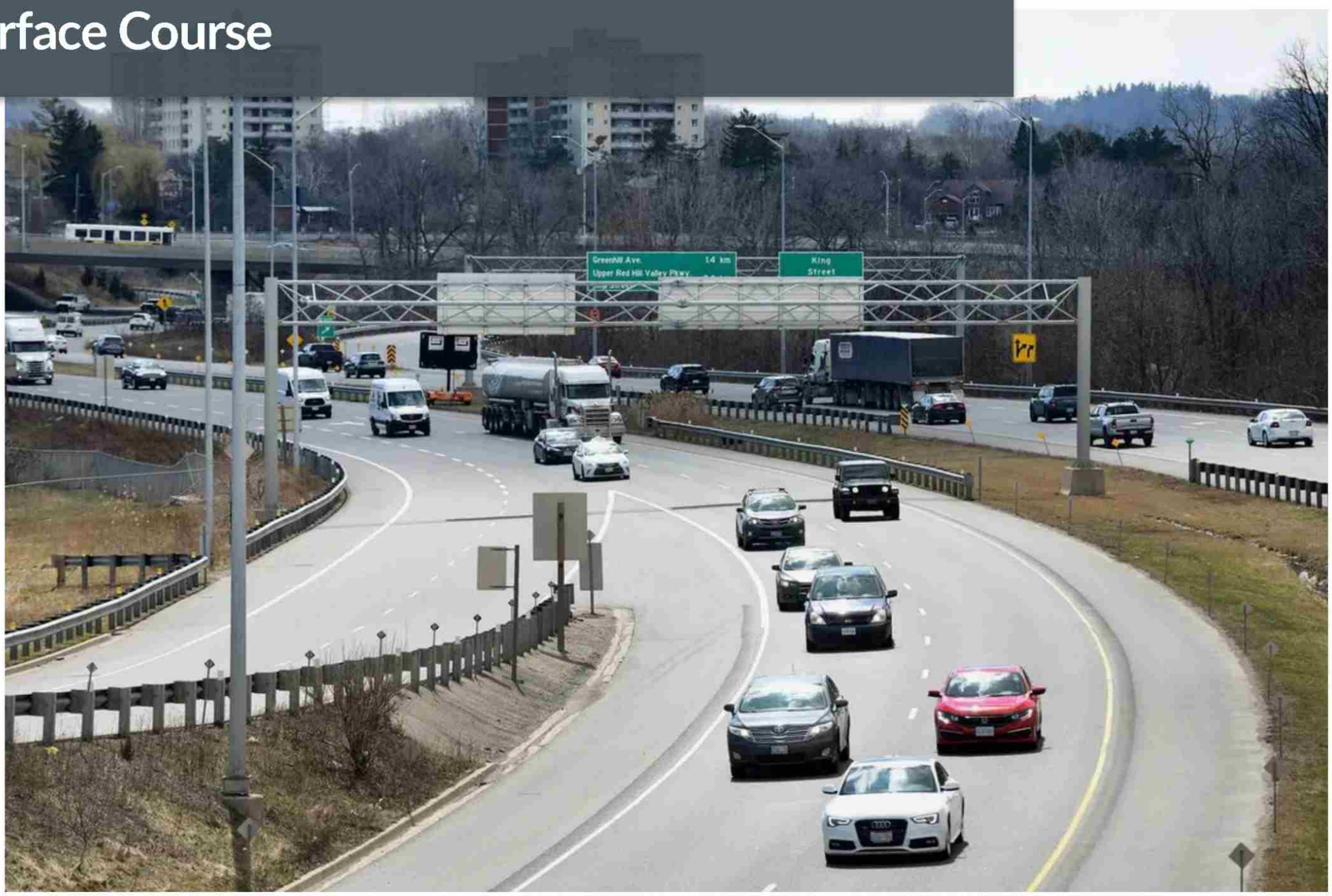
Analysis of Aggregate Testing and Evaluation of the Coarse Aggregate used in RHVP Pavement Surface Course



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Prepared for the RED HILL VALLEY PARKWAY INQUIRY

February 2023

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1 Introduction

The quality of an aggregate in its ability to resist polishing is essential to whether it will provide adequate and enduring frictional characteristics. In 2007, Dufferin provided a number of laboratory performance test results as part of the qualification process of the Aggregate from Varennes Quarry (the “Aggregate”) as suitable for use in the asphalt for the Red Hill Valley Parkway (“RHVP”). The technical data also included the results of a number of tests such as Micro-Deval and Los Angeles Abrasion Tests, Petrographic Number, Physical and Morphological Analysis, Freeze-Thaw and Soundness Tests. The data provided also included the results of the polishing coefficient used in the province of Québec (termed Cpp).

