exiting the landfill and estimated at 33,500 garbage trucks each way per year. This is the equivalent of 149,000 single axle loads (ESALs) in the loaded direction or 4,265,000 ESALs over the pavements 20-year design life. To accommodate this loading the pavement structure consists of 250 mm of concrete, 100 mm asphalt-stabilized open graded drainage layer (OGDL), and 450 mm compacted granular material. Joint spacing followed the MTO construction guidelines using a repeated variable joint spacing of 3.7 m, 4.5m, 4.0 m, and 4.3 m. Load transfer was achieved using 38 mm diameter epoxy coated dowel bars spaced at 300 mm along the width of the pavement.

One slab in each test section was instrumented with six vibrating wire concrete embedment strain gages to measure long-term longitudinal and transverse strain due to environmental changes, two vibrating wire vertical extensometers to monitor slab curling and warping, two vibrating wire inter-panel extensometers to monitor joint movement, and two maturity metres to measure maturity and temperature. The locations of the embedded sensors are presented in Figure 4.

Each of the mix 1 designs was placed at the CPATT test track to monitor the field performance of in-service RCA pavements. The control test section containing only virgin aggregate was 30m in length while the RCA containing test sections were each 50m in length. On June 13, 2007 the 0% RCA test section and half of the 15% RCA test section were placed. On June 14, 2007 the remaining 15% RCA test section, the 30% RCA test section, and the 50% RCA test were placed. For each RCA amount, beams and cylinders were cast for laboratory testing. Twelve cylinders were cast: nine cylinders for compressive strength testing, two cylinders for maturity testing, and one cylinder for air void analysis. Also, for each test section three beams were cast for flexural testing, and two beams for freeze thaw testing.

TEST TRACK INITIAL PERFORMANCE RESULTS

Compressive strength testing was performed using 150 mm x 300 mm cylinders consolidated by vibration. Compressive strength testing was done according to ASTM C 39 - Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens on days seven, fourteen, and twenty-eight *(26)*. Figure 5 shows the compressive strength development from the test track mixes. Compressive strength increased from 0% RCA to 30% RCA. All of the RCA containing mixes reached the 28-day design strength, however, the control section containing no RCA did not. The control section is projected to reach the 28-day design strength at 36 days. The results show an RCA content of 30% can be used without negatively affecting the compressive strength. Strength development was slower for the field placed concrete compared to the trial mixes. This is due to the high air temperature causing loss of moisture in the concrete for hydration. This occurred through air evaporation, water absorption into the RCA and moisture was also drawn from the mix into the asphalt-stabilized OGDL.

Flexural strength was tested with 150 mm X 150 mm X 600 mm beams consolidated by vibration. Beams were tested on day seven, and twenty-eight according to the 3-point bending ASTM C 78 – Standard Test Method for Flexural Strength of Concrete using Simple Beam with Third-Point Loading *(26)*. Figure 6 shows the results of the flexural strength testing. Flexural strength development followed a similar trend as compressive strength. Flexural strength increased up to 30% RCA. Flexural strength results are higher than the CAC recommended value of 8 to 12% of the compressive strength or 0.6 to 0.8 square root of compressive strength *(27)*. Flexural strength values ranged from 23.0% of the compressive strength for the 30% RCA to 28.8% of the compressive strength for 0% RCA.

Freeze-thaw testing was performed according to ASTM C 666 Procedure A – Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing *(26)*. The beams were placed in a freeze-thaw chamber that cycled from -20^{o}C to 4^{o}C and back in four hours. Table 5 shows the results at the end of 300 cycles for relative dynamic modulus and weight change. The relative dynamic modulus (RDM) is similar for all of the beams. The amount of mass loss decreases as the RCA content increases.

RESULTS COMPARED TO LITERATURE

Table 6 compares the characteristics of RCA containing concrete from literature sources and high quality RCA containing concrete from this study with non-RCA containing concrete. By using a mix design containing a high quality RCA within a specific size range, improvements were made on slump, air content, compressive strength and flexural strength compared to literature values.

