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, efficient 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 laboratory testing program which examined five different aggregate blends conforming to Granular B Type II gradation requirements which vary in composition from 100% natural crushed rock to 100% processed reclaimed material. The granular materials in the study were sampled before and after construction of test pads at two job sites in Ontario. These samples were analyzed via sieve gradation, standard and modified Proctor, permeability, California Bearing Ratio (CBR) and resilient modulus (M_R) test procedures. The testing results indicate that RCA and RAP can be successfully utilized as aggregate materials in Granular B Type II subbase applications.

INTRODUCTION

Ontario Provincial Standard Specification (OPSS) 1010, Material Specification for Aggregates – Base, Subbase, Select Subgrade, and Backfill Material, contains 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 only permits the inclusion of 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 lifespan, 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 urbanized regions of Ontario in large quantities as a potential alternative material in road structure 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.

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 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 final test blend listed above, comprising 70% RCA with 30% RAP, departs from the trend of the other four blends, which solely incorporate natural crushed rock and RCA. This was selected as an alternative in order to explore the effects of adding RAP to Granular B Type II, as OPSS 1010 permits the incorporation of up to 30% RAP by mass in Granular B Types I and III.

A field testing program was conducted which consisted of the construction, compaction and examination of a series of five test pads at two separate test sites. This program is not included in this paper, but during the field study procedure, samples of each of the five specified mixes at each site were taken from the material stockpiles prior to compaction and from the test pads after compaction for the purposes of the laboratory tests detailed below.

The laboratory testing program consisted of a series of procedures including grain size distribution analysis tests, standard and modified Proctor tests, permeability tests, California Bearing Ratio (CBR) tests and resilient modulus tests. These tests were carried out a specified number of times on each Granular B Type II mix from each of the two test sites. The above laboratory test procedures were conducted in accordance with the applicable current Ontario Ministry of Transportation (MTO) Laboratory Testing Manual (LS) test methods and American Association of State Highway and Transportation Officials (AASHTO) test methods.

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 recent 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 centerline 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.

TEST MIX BLENDING AND SAMPLING

Two field sites were selected for this study 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 1010 granular base and subbase products including materials incorporating RCA and RAP. At each test site, the five specified test mixes were blended and stockpiled adjacent to the locations where the test pads were to be built. Approximately 300 tonnes of each material was produced at each quarry, and both aggregate suppliers performed gradation and limited physical characteristics testing on each produced material to evaluate against and confirm compliance with 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 50 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 specified test mix proportions by counting filled buckets from each material and blending until visually consistent. A quantity of Granular A base material was also produced separately for use as a lower layer during the test pad construction process to provide a consistent cushion layer on top of the exposed bedrock upon which the test pads 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 and sidewalk 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 specified mix proportions. Each blended material was then subsequently processed though the crusher to meet OPSS 1010 gradation requirements for Granular B Type II. In contrast to Quarry 1, a granular layer of indeterminate thickness already existed at the field test location in Quarry 2, and so only fine grading with a limited amount of additional granular fill was required to provide a level base layer for the test pads.

A front-end loader was utilized at each quarry in obtaining all required samples. Prior to test pad compaction, a sampling pad was created at each stockpile and one or more samples were taken for grain size analysis testing along with multiple other samples for physical characteristics testing on each mix. After test pad construction was complete, four samples were taken from each test mix layer in each pad for post-compaction gradation determinations.

The following laboratory performance tests were conducted on each Granular B Type II mix specified above from both Quarry 1 and Quarry 2. With the exception of the grain size analysis and physical characteristics tests carried out through the aggregate suppliers, these procedures were completed at the Lafarge Canada Inc. (a member of LafargeHolcim) Innovation and Training Centre (ITC), located at 54 Polson Street in Toronto, Ontario.

GRAIN SIZE ANALYSIS AND PHYSICAL CHARACTERISTICS

Gradation and physical characteristic tests of each test material at each test site were completed by the quarry owner or contractor completing the test sections. Grain size testing and analysis was completed in accordance with MTO specification LS-602, Method of Test for Sieve Analysis of Aggregates. The average gradation prior to compaction (comprising one to three samples) was compared to the average gradation after compaction (comprising four samples) for each test material at each test site. The percentage changes via compaction of material passing certain sieves in the grain size distribution are shown below in Tables 1 and 2.