Furthermore, MTO conducted a complete evaluation of the Aggregate in 2008. The study concluded that both fine and coarse aggregates from Varennes Quarry met the criteria for SP 12.5 FC1 and 12.5FC2 Coarse and Fine Aggregates. The evaluation involved a testing campaign that included most of the tests conducted in 2007, presented by Dufferin, in addition to determining the Polished Stone Value (“PSV”) of the Aggregate.

Dr. Flintsch's Report did not consider the test results provided by Dufferin in 2007, nor the results of the evaluation conducted by MTO in 2008, relevant to an assessment of resistance to polishing. In fact, the Report addressed the data in relation to PSV testing only. In this report, I will shed some light on the technical data available in 2007 and the additional data obtained in 2008 to evaluate the suitability of the Aggregate for use in paving projects for high-volume and high-speed highways in the province of Ontario.

Furthermore, Dr. Flintsch's report dedicated a section to the discussion of the PSV values of the Aggregate, with a focus on the PSV test conducted in 2017 on a sample of coarse aggregate obtained by extracting the asphalt binder from some asphalt cores obtained from the RHVP surface course. This report will discuss the purpose and validity of the 2017-PSV Test and whether these results are relevant to evaluate the polishing potential of the Aggregate used in the RHVP in 2007. The report will also examine Dr. Flintsch’s observations related to the drop in friction on the RHVP and whether it would be explained by the PSV test conducted on recovered aggregates in 2017.

2 Polishing Data and Aggregate Properties Analyses

Aggregates are the main component of the bituminous concrete, or the asphalt mixture, representing around 95% of the mass of the asphalt mixture. The aggregates used in an asphalt mix should be selected appropriately in terms of their gradation (particle size distribution), physical properties, mechanical properties and other durability properties that are selected depending on the asphalt mix type. The aggregates should meet the requirements of the standards and specifications of the province or the jurisdiction where they will be used. **Therefore, it is imperative to examine the aggregates based on the standards and available information in 2007**.

The Aggregate used in the design of the Stone Mastic Asphalt ("SMA") for the RHVP surface course was tested and evaluated in 2007 and 2008. At that time, the available data were analyzed, confirming the suitability of the Aggregate for high-traffic, high-speed highways. These data were provided in Appendix 1 and 2 of this report. Appendix 1 contains the datasheet provided by Demix, based on the test methods from Québec. Most of the tests were conducted in 2007, while the polishing test was completed in 2005 by the *Ministère des Transports du Québec* ("MTQ"). Appendix 2 provides the datasheet included in the acceptance letter of the Aggregate by MTO (letter dated Dec. 4, 2008), which contains the results of testing on fine and coarse aggregates conducted by MTO.

This report will focus mainly on the technical properties of the aggregates that impact their polishing and durability. The resistance to abrasion and attrition are two essential properties that would indirectly impact skid resistance. Los Angeles and Micro-Deval are the two tests used to evaluate these properties. The two tests were conducted on the Aggregate in 2007 and 2008. The Petrographic Number, which is a value that reflects the quality of the aggregate based on its mineralogy (rock type), is also available for the 2007 sample. In addition, the PSV is available for the 2008 sample. For the 2007 Aggregate, the available polishing property was the Coefficient of Polishing by Projection ("Cpp"), a property of coarse aggregates used in the province of Québec to assess their adequacy for surface course mixes of the pavement. In this report, the different test methods related to these durability parameters will be briefly described, and the values of these properties will be compared against the Ontario Provincial Standard Specifications ("OPSS") requirements in 2007. It is important to emphasize that, in 2007, the PSV was not a mandatory requirement for coarse aggregates (i.e., OPSS 1003) or the SMA (i.e., OPSS

1151). In addition, the inclusion of the aggregate on the Designated Sources of Material ("DSM") list was not a mandatory OPSS requirement in 2007[1, 2].

2.1 Description of Durability and Polishing Tests

2.1.1 Los Angeles Abrasion Test

The Los Angeles ("LA") Abrasion Test[3] (Figure 1) is a commonly used test to evaluate the resistance to abrasion of coarse aggregates. The LA Test tries to simulate the abrasion that happens to the aggregates during the different stages of aggregate manufacturing, handling, and transportation and then the stages of asphalt production and road construction, such as mixing in the asphalt plant, placing and compaction using heavy and sometimes vibratory compactors. In addition, the granular skeleton in the asphalt mix plays a significant role in transmitting and attenuating the external loads (caused by heavy traffic) to the underlying layers of the pavement structures. This is particularly important in some asphalt mix types, such as SMA, given their high percentage of coarse aggregates compared to conventional asphalt mixes. In the SMA, the stone-to-stone contact leads to a higher level of stresses transmitted through the coarse aggregates. It is, therefore, more efficient to use more abrasion-resistant aggregates with SMA.