IN-SERVICE PAVEMENT PERFORMANCE

Pavement performance of the four test sections was evaluated using visual surveys conducted following the MTO's Manual for Condition Rating of Rigid Pavements *(28)*. The standard uses distress type, severity, and density to calculate a pavement condition index (PCI) value. This value is used for determining maintenance treatments/options, determining pavement deterioration rates, and maintenance priority scheduling; it is not a measure of structural capacity, surface roughness or skid resistance. The PCI scale ranges from 100 (perfect/excellent) to 0 (fully deteriorated/failed). Table 7 illustrates the PCI rating scale.

Six surveys have been conducted since construction in June 2007. Over this time period the test sections have experienced an estimated 100,000 equivalent single axle loads. Figure 7 shows the conditions of the test sections and Table 8 presents the results from the April 2, 2008 condition survey.

All test sections are in excellent condition and performing well. There has been no change in the PCI of the test sections since the last evaluation conducted in September. All test sections are experiencing the same three distresses (patching, lane/shoulder drop-off, and joint spalling) with similar severity and density levels. There is a small amount of patching in each of the test sections resulting from an investigation to check dowel alignment and depth, and a retrofit of the inter-panel extensometers to monitor joint movement. The patching is not in response to construction method or material defects, rather it is from additional research investigations. The lane/shoulder drop-off runs almost the entire length of the southbound loaded travel lane, and is caused by wandering garbage trucks. Failure of the trucks to stay in the designated lane has lead to the deterioration of the pavement edge.

CONCLUSIONS

This study provides evidence that supports the following conclusions.

1. RCA containing concrete was successfully placed for field testing on a test track.
2. By using a mix design that contains quality coarse RCA of a specific size the resulting concrete exhibits similar or improved performance compared to non-RCA containing concrete.
3. There is no significant difference in the performance of all four test sections (0%, 15%, 30%, and 50% RCA), and they are in excellent condition with a PCI greater than 90 after five months of service.

RECOMMENDDATIONS

For RCA to be widely used, consistent and predictable results need to be obtained when using RCA mixes. To achieve this, further studies in the following areas are necessary.

1. Comparing concrete mixes with different sources of RCA including sources of RCA that are clean, contaminated, and cured differently.
2. Compare concrete mixes with a variety of RCA content to find the optimal amount.

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REFERENCES

1 Naik, Tarun R., and Moriconi, G. (2005). "Environmental-Friendly Durable Concrete Made with Recycled Materials for Sustainable Concrete Construction," International Symposium on Sustainable Development of Cement, Concrete and Concrete Structures, Toronto, Ontario, October 5-7, pp. 277-298.

2 Mehta, P. Kumar. (2001). "Reducing the Environmental Impact of Concrete," Concrete International, V. 23, No.10, October, pp. 61-66.

3 McMacNaughton, Ian. (2004). "Ontario's Aggregates Are a Diminishing Resource," Ontario Hot Mix Producers Association Fall Seminar Presentations, December 8.

4 Aggregate Producers Association of Ontario. (2004). "Importance of Aggregate," The About Aggregate Series, Mississauga, Ontario, pp. 1-4.

5 Miller, Gord. (2005). "Running Out of Gravel and Rock," Toronto Star, January 6, p. A22.

6 Hansen, Torben C., and Hedegard , Soren E. (1984). "Properties of Recycled Aggregate Concretes as Affected by Admixtures in Original Concretes," ACI Journal, January-February, pp. 21-26.

7 Bairagi , N. K., Vidyadhara , H. S., and Ravande, Kishore. (1990). "Mix Design Procedure for Recycled Aggregate Concrete," Construction and Building Materials, V. 4, No. 4, December, pp. 188-193.

8 Oikonomou, Nik. D. (2003). "Recycled Concrete Aggregates," Cement and Concrete Composites, V. 25, No. 2, pp. 315-318.

9 Federal Highway Administration. (2004). "Transportation Applications Of Recycled Concrete Aggregate: FHWA State of the Practice National Review September 2004," U.S. Department of Transportation, Washington, DC.