At Quarry 1, the 100% crushed rock and 100% RCA test mix gradations indicate that there is a tendency to further break down during roller compaction. The 100% crushed rock test mix had an increase of 1.5 percent in the material passing the 75 µm sieve after compaction. However, the 100% RCA test mix and the blended materials using crushed rock with RCA and RCA with RAP show only a slight increase in the material passing the 75 µm sieve.

At Quarry 2, the 100% crushed rock test mix shows a tendency to break down further during roller compaction. The 100% crushed rock had an increase of 1.9 percent in the material passing the 75 µm sieve after roller compaction. However, the 100% RCA test mix and blended materials using crushed rock with RCA and RCA with RAP show minimal degradation due to roller compaction.

TABLE 1 Trans-Compaction Change in Percent Passing Sieve Sizes for Quarry 1 Mixes

Sieve Size (mm)	Test Mix Blend				
	100% Crushed Rock	25% RCA – 75% Crushed Rock	50% RCA – 50% Crushed Rock	100% RCA	70% RCA – 30% RAP
150	0.0	0.0	0.0	0.0	0.0
106	0.0	0.0	0.0	0.0	0.0
26.5	6.4%	4.3%	- 1.4%	3.6%	4.9%
9.5	4.6%	5.6%	- 1.5%	6.7%	1.5%
4.75	3.9%	4.3%	- 0.8%	6.0%	0.8%
2.36	4.9%	2.6%	- 0.4%	2.8%	- 0.3%
1.18	4.1%	1.6%	0.0	1.1%	- 0.1%
0.600	3.1%	1.0%	0.6%	0.4%	0.5%
0.300	2.5%	0.7%	1.1%	0.4%	0.8%
0.150	2.0%	0.6%	1.0%	0.5%	0.6%
0.075	1.5%	0.5%	0.7%	0.5%	0.4%

TABLE 2 Trans-Compaction Change in Percent Passing Sieve Sizes for Quarry 2 Mixes

Sieve Size (mm)	Test Mix Blend				
	100% Crushed Rock	25% RCA – 75% Crushed Rock	50% RCA – 50% Crushed Rock	100% RCA	70% RCA – 30% RAP
150	0.0	0.0	0.0	0.0	0.0
106	0.0	0.0	0.0	0.0	0.0
26.5	2.6%	3.0%	- 3.1%	2.8%	- 1.1%
9.5	7.7%	2.8%	- 0.8%	- 0.1%	0.1%
4.75	7.5%	2.8%	0.9%	- 0.5%	0.0%
2.36	5.3%	1.7%	2.4%	- 1.2%	- 0.4%
1.18	3.9%	0.7%	2.0%	- 1.3%	- 0.1%
0.600	3.0%	0.3%	0.9%	- 0.9%	0.0
0.300	2.4%	0.2%	0.6%	- 0.5%	0.0
0.150	2.1%	0.2%	0.5%	- 0.5%	- 0.2%
0.075	1.9%	0.1%	0.4%	0.1%	- 0.2%

Additional physical properties tests were carried out to confirm compliance with OPSS 1010 requirements for Granular B Type II. Abrasion resistance testing was conducted in accordance with LS-618, Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus, and LS-619, Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. The percentage content of asphalt-coated particles was determined according to LS-621, Amount of Asphalt Coated Particles in Coarse Aggregate, and the percentage content of contaminant particles was examined under LS-630, Amount of Contamination of Coarse Aggregate. The plasticity level of the aggregate was determined in accordance with LS-631, Presence of Plastic Fines in Aggregates.

At Quarry 1, each test material met the Granular B Type II Micro-Deval abrasion loss requirements of OPSS 1010 for coarse and fine aggregates, and percent asphalt-coated particles testing confirmed the approximate 30% RAP content of the respective test mix. All mixes tested for the presence of plastic fines were found to be non-plastic. At Quarry 2, each test material met the Granular B Type II requirements of OPSS 1010 for non-plasticity and for Micro-Deval abrasion loss for coarse and fine aggregates. The 30% RAP content of the single test mix was confirmed and all mixes had minimal to no contaminants present.