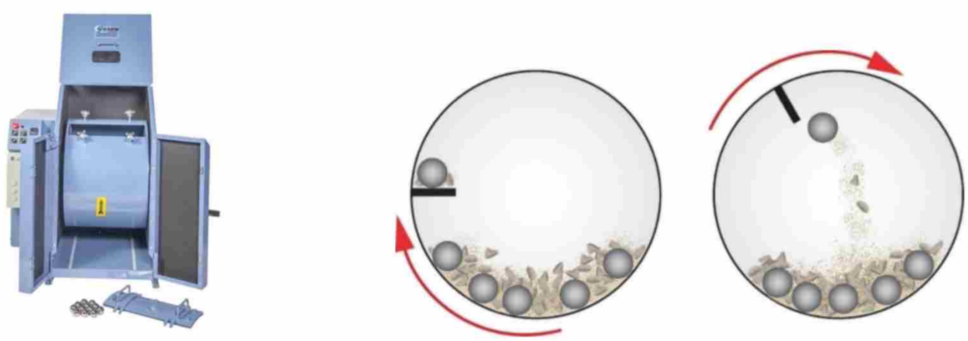

Figure 1. Picture of the Los Angeles apparatus showing the abrasive charge illustrating the concept of the test[4].

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[1] OPSS 1151, Ontario Provincial Standard Specification, Material Specification for Superpave and Stone Mastic Asphalt Mixtures, November 2004

[2] OPSS 1003, Ontario Provincial Standard Specification, Material Specification for Aggregates - Hot Mix Asphalt, November 2004

[3] AASHTO T 96, ASTM C 131: Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

[4] https://www.globalgilson.com/los-angeles-abrasion-machine

The concept of the test is to place the dry, coarse aggregate sample (coarser than 1.70 mm) in a rotating drum, together with an abrasive charge (47-mm diameter steel balls) and rotate the drum at a specific time or number of rotations. As the drum rotates, the aggregate sample becomes subjected to repeated shocks from the abrasive charge. The aggregate particles start to abrade due to the impact of other aggregate particles and the abrasive charge. Some aggregate particles break down into smaller particles, while others become smaller due to the abrasion and attrition caused by the steel balls. At the end of the test, the aggregates are screened using the 1.70 mm sieve, corresponding to the smallest aggregate size used in the test. The portion of the sample that will pass this sieve represents the mass loss of the mineral aggregates by LA abrasion. The test result is expressed as the percentage of the mass of the aggregates that broke down and passed the 1.70 mm sieve (aggregate loss) of the original mass of the sample before the test. Therefore, a high LA value means that the aggregate is more prone to abrasion, while a low LA value indicates that the aggregate is "tougher" and has better resistance to abrasion by impact.

2.1.2 Micro-Deval Attrition Test

Another commonly used test to evaluate the toughness of the coarse aggregates and their resistance to abrasion, or more precisely attrition[5], is the Micro-Deval ("MD") Test[6], developed in France in the 1960s. Aïtcin et al. define attrition as the production of fines due to the friction of aggregate particles against each other[5]. The test is similar to the LA Test but is less aggressive and produces much less particle fragmentation and breakdown than the LA Test.

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[5] Aïtcin P.C., Généreux F., Jolicoeur G., Maurice Y., Technologie des granulats, 4e edition, 2018, Groupe Modulo Inc.

[6] AASHTO TP 58 or ASTM D 6928: Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus

Figure 2. Picture of the Micro-Deval Test Apparatus illustrating the concept of the test[7].

The MD Test can be conducted on fine and coarse aggregates. For the coarse aggregates, a 1500-grams sample of dry aggregates is prepared and placed in a metal jar (Figure 2). An abrasive charge composed of eleven magnetic steel balls is then introduced. The steel balls used in the MD Test are much smaller than those used in the LA Test (9.5 mm diameter versus 47 mm for the LA Test). A specified amount of water is added before starting the rotation of the jar at the rate of 100rpm. Similar to the LA test, the aggregate sample is then recovered, and the mass of the materials that pass sieve No. 16 (1.18 mm) is determined. This fraction of the sample represents the loss of material by attrition.

The test result is expressed as the percentage of the mass of the aggregates that broke down and passed the 1.18 mm sieve (aggregate loss) of the original mass of the sample before the test. Therefore, a high MD value means that the aggregate is more prone to attrition, while a low MD value indicates that the aggregate is "tougher" and has better resistance to attrition.