10 American Concrete Pavement Association. (1993). "Recycling Concrete Pavement," Concrete Paving Technology, TB-014P.

11 Rashwan, M. Shokry, and AbouRizk, Simaanv. (1997) "The Properties of Recycled Concrete," Concrete International, V. 18, No.7, July, pp. 56-60.

12 Olorunsogo, F.T., and Padayachee, N. (2002). "Performance of Recycled Aggregate Concrete Monitored by Durability Indexes," Cement and Concrete Research, V. 32, pp. 179-185.

13 Poon, C. S., Shui, Z. H., and Lam, L. (2004). "Effect of Microstructure of ITZ on Compressive Strength of Concrete Prepared with Recycled Aggregate," Construction and Building Materials, V. 18, No. 6, pp. 461-468.

14 Salem, Rohi M., Burdette, Edwin G., and Jackson, N. Mike. (2003). "Resistance to Freezing and Thawing of Recycled Aggregate Concrete," ACI Materials Journal, V. 100, No. 3, May-June, pp. 216-221.

15 Katz , Ammon. (2003). "Properties of Concrete Made with Recycled Aggregate from Partially Hydrated Old Concrete," Cement and Concrete Research, V. 343 No. 5, pp. 703-711.

16 Shayan, Ahmad, and Xu, Aimin. (2003). "Performance and Properties of Structural Concrete Made with Recycled Concrete Aggregate," ACI Materials Journal, V. 100, No. 5, September-October, pp. 371-380.

17 Abou-Zeid, Mohamed Nagib, Shenouda, Mourad N., McCabe, Steven L., and El-Tawil, Farrah A. (2005). "Reincarnation of Concrete," Concrete International, V. 27, No.2, February, pp. 53-59.

18 Poon, C.S., Kou, S.C., and Lam, L. (2002). "Use of Recycled Aggregates in Molded Concrete Bricks and Blocks," Construction and Building Materials, V. 16, No. 5, pp. 281-289.

19 Gokce, A., Nagataki, S., Saeki, T., and Hisada, M. (2002). "Freezing and Thawing Resistance of Air-Entrained Concrete Incorporating Recycled Coarse Aggregate: The Role of Air Content in Demolished Concrete," Cement and Concrete Research, V. 34, No. 5, pp. 799-806.

20 Salem, Rohi M., and Burdette, Edwin G. (1998). "Role of Chemical and Mineral Admixtures on Physical Properties and Frost-Resistance of Recycled Aggregate Concrete," ACI Materials Journal, V. 95, No. 5, September-October, pp. 558-563.

21 Hansen, Torben C., and Boegh, Erik. (1985). "Elasticity and Drying Shrinkage of Recycled-Aggregate Concrete," ACI Materials Journal, V. 82, No. 5, September-October, pp. 648-652.

22 Ajdukiewicz, Andrzej, and Kliszczewica, Alina. (2002). "Influence of Recycled Aggregates on Mechanical Properties of HS/HPS," Cement and Concrete Composites, V. 24, No. 2, pp. 269-279.

23 Tavakoli, Mostafa, and Soroushian, Parviz. (1996). "Drying Shrinkage Behavior of Recycled Aggregate Concrete," Concrete International, V. 18, No.11, November, pp. 58-61.

24 CSA International. (2000). "Concrete Materials and Methods of Concrete Construction," CSA A23.1-00, Canadian Standards Association, Mississauga, ON.

25 Ontario Provincial Standard Specification. (2005). "Material Specification for Aggregate – Concrete," OPSS 1002 (Draft 2), Ministry of Transportation, Ontario, St. Catherines, ON.

26 ASTM. (2004). "Annual Book of ASTM Standards," Volume 04.02, American Society for Testing and Materials, West Conshohocken, PA.

27 Kosmatka, Steven H., Kerhoff, Beatrix, MacLeod, Norman F., and McGrath, Richard J. (2002). "Design and Control of Concrete Mixtures," EB101, 7th Canadian Edition, Cement Association of Canada, Ottawa, ON.