STANDARD AND MODIFIED PROCTOR MEASUREMENTS

The standard and modified maximum dry density Proctor tests are used to determine the optimum moisture content and maximum compacted dry density for each material. The difference between the two methods lies in the number of layers in which the material is compacted (three layers for the standard Proctor and five layers for the modified Proctor), the drop height for the Proctor hammer (305 mm for the standard test and 457 mm for the modified test) and the weight of the hammer (2.5 kg for the standard test and 4.5 kg for the modified test). All these factors typically contribute to lower optimum moisture contents and higher compacted densities under the modified Proctor test relative to the standard Proctor results. In Ontario, the standard maximum dry density Proctor test is typically conducted on pavements such as roads, highways and parking lots, whereas modified maximum dry density Proctor tests are typically conducted on pavements such as major airports and port facilities. The modified Proctor test was not specifically required for this testing program, but was included in order to further characterize the test mixes and their responses to greater compactive effort.

The standard Proctor test was conducted in accordance with MTO specification LS-706, Method of Test for Moisture-Density Relationship of Soils Using 2.5 kg Rammer and 305 mm Drop, and the modified Proctor test was conducted in accordance with LS-707, Method of Test for Moisture-Density Relationship of Soils Using 4.5 kg Rammer and 457 mm Drop. For the purposes of these tests, a mechanical Proctor hammer apparatus was used to aid in ensuring consistent compaction of the test materials at 56 blows per layer under both the standard and modified conditions. Cylindrical metal moulds of 150 mm diameter were used in the Proctor tests, and any oversized particles in the test samples 26.5 mm in size or greater were removed and replaced with a blend of finer particles from the same test mix ranging from 26.5 mm to 4.75 mm, in accordance with the LS-706 and LS-707 test procedures.

The standard and modified Proctor test results for each test mix are summarized in Table 3. These results are also compared to the final field dry density and moisture content averages for each test pad, as determined by the field testing program which was carried out separately at Quarry 1 and Quarry 2.

The laboratory test results seen in Table 3 reflect the general expectation that greater compaction efforts seen in the modified Proctor test yield lower optimum moisture contents and higher compacted dry densities relative to the standard Proctor test. Furthermore, as the percentage content of RCA increases, the standard and modified optimum moisture contents also increase and the respective optimum dry densities decrease, in accordance with the higher absorption characteristics and lower bulk density of crushed concrete relative to natural aggregate noted by a number of studies reviewed earlier in this paper. No absorption or petrographic testing was carried out on the test mixes from Quarry 1 and Quarry 2, although percent RAP content testing was completed on each mix as noted earlier.

It can also be noted from Table 3 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.

TABLE 3 Standard and Modified Proctor Test Results

Test Mix Blend	Standard Optimum Moisture Content	Standard Maximum Dry Density	Modified Optimum Moisture Content	Modified Maximum Dry Density	Average Final Field Moisture Content	Average Final Field Dry Density	Difference Between FFDD and SMDD
	(%)	(kg/m^3)	(%)	(kg/m^3)	(%)	(kg/m^3)	(kg/m^3)
Quarry 1 - 100% Crushed Rock	4.4	2250	3.6	2344	2.6	2274	+ 24
Quarry 1 - 25% RCA - 75% Crushed Rock	7.2	2201	6.4	2241	5.3	2131	- 70
Quarry 1 - 50% RCA - 50% Crushed Rock	8.1	2144	7.5	2200	6.0	2042	- 102
Quarry 1 - 100% RCA	11.5	2055	9.8	2130	5.4	2024	- 31
Quarry 1 - 70% RCA - 30% RAP	8.5	2094	7.8	2184	10.6	1953	- 141
Quarry 2 - 100% Crushed Rock	5.7	2183	4.9	2375	3.5	2286	+ 103
Quarry 2 - 25% RCA - 75% Crushed Rock	6.1	2231	5.7	2285	5.9	2217	- 14
Quarry 2 - 50% RCA - 50% Crushed Rock	6.6	2135	6.4	2188	6.6	2052	- 83
Quarry 2 - 100% RCA	8.4	1983	7.9	2077	8.7	1973	- 10
Quarry 2 - 70% RCA - 30% RAP	6.2	2025	6.0	2125	8.4	1925	- 100

