FIELD TESTING AND EVALUATION OF RECLAIMED MATERIALS AS AGGREGATE FOR OPSS GRANULAR B TYPE II

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ABSTRACT

In urbanized regions of Ontario, the road construction industry faces a number of challenges due to the growing scarcity of locally-sourced natural aggregate materials and increased restrictions on the approval and development of new aggregate extraction sites. In an effort to maintain sustainable and economical sources of construction aggregates, companies are increasingly seeking to supplement or replace natural aggregates with available artificial materials such as crushed reclaimed concrete aggregate (RCA), and reclaimed asphalt pavement (RAP).

Currently, Ontario Provincial Standard Specification (OPSS) 1010 permits the use of processed reclaimed construction materials in a variety of road base, subbase and asphaltic concrete layers, with the exception of Granular B Type II, which is a higher-performance subbase specification that solely allows primary materials produced from crushed bedrock. Consequently, there is a need to better understand the performance of reclaimed materials as alternative aggregates in Granular B Type II.

This paper focuses on a field testing program carried out at two job sites in Ontario. This testing program assessed five different aggregate blends conforming to Granular B Type II gradation requirements which vary in composition from 100% natural crushed rock to 100% processed RCA. Test pads were constructed from each blended material to assess field compactibility using a nuclear density gauge and to determine the in-situ moduli of the compacted materials using a portable lightweight deflectometer (LWD). The field testing results indicate that RCA and RAP can be successfully utilized as aggregate materials in Granular B Type II subbase applications.

Keywords: granular fill, aggregate recycling, reclaimed concrete, reclaimed asphalt, subbase, field testing

1. INTRODUCTION

Ontario Provincial Standards Specification (OPSS) 1010, Material Specification for Aggregates – Base, Subbase, Select Subgrade, and Backfill Material, contains material requirements for a wide variety of aggregate products utilized in the construction of road base and subbase layers. Among these requirements, OPSS 1010 permits the use of several types of recycled or reclaimed materials, including recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP) in a number of designated classes of aggregate subbase products, including Granular B Type I and Granular B Type III. However, at present, RCA and RAP materials are prohibited from use in Granular B Type II mixes, as this specification is intended for higher-performance applications and prohibits the use of materials other than 100% crushed bedrock, talus, iron blast furnace slag, or nickel slag.

Granular B Types I and III consist of uncrushed materials derived from surficial sand and gravel deposits. Granular B Type III is specified where it is cost effective to avoid problematic uniformly-graded fine sands. Granular B Type II is a 100% crushed high stability material that is primarily specified by MTO in areas where surficial deposits are scarce or in conjunction with grading contracts where excess materials are generated from rock excavations.

As aggregate production pits and quarries progress through and complete their operational lifespans, and as the zoning and application process for new aggregate extraction sites in Ontario grows more restrictive over time, there is a need to continue to characterize and develop sources of reclaimed materials as a sustainable alternative to natural aggregates. Materials such as RCA and RAP are readily available in large quantities in urbanized regions of Ontario as potential alternative materials in pavement structural layers. Consequently, there is a need to examine, assess and validate the performance of RCA and RAP in a variety of potential alternative applications, including as potential replacements for quarried rock in Granular B Type II road subbase materials.

2. OBJECTIVE AND SCOPE

The objective of this project and of the testing described in this paper is to evaluate the performance of reclaimed materials meeting the particle size and physical quality requirements of OPSS 1010 for Granular B Type II unbound subbase mixes as an alternative to the use of quarried rock (either in whole or in part). The study has included the evaluation of five mixes of differing volumetric proportions of crushed bedrock, crushed RCA and processed RAP in the following combinations from two different source locations:

- 100% natural crushed bedrock (used as a control mix);
- 25% crushed RCA blended with 75% crushed bedrock;
- 50% crushed RCA blended with 50% crushed bedrock;
- 100% crushed RCA; and
- 70% crushed RCA blended with 30% crushed RAP.

The field testing program consisted of the construction and compaction of a set of five test pads at two separate test sites, with each pad containing both a lower control layer consisting either of OPSS 1010 Granular A unbound base material or existing compacted granular fill, and a top layer consisting of one of the five proposed subbase mixes under examination (differing for each test pad). Density testing and lightweight deflectometer (LWD) testing was carried out on each layer of each test pad. Samples of the Granular B Type II mixes were taken from the stockpiles on site prior to compaction and from the test pads after compaction for a laboratory testing program which is not detailed in this paper.