2.1.3 Aggregate Soundness and Freeze-Thaw Loss

Aggregates are exposed during their service life to different climatic conditions that would affect their integrity. In Canada, it is important to test the aggregates used in most civil engineering applications for cold weather durability. Therefore, different freeze-thaw test

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[7] https://www.globalgilson.com/micro-deval-apparatus

procedures were developed to simulate the impact of cyclic changes in the temperature on coarse aggregates. The Soundness Test and Unconfined Freeze-Thaw are the commonly used tests for this purpose.

The soundness of the coarse aggregate is determined by soaking the aggregates in a Magnesium Sulphate ($MgSO_4$) solution and then determining the percentage of the loss in the aggregate. The severe conditioning in this test is intended to simulate the impact of the exposure to freeze-thaw cycles on the aggregate. However, it is reported that some aggregates can fail this test but still perform well in real-life conditions[5]. The picture in Figure 3 shows an aggregate sample before and after the conditioning in Magnesium Sulphate in the soundness test.

Figure 3. Aggregate before (left) & after (right) the soundness test (Pictures from Pavement Interactive)[8].

The resistance to Unconfined Freeze-Thaw exposure is another test developed in Ontario in the 1980s as a better alternative to the Soundness Test[5]. According to the OPSS LS-614 Standard[9], the aggregate sample is first immersed in a sodium chloride solution for a full day and then exposed to five freezing and thawing cycles. Each cycle includes 16 hours at a temperature of −18 °C followed by 8 hours of thawing at room temperature. The aggregate sample is washed and dried, and the weight loss is calculated.

In both tests, the weight loss percentage determines the soundness or the resistance to freeze-thaw. A lower weight loss percentage indicates better soundness or better resistance to freeze-thaw.

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[8] https://pavementinteractive.org/reference-desk/materials/aggregate/durability-and-soundness/
[9] OPSS LS-614, Test Method for the Resistance of Unconfined CA to Freezing and Thawing

2.1.4 Petrographic Number (PN)

Another important indicator of an aggregate's quality is the Petrographic Number ("PN"). Developed in Ontario in the 1940s, the test method is standardized in the province of Ontario[10]. The aggregates used in road construction should meet the PN requirements associated with their type. Determining the PN includes examining the different features of the aggregate sample, such as scratch hardness, strength, density, shape, texture, colour, mineralogy, structure, reaction with hydrochloric acid, weathering, and magnetism[10]. The procedure requires the determination of each rock type's percentage and the percentage of good, fair, poor, and deleterious particles from the entire sample. According to Aïtcin et al., the PN typically ranges from 100 to 1000[3]. Based on a study conducted in Ontario[11], it is indicated that PN can go from 90 to 600, with 90 being the PN of a strong, unweathered basalt (very hard and durable aggregate) and 600 being the PN of a clay or soft shale (very soft and friable)[12].

2.1.5 Polishing by Projection – MTQ Method

Polishing resistance refers to the ability of aggregates that will be used on the surface of road surfaces to resist wear caused by tire-pavement contact. In 1996, MTQ developed a test method called "Polishing Resistance of Aggregates: Projection Method." This method is standardized in Québec under test method LC 21-102[13]. The test aims to optimize the evaluation and qualification of aggregates to be used in the surface course of flexible pavements. The polishing resistance test first subjects the aggregates to repeated polishing cycles using a jet of water and abrasives and then measures their roughness using a friction pendulum. The test results translate into a parameter called Cpp. The higher the Cpp, the higher the residual roughness of the aggregates after polishing, which translates

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[10] OPSS LS-609, Procedure for the Petrographic Analysis of Coarse Aggregate, Ministry of Transportation, Ontario, Laboratory Testing Manual, May 17, 2019

[11] Rogers, Christopher A. "Petrographic Examination of Aggregate and Concrete in Ontario," Petrography Applied to Concrete and Concrete Aggregates, ASTM STP 1061, Philadelphia, American Society for Testing and Materials, 1990.

[12] https://www.betonconsultingeng.com/rating-suitability-of-local-aggregates/

[13] LC 21-102, Résistance au Polissage des Granulats : Méthode par Projection, Transports Québec, 2008

into a better grip and higher skid resistance. The test is also described in a US Army Corp of Engineers Report in 1999[14].

Figure 4. Cpp device (left) and tested specimen (right)[14].

The Cpp varies from one aggregate to another, depending on the petrographic nature of the aggregate. The higher the Cpp, the more the tested aggregates are efficient and, therefore, resistant to wear. According to the requirements defined in the NQ 2560-114 standard, MTQ requires that the Cpp must be a minimum of 0.45.