For the Quarry 1 test mixes, the field moisture contents to achieve maximum field dry density were generally lower than the optimum moisture contents determined by standard Proctor testing, with the exception of the 70% RCA - 30% RAP blend where the field moisture content was higher than the standard Proctor result for the same blend. The average compacted field dry densities were lower than the optimal dry densities determined by the standard Proctor test, except for the 100% crushed rock control mix, where the field dry density was higher than the standard Proctor density. Furthermore, as the proportion of RCA increased, the resulting standard and modified maximum Proctor density values and final field densities decreased correspondingly.

For the Quarry 2 test mixes, the field moisture contents to achieve maximum field dry density were predominantly similar to optimum moisture contents determined by standard Proctor testing, with the exception of the 100% crushed rock test mix where the field moisture content was lower than the moisture content for the standard Proctor result and the 70% RCA - 30% RAP blend where the field moisture content was higher than the standard Proctor result. The field dry density results were lower than the standard Proctor result for each blend, with the exception of the 100% crushed rock test mix, where the field dry density was higher than the standard Proctor density result for the same material. Similar to Quarry 1, as the proportion of RCA increased, the resulting standard and modified maximum dry density values and final field densities decreased correspondingly.

It is not clearly known why the final dry density and moisture content levels seen in the field trials are generally lower than those predicted by the standard Proctor test. Complete compaction may not have been achieved by the field construction equipment, or insufficient water may have been added to the mix during compaction, leading to sub-optimal dry density. Water may also have been absorbed by the test blend aggregates, both artificial and natural, without contributing to the densification of the Granular B Type II layers.

It is also theorized that, to some extent, the variations seen between the laboratory Proctor results and the field density and moisture content testing results may be a function of the 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. If the processed RCA was produced and added primarily in the form of coarse aggregate, then this oversize removal requirement would have disproportionately shifted the characteristics of the Proctor test samples towards those of natural rock- and soil-derived aggregates, increasing the average density of the blended materials and decreasing their absorption characteristics.

As mentioned earlier in this paper, the standard Proctor density test is typically conducted for pavement structures such as roads, highways and parking lots. When comparing the standard Proctor density and field dry density of the 100% crushed rock control mixes at Quarries 1 and 2 to gradations before and after field compaction, there is a pattern indicating that as the gradation gets finer and there is an increase in material passing the 75 µm sieve, then there is also an increase in the dry density value. However, the field moisture contents decreased in both materials compared to the standard Proctor moisture content results. A comparison of the remaining test blend materials indicates the field dry densities are lower than the standard Proctor densities as measured from materials from both Quarries 1 and 2, even though for the Quarry 1 test blends of 25% RCA with 75% crushed rock and 100% RCA as well as the Quarry 2 test blend of 25% RCA with 75% crushed rock, the field gradations were finer overall but the proportion passing the 75 µm sieve did not increase after field compaction. When reviewing the absolute difference between the average standard Proctor density and the field dry density, the magnitude of the difference is smaller where the field gradation after compaction was finer than the stockpiled material (the Quarry 1 test blends of 25% RCA with 75% crushed rock and 100% RCA and the Quarry 2 test blend of 25% RCA with 75% crushed rock), except for the Quarry 2 100% RCA test material.

PERMEABILITY MEASUREMENTS

One main characteristic of granular subbase materials and layers is their ability to drain water, thus making permeability an important factor to consider. If a reclaimed material has a propensity to break down during processing or compaction, the increased amount of fines present may impede water flow through the material and yield lower overall permeability values than natural aggregates.

The permeability testing was completed in accordance with MTO test method LS-709, Method of Test for Determination of Permeability of Granular Soils. For this study, two permeability tests were conducted on specimens of each Granular B Type II mix from each of the two test sites and the results were combined to obtain an average permeability value for each material. The results of the permeability tests shown below in Table 4 indicate that the Granular B Type II materials tested are all relatively free-draining granular materials, and the increased amount of reclaimed materials has minimal impact on the overall permeability. This property would likely have been aided by the low susceptibility of the reclaimed materials to breakdown during compaction, as noted earlier in this paper.