3. LITERATURE REVIEW

A number of previous studies conducted in Ontario and elsewhere in North America and around the world have examined the impact and viability of RCA and/or RAP as constituent materials of unbound granular layers in the pavement structure. The use of crushed, reclaimed materials such as asphaltic concrete and hydraulic cement concrete as acceptable substitutes for natural mineral aggregates is well established in Ontario. OPSS 1010 allows the use of 100% RCA and up to 30% RAP in a number of unbound granular base and subbase pavement layers for infrastructure projects. However, the specification does not allow RCA or RAP to be used in Granular B Type II, a road subbase material 100% derived from quarried bedrock.

As a recent example of the successful use of recycled materials in Ontario municipal infrastructure projects, a paper by Moore, Jagdat, Kazmierowski and Ng (2014) presented to the Transportation Association of Canada (TAC) examined a case study of a six kilometre long section of Ontario Highway 7 running between the Town of Richmond Hill and the City of Markham in the Regional Municipality of York. This stretch of Highway 7 was being reconstructed to include an at-grade centreline bus rapid transit right-of-way incorporating RCA into its granular base and subbase layers. The authors analyzed the results of a number of standard granular laboratory tests and concluded that, with proper quality control practices during crushing and manufacturing, RCA is a viable and economical solution for conserving high-quality natural aggregates and can be used successfully as replacement material in granular subbase layers.

In a 1989 MTO report, Hanks and Magni completed a field and laboratory study investigating the use of recovered bituminous material (RBM, another term for RAP) in crushed rock granular base material, both pulverized in-situ as well as processed and blended at the aggregate source. Laboratory data indicated that the strength of the blended product will be of the same order as that of a standard naturally-sourced granular material, and may increase with time. The permeability of the blended granular materials was found to be of the same order as compacted natural granular materials and, in some cases, higher. The authors recommended that contracts to be constructed in the near future should use a maximum of 30 percent RBM (RAP) content based on the California Bearing Ratio (CBR) performance values in the study. By contrast, granular materials blended with greater than 30 percent RAP were found to have much lower CBR results.

A later MTO report by Senior, Szoke and Rogers (1994) to the International Road Federation and TAC addresses the use of RAP in Ontario along with other reclaimed materials including steel slag, glass, ceramic whiteware (porcelain), brick and crumb rubber. The report notes that RAP has been in use in Ontario since 1971 and has been successful at a variety of percent content levels and in a number of paving applications including direct recycling into new asphalt and unbound applications such as the construction of highway shoulders. This report also notes that the presence of RAP tends to lower the maximum compacted density of granular fill, increases the optimum moisture content for compaction, lowers the material's California Bearing Ratio (CBR) and, depending on the amount of fine material in the RAP gradation, can negatively impact permeability of the granular material, necessitating tight control over the consistency of the RAP utilized in any given project.

Outside of Ontario's borders, a synthesis of current practices by the Transportation Research Board's National Cooperative Highway Research Program (2013) includes sections on the use of reclaimed materials in the pavement structure. The report states that RAP performance is comparable to that of a crushed stone base, though concerns remain about lower bearing capacities and the potential for the aggregate to expand during aging and oxidation similar to metal slag. The report also notes the feasibility of the use of RCA as a substitute aggregate, while mentioning a number of areas where processed reclaimed concrete materials typically differ from conventional natural aggregates, such as increased absorption capacity, lower specific gravity and high angularity. The authors go on to stress the need for strong quality control practices during the production of RCA as well as testing to confirm its performance when used in construction projects.

Two similar documents by the United States Department of Transportation's Federal Highway Administration (2010) and the Recycled Materials Resource Center at the University of New Hampshire (2008) both note that the use of RCA as a cost-effective aggregate substitute in pavement construction is well-established for a variety of potential applications. Both organizations note a number of areas in which the physical properties of RCA differ from natural aggregates, including RCA generally having a rougher surface texture, lower specific gravity and higher water absorption than similarly-sized natural aggregate particles, with a corresponding increase in water absorption for RCA relative to natural materials in finer sizes of crushed aggregates. Both guidelines state that although variations in RCA can readily occur due to differences between the types of concrete being processed, RCA overall has favourable mechanical properties including good abrasion resistance, soundness characteristics and bearing strength.