The *Laboratoire des Chaussées* of the MTQ conducted a study to evaluate the relationship between the polishing resistance of aggregates, using the Cpp Test method, and the skid resistance of the pavements[15]. Six different aggregate types were used in this study (limestone, sandstone, volcanic, dolomite, granitic gneiss, and gravel). The Cpp values ranged from 0.35 to 0.60. The most efficient aggregate is sandstone (Cpp of 0.60), and the least efficient aggregate is limestone (Cpp of 0.35). The Cpp correlates relatively well with the British Pendulum Number ("BPN") measured on asphalt mixes, as illustrated in Figure 5[15].

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[14] V. C. Janoo, C. Korhonen, Performance Testing of Hot-Mix Asphalt Aggregates, Special Report 99-20, US Army Corp of Engineers, Dec 1999
[15] Info DLC, Relation entre la résistance au polissage des granulats et l'adhérence des chaussées, Vol. 1, no 5, January 1996

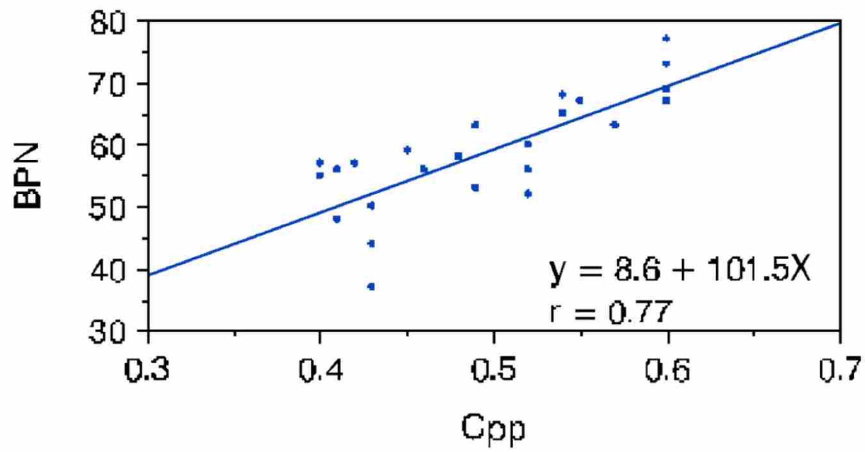

Figure 5. Correlation between Cpp and BPN[15].

The MTQ requires the Cpp Test for any aggregate source used in asphalt mixes destined to surface courses of pavements when the Annual Equivalent Single Axle Load ("ESAL") is higher than 300,000[16].

The test used in Québec to determine the Cpp is inspired by a French test called Resistance to Accelerated Polishing (*RPA: Resistance au Polissage Accéléré*), which is standardized in France (XP P 18-580)[17]. The polishing in both tests is carried out by spraying the samples with a mixture of abrasive emery (silica powder) and water under a pressure of 10 MPa. The test concept differs from the PSV test, but the two tests correlate well, as illustrated in Figure 6.

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[16] InfoDLC, Choix des composants d'enrobés selon l'usage, Vol. 10, no 4, April 2005

[17] XP P 18-580, Granulats – Mesure de la résistance au polissage accéléré des Gravillons – Méthode par projection, AFNOR

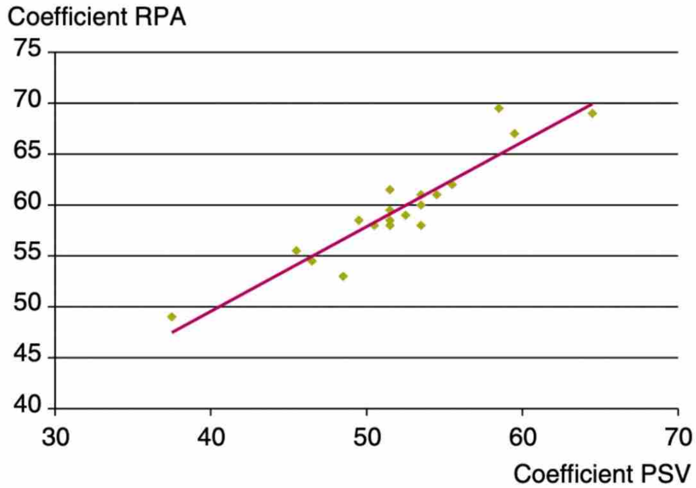

Figure 6. Correlation between RPA and PSV[18]

2.2 Analysis of the Aggregate Properties

As mentioned earlier in this report, the aggregates used in the design of the SMA for the RHVP surface course were tested and evaluated in 2007 and 2008. In this report, the available data will be analyzed to assess the suitability of this Aggregate for the surface course of the RHVP pavement. The following paragraphs will discuss the durability and polishing properties of the Aggregate based on the results of the testing in 2007 and 2008 and the enforceable Ontario Provincial Standards in 2007 at the design stage of the RHVP project.