TABLE 4 Permeability Testing Results

Test Mix Blend	Quarry 1 (cm/s)	Quarry 2 (cm/s)
100% Crushed Rock	1.45E-03	6.65E-03
25% RCA – 75% Crushed Rock	1.02E-03	1.00E-02
50% RCA – 50% Crushed Rock	4.65E-03	8.65E-03
100% RCA	8.95E-04	4.75E-03
70% RCA – 30% RAP	3.30E-03	9.10E-03

CALIFORNIA BEARING RATIO MEASUREMENTS

The California Bearing Ratio (CBR) test is used as a measurement of the bearing capacity of granular materials compared to a reference material. The primary specification for the CBR test is ASTM D1883-14, Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. Each sample was compacted in 150 mm diameter moulds using the mechanical Proctor hammer apparatus with compactive effort equal to the standard Proctor test (three layers each receiving 56 blows of a 2.5 kg hammer with a 305 mm drop) and with moisture content equal to the optimum moisture content determined by the standard Proctor test. During mixing, material retained on the 19 mm sieve was removed and replaced with an equal mass of material from the same mix passing the 19 mm sieve and retained on the 4.75 mm sieve in accordance with the ASTM D1883 procedure. After compaction each sample was subjected to a 4.5 kg surcharge weight while being immersed in water for a period of 96 hours. For this study, two CBR tests were conducted on each Granular B Type II test mix from each of the two test sites, and the results were combined to obtain an average CBR value for each material.

The CBR values seen below in Table 5 are all relatively high, achieving above 100% for most of the Granular B Type II test blends. Furthermore, the blends with high replacement levels of

RCA achieved high bearing capacities which were similar to the control mix, which indicate that the introduction of RCA did not hinder the performance of the subbase material. However, one key observation is the lower CBR values achieved by the blends containing 30% RAP, where the CBR values of the aggregate mixes were lower by 30% to 40% when compared to the majority of the other blends containing solely natural crushed rock and RCA. This effect is generally known in the industry, as RAP particles characteristically tend to attract and hold moisture, which in turn causes RAP particles and fragments to come together to form larger conglomerates. At high RAP concentrations, this can result in segregation and heterogeneity in the mix, leading to problems with constructability and the consequent development of inconsistent strength properties in the compacted granular fill material.

Additionally, it is possible that the replacement of oversize particles that are normally present in Granular B Type II class materials in accordance with the ASTM D1883 procedure may have had an effect on the results of this test, as the altered material would be more similar in composition to a Granular A class material.

TABLE 5 California Bearing Ratio Test Results

Test Mix Blend	Quarry 1 (%)	Quarry 2 (%)
100% Crushed Rock	108.5	94
25% RCA – 75% Crushed Rock	108.5	90
50% RCA – 50% Crushed Rock	114.5	91
100% RCA	107.5	114
70% RCA – 30% RAP	78.5	72

RESILIENT MODULUS MEASUREMENTS

The samples for the resilient modulus test were prepared in accordance with AASHTO T307, Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials. The triaxial test apparatus used in the Lafarge Canada ITC laboratory is a Servo-Hydraulic Universal Testing Machine produced by Cooper Research Technology Ltd. For this study, three specimens were compacted and tested for each Granular B Type II mix from each of the two test sites. Each specimen was compacted by adding the granular test mix to a cylindrical mould 100 mm in diameter and 200 mm in height in a series of six equal layers, with any oversized particles (50 mm or greater in diameter) removed and substituted with finer material from the same mix. The total mass of material for each test specimen was calculated to achieve the maximum dry density as determined in the standard Proctor test, with the moisture content reduced by 1% from the standard optimum moisture content as permitted by AASHTO T307. This reduction from the optimum moisture content is a standard practice with the apparatus at the ITC laboratory in order to achieve the optimum dry density within the compaction mould.

As the six equal layers were added, they were each compacted for a period of two to three seconds using a Bosch 11264EVS handheld combination hammer, with an additional slight downwards pressure applied to keep the vibratory hammer head in contact with the sample. Once all six layers were compacted, the completed sample was removed from the mould, surrounded with an impermeable rubber membrane and placed into the loading cell as seen above in Figure 13. Each test yields a range of resilient modulus values as the apparatus cycles through a pre-programmed standard series of loading stages which vary the levels of applied axial stress and confining pressure on the compacted sample.