28 Chong, G. J., and Wrong, G. A. (1995). "Manual for Condition Rating of Rigid Pavements – Concrete Surface and Composite Distress Manifestations," Research and Development Branch, Ministry of Transportation, Ontario, St. Catherines, ON.

Table 1. Properties of Coarse and Fine Aggregate

Properties	Upper Limit *(24)*	Aggregate Type 37.5mm	19mm	RCA 19mm	Sand
Material Finer than 75um (%)	2	1.12	1.41	-	-
Absorption (%)	2	1.47	1.47	4.41	1.16
Bulk Relative Density (kg/m^3)		2641	2713	2379	2683
Flat and Elongated Particles (%)	20	4.9	2.8	-	-
Unconfined Freeze/Thaw Loss (%)	6	1.9	1.5	-	-
Petrographic Number	125	107	105	-	-
Crushed Particles (%)	80	100	100	100	-
Micro-Deval (%)	14 / 20 *	-	9.6	14.6	14.7
Organic Impurities	3	-	-	-	1

* 14% coarse aggregate, 20% fine aggregate

Table 2. Material Quantities In Test Mixes Per m^3 Of Concrete

		Cement (kg)	Slag (kg)	Water (kg)	39mm Vir (kg)	19mm Vir (kg)	19mm RCA (kg)	Sand (kg)	Air (ml)	WR (ml)
0% RCA	Mix 1	236	79	135	504	777	0	620	174	788
	Mix 2	247	83	137	504	776	0	620	182	825
	Mix 3	259	86	144	492	758	0	599	190	863
15% RCA	Mix 1	236	79	135	504	582	170	619	174	788
	Mix 2	247	83	142	502	580	170	616	182	825
	Mix 3	259	86	150	496	573	167	607	190	863
30% RCA	Mix 1	236	79	134	509	392	344	629	174	788
	Mix 2	247	83	143	501	386	339	616	182	825
	Mix 3	259	86	149	498	383	336	610	190	863
50% RCA	Mix 1	236	79	137	512	131	576	634	174	788
	Mix 2	247	83	145	505	130	569	623	182	825
	Mix 3	259	86	147	499	128	562	613	190	863

* Vir. = Virgin aggregate, Air = Air entrainment, WR = Water reducer

Table 3. Laboratory Test Results

		Unit Wt. (kg/m^3)	Air (%)	Slump (mm)	Compressive Strength (MPa) 4-Day	5-Day	6-Day	7-Day	14-Day	28-Day
0% RCA	Mix 1	2350	5.9	40	-	-	23.2	24.1	34.7	40.7
	Mix 2	2367	5.6	40	-	-	22.2	25.3	37.4	40.0
	Mix 3	2338	6.1	40	-	-	24.4	25.9	34.1	39.1
15% RCA	Mix 1	2325	6.8	60	-	20.8	-	22.5	34.1	36.0
	Mix 2	2340	5.8	40	-	25.7	-	27.6	39.0	43.0
	Mix 3	2338	5.8	40	-	23.9	-	27.0	40.9	44.3
30% RCA	Mix 1	2323	6.1	40	15.9	-	-	22.2	31.1	36.9
	Mix 2	2315	6.0	40	21.0	-	-	27.1	35.4	42.4
	Mix 3	2321	6.1	40	19.9	-	-	28.4	36.6	43.0
50% RCA	Mix 1	2306	5.7	40	-	-	24.4	26.9	34.1	42.7
	Mix 2	2301	6.1	40	-	-	24.8	26.8	33.5	43.0
	Mix 3	2293	5.8	40	-	-	28.0	29.6	37.8	43.0

Table 4. Results of Air Void Analysis

Mix	Air Content (%) Fresh	Harden	Spacing (mm)
0% RCA	5.2	5.9	0.134
15% RCA	6.6	6.8	0.180
30% RCA	5.3	6.1	0.125
50% RCA	5.6	5.7	0.143