An earlier report by Kuo, Mahgoub, Ortega, Chini and Monteiro (2001) to the Florida Department of Transportation included examination of RCA through a variety of field and laboratory tests, and concluded that RCA can be used effectively as a base course material as long as strong quality control techniques are applied during its manufacture, mixing and placement. The authors went on to specify a number of recommended guidelines for the use of RCA in roads within the state of Florida.

In a more global context, two papers by Aurstad, Asknes, Dahlhaug, Berntsen and Uthus (date at least 2004) and Aurstad, Berntsen and Petkovic (date at least 2006) examine the use of RCA in a field trial of a segment of the major Highway E6 south of Trondheim, Norway. These reports analyzed a range of field and laboratory tests on the granular materials incorporating RCA in the project and found good mechanical strength properties including bearing capacity, shear strength, elastic stiffness (modulus) and resistance to in-situ deformation. Both papers noted the high absorption and optimum water content of RCA and stressed the need for abundant water addition during construction to improve workability and compaction and to guard against crushing and disintegration during the construction process. It was also noted that field bearing capacity measurements taken later after construction of the highway segment yielded increased stiffness values for the test sections constructed using RCA.

An earlier report by Yeo and Sharp (1997) to the State Road Authority of Victoria (VicRoads) in Australia examined the existing standard specifications in force at the time for RCA as well as a laboratory-based study which investigated the properties of RCA stabilized using cementitious binders. The report noted that RCA had been used successfully in Australia for some time as of the date of writing, and also recommended the use of blends of ground blast furnace slag with either lime or Portland cement as effective binders in mixes incorporating RCA.

4. FIELD TESTING

4.1 Test Section Construction

Two test sites were selected for the field tests detailed in this paper and are designated as follows:

- Quarry 1: Moodie Drive Quarry, R.W. Tomlinson Ltd., Ottawa, ON; and
- Quarry 2: Nelson Quarry, Nelson Aggregate Co., Burlington, ON.

Both quarries produce aggregates from Paleozoic carbonate bedrock and sell OPSS granular base and subbase products along with recycled granular base and subbase materials incorporating RCA and RAP. At each test site, five different subbase products (described previously in Section 2) were blended and stockpiled adjacent to the locations where the test pads were to be built. Approximately 300 tonnes of each material was produced and each aggregate supplier performed gradation and physical characteristics tests on each manufactured material to evaluate against and confirm compliance with the OPSS 1010 Granular B Type II specifications.

At Quarry 1, the test mixes were blended on site utilizing natural material sourced from the quarry itself, RAP sourced from local parking lots, roads and highways (excluding premium "FC2" friction course material) crushed to 12.5 mm and below, and RCA from a variety of sources (excluding concrete wash-out material) crushed to 50 mm and below. Granular B Type II material was produced in accordance with the OPSS 1010 specification. The mixing process took place after the materials were crushed separately and was completed using a front-end loader keeping to the test mix proportions specified in Section 2 by counting filled buckets from each material and blending until visually consistent. During construction of the test pads, Granular A base material was placed and compacted as a lower layer 150 mm in thickness underneath the Granular B Type II test material. The purpose for placing a lower layer of Granular A material was to provide consistent subgrade conditions for the test pad sections, as well as a cushion on top of the exposed bedrock upon which the test materials were being constructed so as to minimize the potential for prematurely shattering stone aggregate in the test materials due to the highly rigid underlying bedrock.

At Quarry 2, the test mixes were blended on site utilizing natural material sourced from the quarry itself, RAP sourced from local municipal roads and parking lots, and RCA sourced from demolished bridge and curb concrete material. Natural rock was blended with RCA and RCA was blended with RAP using a front-end loader by keeping count of the number of filled buckets to match the proportions as described in Section 2 above. Each blended material was then subsequently processed though the crusher to meet OPSS 1010 gradation requirements for Granular B Type II. Prior to construction of the test pads, a granular layer of indeterminate thickness existed at the test location, necessitating localized fine grading and compaction to prepare the site for the test pads. This granular layer consisted of an existing compacted haul road and surrounding previously-compacted fill forming the floor of the aggregate pit. As local bedrock was not in proximity to the working surface, additional placement of Granular A was considered unnecessary, except where needed to level out irregularities in the immediate test area.