For the analysis of resilient modulus triaxial testing results, the data points obtained from the triaxial testing apparatus were fitted to the k_1-k_3 model (Buchanan, 2007) used in the new mechanistic empirical design guide. The following model was used, denoted below as Equation (1), and the method of least squares regression was then used to calculate the values of k_1, k_2 and k_3.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left[\left(\frac{\tau_{oct}}{P_a}\right) + 1\right]^{k_3} \tag{1}$$

Where,

- k_1, k_2, and k_3 = material-specific regression coefficients;
- θ = bulk stress;
- P_a = atmospheric pressure (i.e. 101.3 kPa); and
- τ_{oct} = octahedral shear stress $= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$

For all three test samples of each material from each quarry, at each of the fifteen loading stages contained in the triaxial testing procedure, the bulk stress was determined and the resilient modulus was calculated using the regression coefficients estimated from the raw data and using Equation (1) above. For each set of three tests on each material, the average bulk stress and resilient modulus were determined at each of the fifteen loading stages, and using the average resilient modulus values at each loading stage, the percent deviation was calculated for the respective individual test sample resilient moduli.

Kancherla (2004) gives an approximate tolerable error of 12.5% corresponding to a population of three resilient modulus tests on any given material. However, this limit was calculated based on testing unbound granular materials composed solely of natural aggregates; correspondingly, the variability will generally be anticipated to be higher when dealing with recycled or reclaimed materials, where the consistency of the material cannot be assured to the same degree. Consequently, a limit of 20% allowable error was chosen for this study, and among each set of three tests on each mix, any samples where the resilient modulus results deviated more than 20% (averaged across all fifteen loading stages) from the overall average profile was excluded as an outlier and the average bulk stress and resilient modulus profile was recalculated using the remaining test samples for that material.

The average resilient modulus vs. bulk stress profiles for each material, excluding outliers as described above, are presented below in Figures 1 and 2. Across all materials from Quarry 1 and Quarry 2, none of the mixes tested had any more than one sample identified and excluded as an outlier; as a result, all of the average profiles in the figures below are based on a total of two to three triaxial tests completed on each material.

Among Quarry 1 materials, the 25% RCA - 75% crushed rock and 50% RCA - 50% crushed rock blends were found to have higher average resilient modulus values than the respective 100% crushed rock control material, while the 100% RCA and 70% RCA - 30% RAP blends had similar results to the control material. Among Quarry 2 materials, the 25% RCA - 75% crushed rock and 50% RCA - 50% crushed rock blends and the 70% RCA - 30% RAP blend were found to have similar average resilient modulus values compared to the 100% crushed rock control material, while the 100% RCA material had lower average resilient modulus results at higher levels of bulk stress.

Overall, the average resilient modulus values found for the blends containing RCA and RAP are broadly similar to those obtained from the 100% crushed rock control materials, although some variability is apparent between the granular materials produced at Quarry 1 and at Quarry 2.