Table 5. Freeze-Thaw Test Results

	0%RCA RDM	0%RCA Δ Mass	15%RCA RDM	15%RCA Δ Mass	30%RCA RDM	30%RCA Δ Mass	50%RCA RDM	50%RCA Δ Mass
Beam 1	91.2%	-0.54%	90.3%	-0.62%	92.0%	-0.68%	88.9%	-0.19%
Beam 2	89.3%	-0.54%	89.7%	-0.54%	86.2%	-0.84%	91.3%	-0.35%
Average	90.3%	-0.54%	90.0%	-0.58%	89.1%	-0.76%	90.1%	-0.27%

* RDM = Relative dynamic modulus, Δ Mass = Change in mass

Table 6. Concrete Characteristics For RCA vs. Non-RCA Concrete

Properties	Literature	UW RCA
Workability	Decreases	Decreases
Slump	Decreases	Similar
Air Content	Increases	Similar or Increased
Absorption	Increases	Increases
Compressive Strength	Decreases	Increases
Flexural Strength	Decreases	Increases
Freeze-Thaw	Mix Results	Similar

Table 7. Pavement Condition Index Rating Scale

PCI Value	100 - 85	85 - 70	70 - 55	55 - 40	40 - 25	25 - 10	10 - 0
Rating	Excellent	V. Good	Good	Fair	Poor	V. Poor	Failed

* V. = Very

Table 8. Test Section PCI Evaluation Results – Apr. 2, 2008

Test Section	PCI (x/100)	Distress Type	Severity	Density*
0% RCA	89	Scaling	Very Severe	Frequent
		Joint and Crack Spalling	Moderate	Frequent
15% RCA	95	Joint and Crack Spalling	Moderate	Frequent
30% RCA	94	Potholing	Slight	Few
		Joint and Crack Spalling	Moderate	Frequent
50% RCA	95	Joint and Crack Spalling	Moderate	Frequent

* Density (% of pavement surface affected): Few (less than 10%), Intermittent (10% to 20%), Frequent (20% to 50%), Extensive (50% to 80%), and Throughout (80% to 100%).