Dufferin provided a technical data sheet in 2007 that contains the physical and mechanical properties of the aggregates, in addition to other properties, such as Cpp. The datasheet is shown in Appendix 1. A summary of the properties required by MTQ for the qualification of the Aggregate to be used in surface courses of highways is summarized in Table 1. The test results reported in MTO's Mr. Stephen Senior's letter to Estel Gagnon, Chef Section Qualité at Demix Agrégats, dated December 2008, will also be discussed. These results are shown in Table 2. In this letter, MTO confirms the approval of Varennes Aggregates for SP 12.5 FC1 and SP 12.5 FC2 asphalt mixes.

[18] Lédée V., Delalande G., Dupont P., Adhérence et granulats, Bulletin des Laboratoires des Ponts et Chaussées – 255, Avril-Mai-Juin 2005 - Réf. 4578 - Pp. 91-116

Table 1. Physical, mechanical and other properties required for the qualification of the aggregates to be used in the surface course of highways in QC according to NQ 2560-114 Standard

Description	Test Method	Results	Specification NQ 2560-114*	Executed by
Micro-Deval (MD), %	LC-21-070	2.0%	Max. 15%	Demix
Los Angeles (LA), %	LC-21-400	13.6%	Max. 35%	Demix
(MD+LA), %	-	15.6%	Max. 40%	Demix
$MgSO_4$ Soundness Loss	CSA A23.2-BA	0.1%	Max. 12%	LVM
Unconfined freeze-thaw	CSA A23.2-24A	0.6%	Max. 4%	LVM
Fractured Particles %	LC 21-265	100%	100%	Demix
Flat Particles %	LC 21-265	18.0%	Max. 25%	Demix
Elongated Particles %	LC 21-265	12.0%	Max. 40%	Demix
Flat and Elongated Particles %	LC 21-265	1.8%	NA	Demix
Coefficient of Polishing by Projection (Cpp)	LC 21-102	0.49	Min. 0.45**	MTQ Lab.

* Requirements that should be met for Aggregate Cat. 1-a according to NQ 2560-114

** Min of 0.50 is required for high-volume highways in Montreal Island (île de Montréal)[5]

Table 2. Physical, mechanical, and other properties required for the qualification of the aggregates to meet the requirements of SP 12.5 FC2 according to OPSS 1003 Standards

Description	Test Method	Results in 2008	Results in 1992	Specification OPSS*
Micro-Deval Abrasion, %	LS-618	2.7%	3.5%	Max. 10%
Los Angeles Abrasion, %	ASTM C 131	17%	15%	N.A.
Magnesium Sulphate Soundness, %	LS-606	-	0%	N.A.
Freeze-Thaw, %	LS-614	1.6%	-	6%
Granular Petrographic Number (PN)	LS-609	100	100	Max. 120
Fractured (Crushed) Particles, %	LS-607	100%	-	100%
Flat & Elongated, %, 4:1	LS-608	2.8%	13%	15%
Flat & Elongated, %, 5:1	LS-608	0.3%	-	10%
Polished Stone Value (PSV)	BS EN 1097-8-2020	52	45	N.A.

*Requirements for the highest traffic category (Cat. E).

The properties of the 2008 Aggregate are compared against the requirements of OPSS Standard 1003 – Nov. 2004 (Material Specification for Aggregates – Hot Mix Asphalt) and OPSS Standard 1151 – Nov. 2004 (Material Specification for Superpave and Stone Mastic Asphalt Mixtures). Based on these standards, the Aggregate meets all the mandatory requirements for SMA 12.5 for Traffic Category E, which corresponds to the highest traffic level in the OPSS specifications. This traffic category corresponds to a 20-Year Design ESAL of 30,000,000 or higher.

2.2.1 Abrasion and Attrition Resistance

The examination of the test results in Table 1 demonstrates that the quality of the Aggregate, based on the NQ Standards, is excellent[19]. The Micro-Deval and Los Angeles values are very low (2.0% and 13.6%), indicating excellent resistance to abrasion and attrition. Similarly, the examination of the test results in Table 2 also demonstrates that the quality of the Aggregate, based on the OPSS Standards for the SMA 12.5 and highest traffic category (Cat. E), is excellent. The Micro-Deval and Los Angeles values in 2008 were also very low (2.7% and 17.0%, respectively), indicating excellent resistance to abrasion and attrition. It is worth noting that the LA Test is not part of the OPSS Standards.