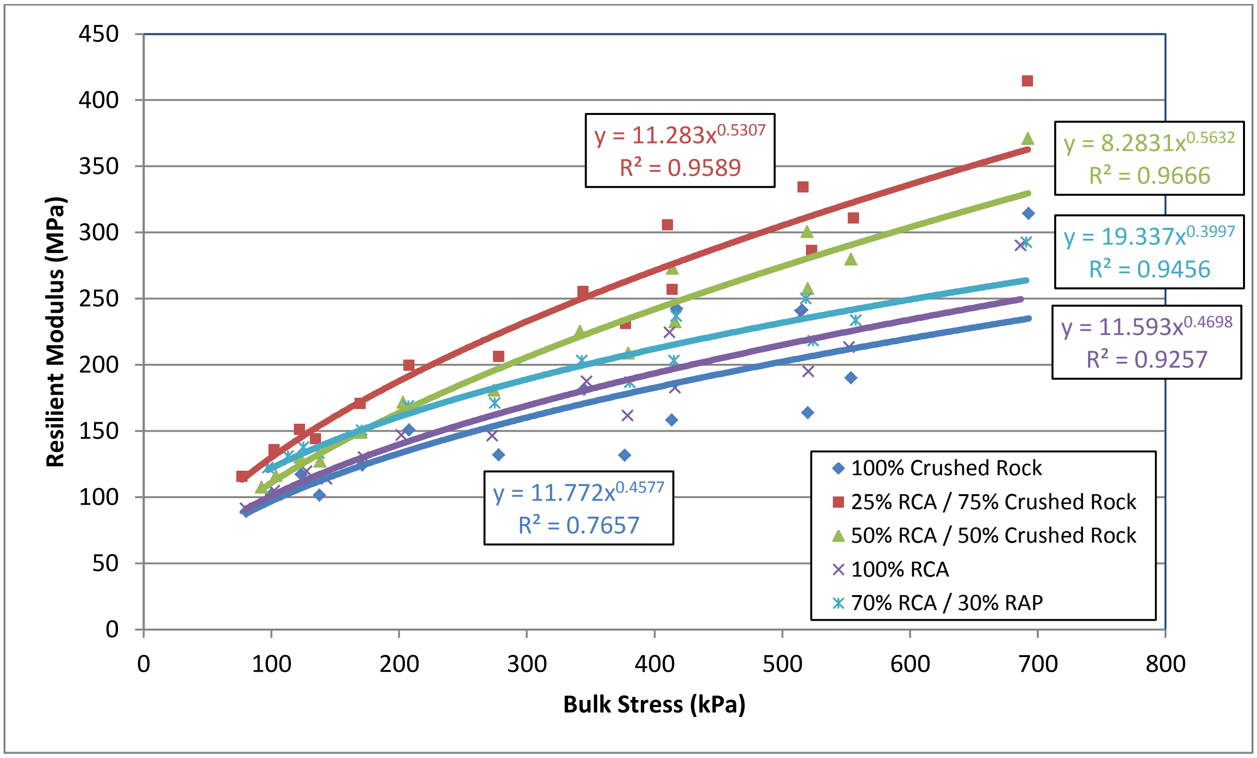

FIGURE 1 Resilient Modulus Testing Results for Granular B Type II Mixes at Quarry 1