Figure 1. 19 mm RCA Coarse Aggregate Before and After Crushing

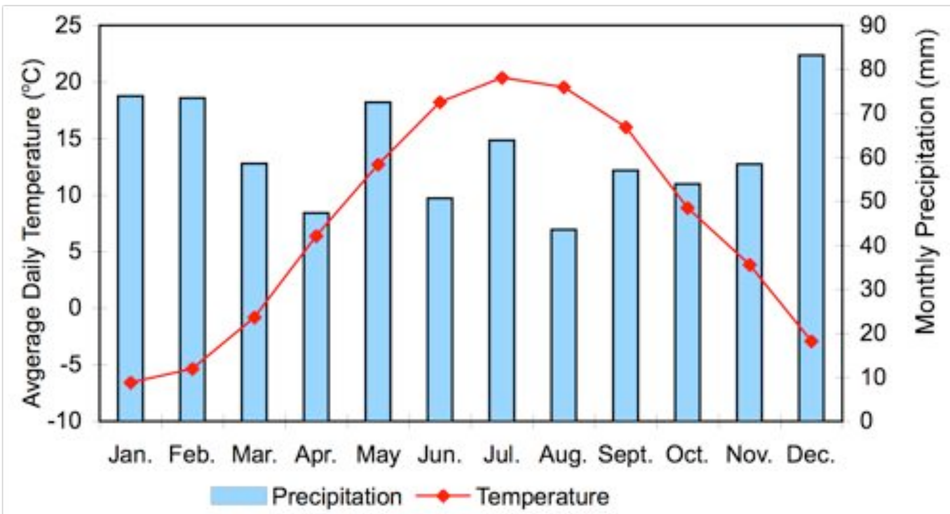

Figure 2. Waterloo's Average Daily Temperature and Average Monthly Precipitation

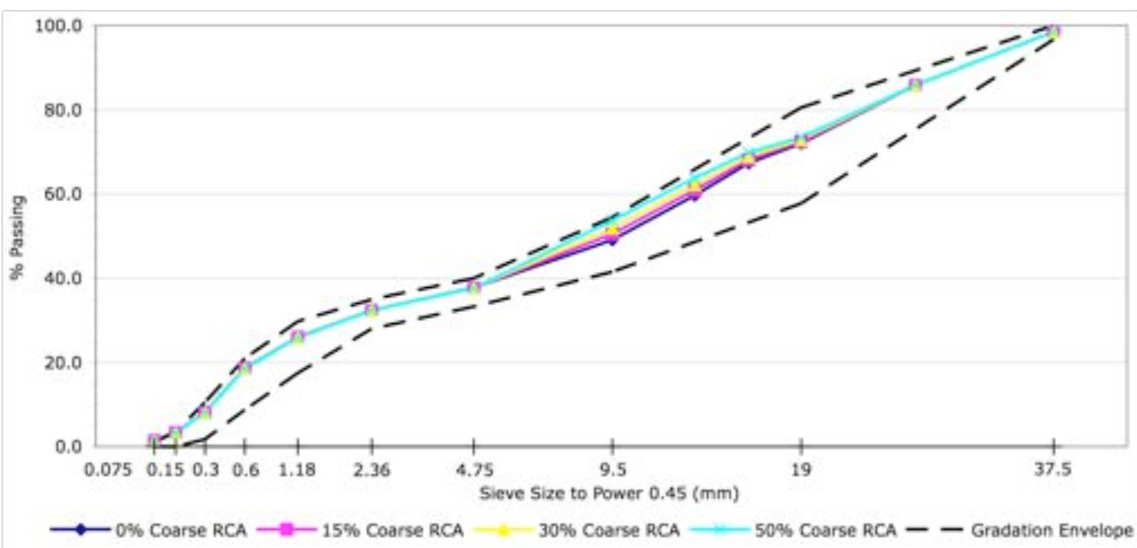

Figure 3. Combined Aggregate Gradings