For both quarries, asphalt-coated particle content and deleterious material content testing was performed on each test mix to confirm compliance with the selected test blends and with OPSS 1010 specifications. In total, five (5) test pads were constructed at each test site, each using one of the five individual Granular B Type II test mixes listed previously. Each test pad measured approximately 40 metres in length and 3 metres in width, and the compacted lift thicknesses were set at 150 mm for the Granular A lower layers (placed solely at Quarry 1) and 300 mm for the Granular B Type II test mix top layers. A standard single steel drum roller with vibration active was utilized at each test site to compact each test pad. The layouts of each test quarry site can be seen in Figures 1 and 2.

Figure 1: Overview of test pads and stockpiles at Quarry 1

Figure 2: Overview of test pads and stockpiles at Quarry 2

4.2 Testing Procedure

Dry density measurements were completed using a calibrated nuclear densometer. The Granular A lower layer placed at Quarry 1 was measured to ensure it was properly compacted to maximum dry density prior to the placement of the Granular B Type II test materials and the densometer probe was set to a depth of 100 mm. During the compaction of the test materials, the nuclear densometer probe was set to a depth of 250 mm for the Granular B top layers. The density measurements were obtained at points spaced five (5) metres apart along the centerline of each pad, corresponding to locations where deflectometer measurements were subsequently taken. Density measurements were taken after each roller pass and were stopped after it was determined that there was no further significant increase in dry density measurements. Water was also added before and after each pass of the vibratory roller when it was deemed necessary based on the appearance of the compacted material, or when the moisture content readings from the nuclear densometer indicated that it was lower than expected for the test mix.

A Dynatest Keros Prima 100 portable falling weight deflectometer (FWD), commonly known as a lightweight deflectometer (LWD), was utilized to measure deflection after compaction at the surface of the Granular A base layer and at the surface of the Granular B Type II layer in each test pad. Seven test points were completed on each test pad, spaced five (5) metres apart along the pad centerline. At each test point, a number of measurements were taken in succession; typically, the first one to three measurements were anomalous and were discarded due to the need to allow the LWD to seat itself properly on the compacted granular material. Once relatively consistent measurements were obtained, a minimum of five successful drops were conducted at each test point in order to obtain average deflection and loading values with which to determine the surface modulus of the compacted material in the field.

5. RESULTS AND DISCUSSION

5.1 Density and Compaction Results

At Quarry 1, the 100% crushed rock Granular B Type II control material required between 5 to 7 roller passes to achieve maximum field compaction, whereas the different test blends of crushed rock with RCA and RCA with RAP required 4 to 8 roller passes to achieve maximum field compaction. At Quarry 2, the 100% crushed rock Granular B Type II control material again required between 5 to 7 roller passes to achieve maximum field compaction, whereas the different test blends of crushed rock with RCA and RCA with RAP required 3 to 8 roller passes to achieve maximum field compaction.

Standard and modified Proctor testing was conducted separately on each test blend from each quarry. These results are summarized and compared to the average final moisture contents and dry densities determined by the nuclear gauge compaction testing on site.

Table 1: Comparison of field compaction results to Proctor testing results

Test Blend	Standard Optimum Moisture Content (%)	Standard Maximum Dry Density (kg/m^3)	Modified Optimum Moisture Content (%)	Modified Maximum Dry Density (kg/m^3)	Average Final Field Moisture Content (%)	Average Final Field Dry Density (kg/m^3)
Quarry 1 - 100% Crushed Rock	4.4	2250	3.6	2344	2.6	2274
Quarry 1 - 25% RCA - 75% Crushed Rock	7.2	2201	6.4	2241	5.3	2131
Quarry 1 - 50% RCA - 50% Crushed Rock	8.1	2144	7.5	2200	6.0	2042
Quarry 1 - 100% RCA	11.5	2055	9.8	2130	5.4	2024
Quarry 1 - 70% RCA - 30% RAP	8.5	2094	7.8	2184	10.6	1953
Quarry 2 - 100% Crushed Rock	5.7	2183	4.9	2375	3.5	2286
Quarry 2 - 25% RCA - 75% Crushed Rock	6.1	2231	5.7	2285	5.9	2217
Quarry 2 - 50% RCA - 50% Crushed Rock	6.6	2135	6.4	2188	6.6	2052
Quarry 2 - 100% RCA	8.4	1983	7.9	2077	8.7	1973
Quarry 2 - 70% RCA - 30% RAP	6.2	2025	6.0	2125	8.4	1925