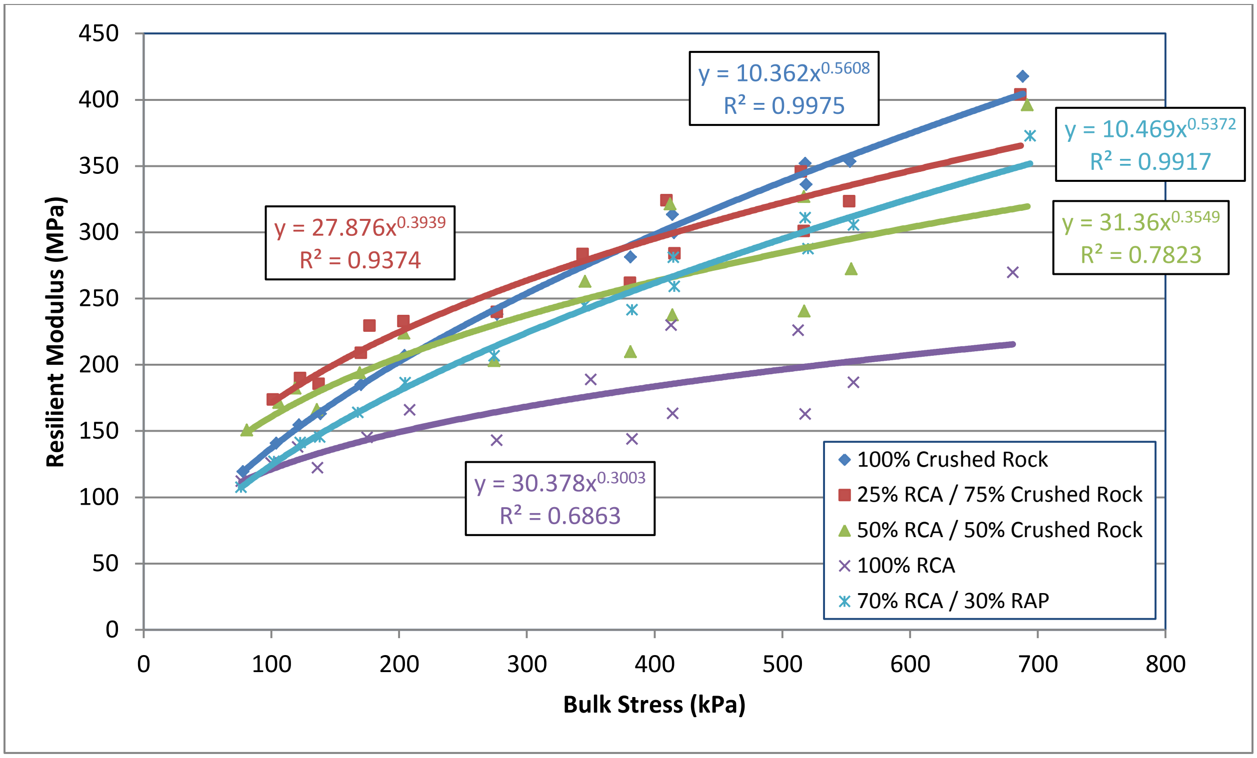

FIGURE 2 Resilient Modulus Testing Results for Granular B Type II Mixes at Quarry 2

The results shown in Figures 1 and 2 also show that the values of the resilient modulus (M_r) increase along with increased bulk stress as expected. The overall bulk stress reflects the state of confinement of the granular material within the pavement structure. In Ontario, the default value of M_r used in AASHTOWare Pavement ME Design software for Granular B Type II material is 200 MPa (MTO, 2012). Although this value appears relatively high, it should be noted that it is attained by most of the tested materials at bulk stress levels between 150 and 520 kPa. In the case of Quarry 1, it is the 100% crushed rock control material that has the lowest slope of M_r versus bulk stress and the lowest values of M_r overall, where the level of 200 MPa is obtained at approximately 500 kPa bulk stress. In the case of the Quarry 2 materials, it is the 100% RCA material that has the lowest slope and lowest values of M_r, and the 200 MPa level is obtained when the bulk stress reaches approximately 520 kPa. These two test materials (100% crushed rock from Quarry 1 and 100% RCA from Quarry 2) showed high variability in the obtained results; however, all of the obtained results across all of the tested materials are relatively good. Even at very low bulk stress states of approximately 80 kPa, most of the resilient modulus values obtained were higher than 100 MPa.

CONCLUSION

Based on the laboratory testing program completed and detailed in this paper, it can be observed that the Granular B Type II subbase mixes incorporating RCA and RAP exhibited minimal tendency to break down under roller compaction in the field, with the exception of the 100% crushed bedrock and 100% RCA mixes at Quarry 1 and the 100% crushed bedrock control mix at Quarry 2. In all cases, the mixes bearing RCA and RAP showed a lower susceptibility to increases in material passing the 75 µm sieve relative to the 100% crushed rock control materials, and all of the mixes tested met OPSS 1010 requirements for coarse and fine aggregate abrasion resistance in the Micro-Deval apparatus.

Standard and modified Proctor testing showed generally lower maximum dry density values and higher optimum moisture content levels for mixes bearing increasing amounts of RCA. In most cases, the final field dry density and moisture content levels were similar to or lower than the results obtained in the standard Proctor test for each material. The measured permeability coefficients indicated good drainage characteristics in all of the test mixes. California Bearing Ratio (CBR) results for each of the test mixes incorporating natural crushed bedrock and RCA were broadly similar to the result for the 100% crushed rock control mix, with the exception of the 70% RCA to 30% RAP test mix, where the CBR results were approximately 30% to 40% lower than for the other blends. Triaxial resilient modulus testing yielded results for blends containing crushed rock with RCA as well as RCA with RAP which were similar overall to average resilient modulus values obtained from the 100% crushed bedrock control material.

Based on the results of the laboratory testing program, it appears that processed RCA and RAP can successfully be utilized as alternative aggregate materials in Granular B Type II subbase fill. Further analysis and reporting work will continue in order to incorporate the results of the field testing program not detailed in this paper. This evaluation work is expected 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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