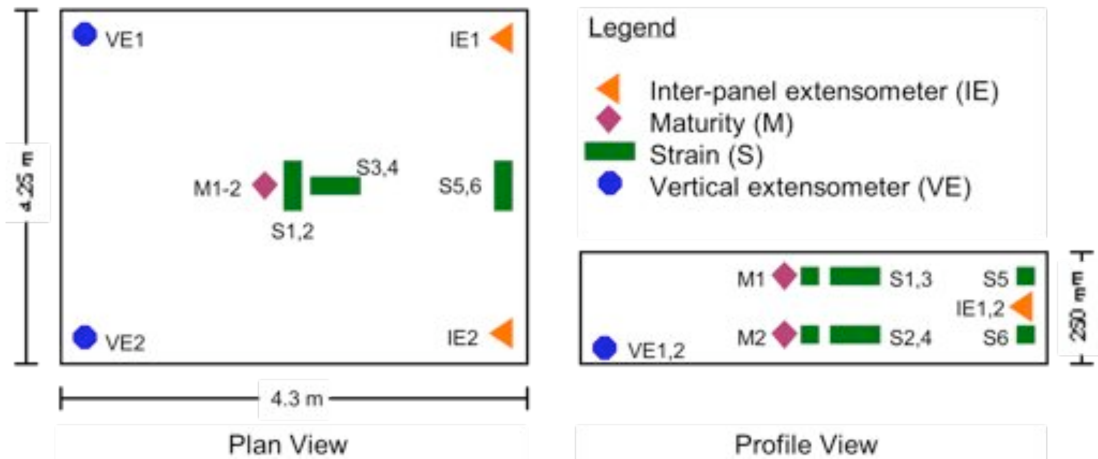

Figure 4. Sensor Layout

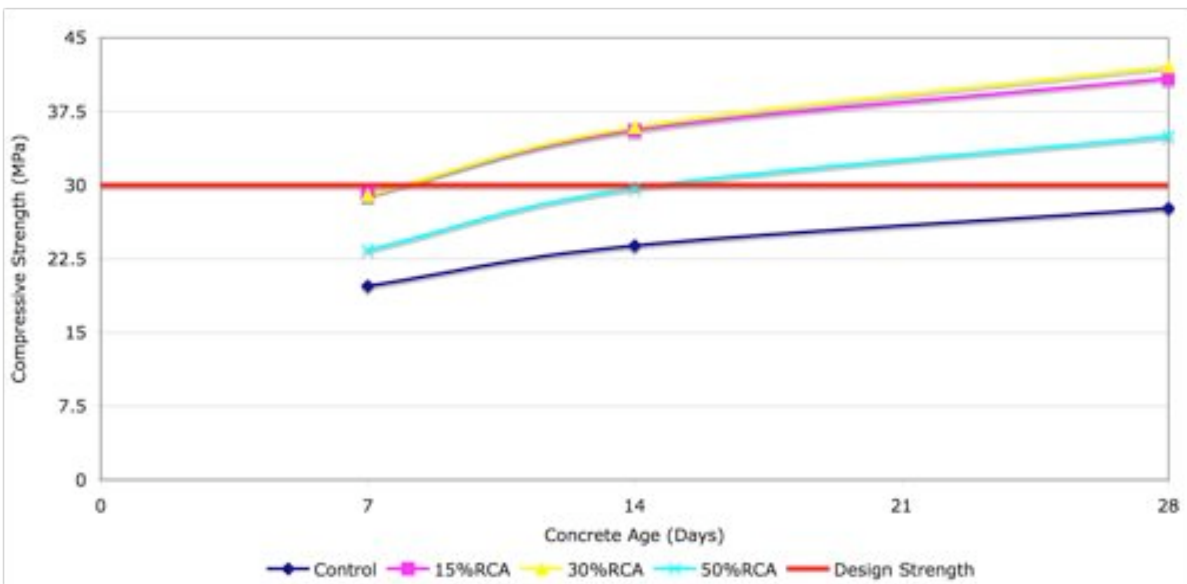

Figure 5. Compressive Strength Development

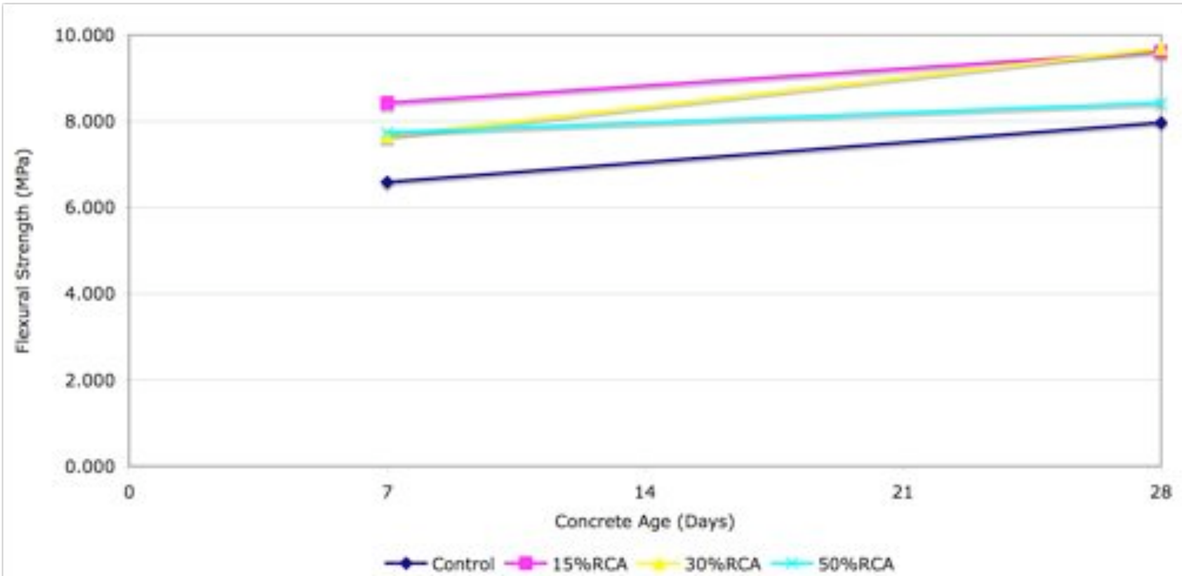

Figure 6. Flexural Strength Development

Figure 7. Test Section PCI Photos – Apr. 2, 2008