2.2.2 Aggregates Soundness and Freeze-Thaw Resistance

Based on the 2007 test results for the Soundness Test, the soundness of the Aggregate is excellent. The percentage of the mass loss in the soundness test is 0.1% only, while the CSA standards accept up to 12% loss (Table 1). The resistance to freeze-thaw exposure is also excellent, as the mass loss is 0.6%, which is well below the limit of 4%. Similarly, the test results in 2008 (Table 2) confirm that the resistance to freeze-thaw is excellent. The Freeze-Thaw resistance was determined directly for the 2008 sample, per the OPS Specifications. The test result was excellent (1.6% only). The 2008 testing does not include the Soundness Test.

2.2.3 Petrographic Number (PN)

As explained earlier, the PN is a strong indicator of the quality of the aggregates in Ontario. The PN was determined in 2007 (Table 1) and 2008 (Table 2) in Québec and Ontario. Both tests reported a PN value of 100, close to the lowest PN obtained for an aggregate in Ontario (See 2.1.4 for more details). The low PN indicates that the aggregate is composed of hard and clean minerals. A coarse aggregate with a low PN is generally more durable and expected to have higher resistance to wear and tear.

2.2.4 Physical Properties of the Aggregate

In addition to the durability tests, the physical properties of aggregates are important indicators of how the aggregates will behave in the asphalt mix. Aggregates with a high

[19] The specified values according to 2007 specifications are reported in the fourth column of the table.

percentage of crushed particles and a low percentage of flat and elongated particles will help achieve a more robust aggregate structure in the mix, contributing to the pavement's durability and resistance to permanent deformation (rutting) in hot weather. For both the 2007 and 2008 samples, the test results show that the Aggregate is composed of 100% Fractured (Crushed) Particles and that the percentage of flat and elongated particles is low, indicating that the Aggregate's particle shape is adequate for SMA.

2.2.5 Resistance to Polishing

The resistance to polishing of the Aggregate was evaluated using the Polishing by Projection method in 2005, and the test result was reported in Dufferin's datasheet (Table 1). The test result is expressed using the Cpp value. The Cpp value for the Aggregate was 0.49, which is higher than the minimum value of 0.45 required by the MTQ in their specifications. It is worth mentioning that this test was conducted at the MTQ's Central Laboratory (*Laboratoire des Chaussées*) and is valid for three years for aggregates with a Cpp of 0.49 or above[20].

The MTO also tested the Aggregate in 2008; the PSV was determined to be 52 (Table 2). Although the PSV was not part of the OPS Specifications and it was not a mandatory requirement for the aggregate to be part of the DSM list in 2007[21, 22], the value of the PSV reported for the Aggregate was higher than the value required in the current specifications.

In summary, based on the Aggregate's mechanical, physical, petrographic, and polishing properties, as per the testing conducted in 2007 and 2008, I conclude that the Aggregate meets all the requirements for SMA 12.5 Mix and Traffic Category E in Ontario. Accordingly, the Aggregate could have been expected to be adequate for projects requiring good skid resistance. The Aggregate is, therefore, suitable for surface-course asphalt mixes used for high-volume, high-speed highways in Ontario.

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[20] Ouvrage Routiers, Normes, Tome VII - Matériaux, Gouvernement du Québec, December 2020, ISSN 1927-5455

[21] OPSS 1151, Ontario Provincial Standard Specification, Material Specification for Superpave and Stone Mastic Asphalt Mixtures, November 2004

[22] OPSS 1003, Ontario Provincial Standard Specification, Material Specification for Aggregates - Hot Mix Asphalt, November 2004

3 Discussion of Section 2.1.5 – Dr. Flintsch's Report

In his Report, Dr. Flintsch covered most aspects of skid resistance and provided comprehensive analyses of field testing. However, the analyses and discussions of laboratory testing on the aggregates, reported in Section 2.1.5 of Flintsch's Report, contain some ideas and observations that are not justified, in my opinion. The last two paragraphs of Section 2.1.5 of the Report will be discussed in detail in the following sections.

3.1 Purpose and Validity of the 2017-PSV Test

Dr. Flintsch referred to the PSV test conducted on the coarse aggregates recovered from the asphalt cores in 2017 and sent to Ireland, where the PSV testing was conducted (2017-PSV Test). This test resulted in a PSV of 45, which I will refer to as PSV_{2017}. Dr. Flintsch then compares this value against British and MTO standards for virgin aggregates and concludes that the value is "relatively low".

In fact, the unique purpose of the 2017-PSV Test was to evaluate the potential of using the Hot In-place Recycling ("HIR") technique with SMA[23]. This test was not intended for forensic analysis to verify the quality of the virgin coarse aggregates used in the SMA in 2007. However, Dr. Flintsch compares this PSV_{2017} to the British standards and Ontario requirements which, in my opinion, is not a relevant comparison.