It can be noted from Table 1 that both the field and laboratory optimum moisture content and dry density results vary, sometimes significantly, between Quarry 1 and Quarry 2. This is to be anticipated as the physical characteristics of the crushed rock, RCA and RAP materials, the individual test mix gradations and the existing subgrade conditions will naturally differ between quarries located in separate and distinct regions of Ontario.

In addition, the average final field densities determined on site are generally similar to or lower than the maximum densities predicted by the standard Proctor test, while the average final field moisture contents for each pad are generally lower than or similar to both the standard and modified Proctor results, with the exception of the 70% RCA - 30% RAP test blends, where the field moisture contents were elevated compared to the Proctor results. It is theorized that this is a function of standard practices governing Proctor testing, which mandate the removal of oversized particles and replacement of these particles with finer material. This would have a significant effect on the consistency of Granular B class materials, which under OPSS 1010 are permitted to have up to 50% by mass of their material greater than 26.5 mm in size.

5.2 Lightweight Deflectometer Results

As described in Section 4.2, a portable lightweight deflectometer (LWD) unit was used to obtain loading and deflection values for the Granular A and Granular B Type II layers in the test pads at each field test site. The in-situ moduli were calculated using Equation 1, from Boussinesq's theory for an elastic half-space assuming a rigid plate:

[1] $$E = \frac{\pi\left(1-\nu^2\right)r\sigma_0}{2d_1}$$

Where:

- E = material modulus (MPa);
- ν = Poisson's ratio (assumed to be 0.35 for a subbase material);
- r = radius of the LWD loading plate (150 mm);
- σ_0 = maximum applied stress (kPa); and
- d_1 = maximum deflection under the plate center (μm).

The in-situ material moduli were calculated for each LWD test point on each pad and average, minimum and maximum in-situ moduli and standard deviations were calculated for each test pad at Quarry 1 and Quarry 2. These values are shown below in Table 2.

Table 2: Granular material moduli calculated from LWD measurements

		Granular A / Fill Lower Layer				Granular B Type II Top Layer				
Site	Pad	Avg. (MPa)	Std. Dev. (MPa)	Min. (MPa)	Max. (MPa)	Avg. (MPa)	Std. Dev. (MPa)	Min. (MPa)	Max. (MPa)	Test Mix
Quarry 1	#1	97.5	13.8	66.8	124.1	85.3	8.0	64.7	99.4	100% crushed rock
Quarry 1	#4	103.2	15.0	67.2	131.6	79.6	11.0	57.7	96.4	25% RCA - 75% rock
Quarry 1	#3	91.5	26.3	50.4	143.7	60.4	12.6	38.0	78.8	50% RCA - 50% rock
Quarry 1	#2	91.2	8.8	74.0	104.9	59.9	6.1	47.7	73.6	100% RCA
Quarry 1	#5	98.3	15.0	63.2	123.3	75.9	9.7	52.2	93.7	70% RCA - 30% RAP
Quarry 2	#1	100.2	32.0	63.0	172.3	73.0	19.2	39.5	109.3	100% crushed rock
Quarry 2	#4	227.5	76.0	85.9	339.5	85.3	12.9	62.9	108.6	25% RCA - 75% rock
Quarry 2	#5	125.6	35.6	64.2	188.0	62.1	23.3	23.7	92.2	50% RCA - 50% rock
Quarry 2	#2	133.3	63.7	61.7	267.7	64.6	16.5	26.5	88.0	100% RCA
Quarry 2	#3	119.8	37.9	72.9	185.0	81.1	20.9	47.0	124.0	70% RCA - 30% RAP

A visual representation and comparison of the test pad average in-situ moduli and single standard deviations for the Granular B Type II test blend layers is shown in Figure 3.

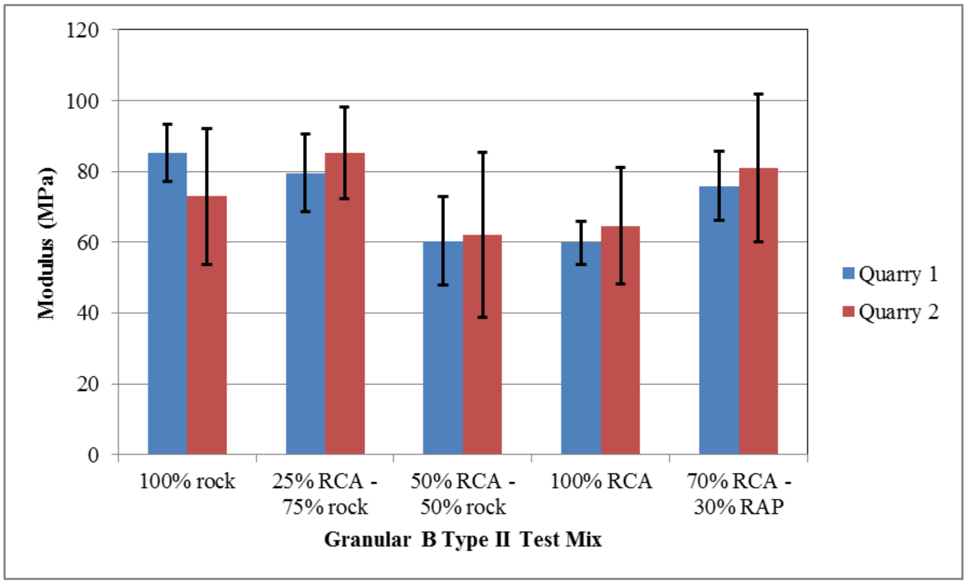

Figure 3: Granular B Type II test pad LWD moduli mean values and standard deviations

At Quarry 1, the average compacted in-situ moduli for the compacted test materials appear to generally be lowest for the 100% RCA and 50% RCA - 50% crushed rock mixes relative to the 100% crushed rock, 25% RCA - 75% crushed rock, and 70% RCA - 30% RAP test mixes. Both of the Granular B Type II layers where the lowest average results occurred also had the lowest average in-situ moduli in the underlying 15 cm thick Granular A layers.

At Quarry 2, the 25% RCA - 75% crushed rock and 70% RCA - 30% RAP mixes were found to have higher in-situ moduli on average than the respective 100% crushed rock control material. Correspondingly, the 50% RCA - 50% crushed rock and 100% RCA test mixes showed lower average in-situ moduli compared to the control material test pad. It should, however, be noted that the elevated average modulus for the compacted 25% RCA - 75% crushed rock test mix at Quarry 2 occurred in a test pad that also exhibited an unusually high average in-situ modulus for the underlying existing granular fill layer, which showed high variability at all Quarry 2 test pads.

The greater variability at Quarry 2 relative to Quarry 1 may possibly result from differences in control and compaction of the test pad layers between both quarries. The test pads at Quarry 1 were constructed with the Granular A base layer in each test pad placed and compacted directly on top of the bedrock prior to the addition and compaction of the Granular B Type II test materials. By contrast, Quarry 2 utilized an existing granular haul road as the working area for the construction of the test pads. As described in Section 4.1, localized grading and compacting was conducted to level the test pad locations at Quarry 2 prior to adding the Granular B Type II test materials. The existing haul road materials appeared inconsistent in both composition and gradation and would have been subject to highly variable compaction and intermittent disturbances over the entire operational lifespan of the local portion of Quarry 2. Additional variation in both the existing road granular material and the Granular B Type II test materials at Quarry 2 may have been introduced due to local rainfall which occurred on the days leading up to the test pad construction as well as on the morning of the field test.

A standard Student's *t*-test was performed on the LWD in-situ modulus results, comparing the samples of 35 measurements used to determine the pad averages and standard deviations seen in Table 2 and Figure 3. Each pad was evaluated separately against the four other pads at the same quarry location. The *t*-test was performed assuming independent samples, different variances for each sample and a two-tailed distribution (also known as Welch's *t*-test) to evaluate the percentage probability that the samples compared are statistically identical to one another. The results of this *t*-test are presented in Tables 3 and 4.

Table 3: Student's *t*-test results for LWD measurements at Quarry 1

Test Mix	100% Crushed Rock	25% RCA - 75% Rock	50% RCA - 50% Rock	100% RCA	70% RCA - 30% RAP
100% Crushed Rock	*n/a*	1.53%	0.00%	0.00%	0.00%
25% RCA - 75% Rock	-	*n/a*	0.00%	0.00%	14.42%
50% RCA - 50% Rock	-	-	*n/a*	84.16%	0.00%
100% RCA	-	-	-	*n/a*	0.00%
70% RCA - 30% RAP	-	-	-	-	*n/a*

Table 4: Student's *t*-test results for LWD measurements at Quarry 2

Test Mix	100% Crushed Rock	25% RCA - 75% Rock	50% RCA - 50% Rock	100% RCA	70% RCA - 30% RAP
100% Crushed Rock	*n/a*	0.25%	3.63%	5.48%	9.41%
25% RCA - 75% Rock	-	*n/a*	0.00%	0.00%	31.53%
50% RCA - 50% Rock	-	-	*n/a*	60.22%	0.06%
100% RCA	-	-	-	*n/a*	0.05%
70% RCA - 30% RAP	-	-	-	-	*n/a*

At Quarry 1 there were few pairings of pad samples that indicated significant probabilities of being statistically identical. The greatest similarity was seen between the LWD measurements taken from the 50% RCA - 50% crushed rock and 100% RCA test mix pads, with a lower probability associated with the pairing of the 25% RCA - 75% crushed rock and 70% RCA - 30% RAP test blends. At Quarry 2, the calculated probabilities tended to be higher in general, coinciding with greater variability in LWD results for that quarry shown in Table 2 and Figure 3. The highest probabilities of statistical similarity occurred between the same pairings noted for Quarry 1, while lower percentage probabilities existed between the 100% crushed rock control mix and the test blends incorporating 50% to 100% RCA.

It is unclear whether the statistical difference between mixes across Quarry 1 and Quarry 2 indicated by the Student's *t*-test is or is not conclusive as to whether the lower average in-situ moduli measured by the LWD for the 50% RCA - 50% crushed rock and 100% RCA test mixes is characteristic of these blends. Mixes produced at other quarries may differ depending on the concrete recycled in different areas and facilities. The LWD apparatus itself may also be highly sensitive to localized variations in the material upon which it sits.

Previous studies have also noted the high variability of in-situ modulus results using LWD testing and expressed the need for caution when using the LWD to examine the stiffness of pavement layers. Volovski, Arman and Labi (2014) noted that such a level of variability was observed across different LWD contact locations, even locations with the same material type, that it was not possible to guarantee that measurements obtained from a limited number of test sections could be transferred with confidence to another site of the same material type. In an earlier report, Hossain and Apeagyei (2010) investigated the suitability of the LWD in measuring in-situ pavement layer moduli and recommended that LWD testing should not be used for construction quality control until further research could be conducted to determine the underlying causes of the high spatial variability on moduli measured using an LWD and the effect of moisture content on the same results.

6. CONCLUSIONS

Based on the field testing completed, it can be observed that the subbase materials incorporating RCA and RAP demonstrated similar field compaction capability to 100% crushed rock, in some cases requiring fewer roller passes than the crushed rock control mix to achieve their respective maximum compacted field densities. Moisture content and dry density values for field compaction varied between the two test sites and may be a function of the physical characteristics of the crushed rock, RCA and RAP materials, the individual test mix gradations, and the differing subgrade conditions in existence at each quarry. Testing using the lightweight deflectometer (LWD) indicated that mixes using elevated levels of RCA (50% to 100%) and crushed rock resulted in generally lower in-situ moduli of compacted subbase layers compared to 100% crushed rock and blends of 70% RCA - 30% RAP and 25% RCA -

75% crushed rock. However, it should be noted that the LWD field measurements can be subject to substantial variability depending on local physical and hydrogeological conditions, as experienced in Quarry 2.

Further analysis and reporting work will continue in order to incorporate the results of the laboratory testing programme not detailed in this paper. This evaluation work is intended to lead to recommendations on the expanded use of RCA and RAP in Granular B Type II class materials in the province of Ontario.

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