PSV test is meant to be conducted on virgin aggregates from the quarry source to evaluate the ability of the aggregate source to withstand polishing[24]. The test standard BS EN 1097-8-2020 states: "*The Sample is taken from normal run of production from the plant. Chippings that have been freshly crushed in the laboratory or recovered from bituminous materials may give misleading results*"[25]. Hence, conducting a PSV test on recovered aggregates from an

[23] It is important to mention that, based on the results of the PSV testing in 2017 and other technical concerns, Golder's recommendation was against using HIR as a pavement rehabilitation solution to address observed existing pavement distress on the RHVP.
[24] Burton D., The skid resistance of aggregate blends on in-service pavements, retrieved from https://saferroadsconference.com/wp-content/uploads/2016/05/Donald-Burton_30_V2_200712241.pdf
[25] BS EN 1097-8-2020, Tests for mechanical and physical properties of aggregates. Determination of the polished stone value

in-service asphalt mix may give misleading results and is, therefore, irrelevant to predict the PSV value of the virgin aggregates.

I searched the scientific literature but could not find any study that used the PSV test with recovered aggregates from Reclaimed Asphalt Pavement ("RAP") for a similar purpose. Some studies in Europe and the USA were interested in evaluating the impact of the addition of RAP in surface mixes as a substitution for some of the virgin aggregates. Nevertheless, none of these studies used PSV with recovered RAP aggregates. Instead, the researchers prepared asphalt mixes using virgin aggregates and RAP and evaluated the skid resistance of the asphalt slabs[26, 27] or directly tested the pavement in the field rather than testing the recovered aggregates[28].

The primary issue with conducting a PSV test on in-situ recovered aggregates for forensic purposes is that the recovered aggregate sample will be very different from the virgin aggregates and will not give an accurate representation of the intrinsic properties of this aggregate. The PSV test is conducted on virgin quarried aggregates only. When a PSV test is performed on a virgin aggregate sample, the particles are polished in the laboratory to simulate the effect of wear and tear over time on the aggregate's microstructure. Therefore, the PSV value obtained for an aggregate corresponds to the friction properties after a number of years of in-service polishing of the aggregate. Now, if one recovers in-service aggregates (by asphalt extraction) and then runs a PSV test on them, this person would be polishing the aggregate sample beyond the polishing state at the time of the recuperation of the aggregate sample from the in-service pavement. In other words, when the PSV test was conducted on the SMA aggregates recovered in 2017, the only information that it gave was "an idea" of how the recovered aggregate would behave a number of years down the road if it were to be reused, as a RAP in an asphalt mix, or in HIR technique.

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[26] McDaniel, R. S., K. J. Kowalski, and A. Shah. Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures. Publication FHWA/IN/JTRP-2012/03. Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012. doi: 10.5703/1288284314665.

[27] Hu S., Zhou F., Scullion T., Fernando E., Souliman M., Develop Surface Aggregate Classification of Reclaimed Asphalt Pavement: Technical Report, The University of Texas at Tyler, Report 0-7025-R1, Project 0-7025 Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration, Published: June 2022

[28] Dunford A., Laboratory Studies Investigating the Use of Blended PSV Aggregates, PPR710, Transport Research Laboratory TRL, UK, 2014

Furthermore, the most important contributing factor to aggregate polishing in-service is traffic loading. In fact, natural aggregates polish under the abrasive effect of the tires and lose their microstructure, which leads to the loss of skid resistance with time. In addition to aggregate polishing at the pavement's surface, heavy vehicle loading will generate stresses within the asphalt course, leading to the coarse aggregates' attrition with time. In fact, SMA is a gap-graded asphalt mix that contains a high percentage of coarse aggregates (Figure 7). This design aims to ensure stone-to-stone contact, which contributes to the improved rutting resistance of the SMA. The downside is that coarse aggregates in the SMA would abrade due to the high stresses transmitted locally from one another under the traffic loading. After a 10-year service life, the SMA aggregates will be very different from the original aggregates.

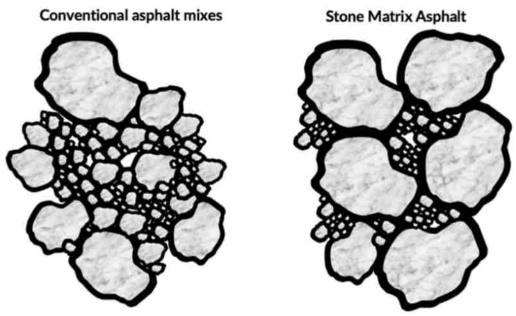

Figure 7. Stone-to-Stone Granular Skeleton of the SMA.

Moreover, undergoing freeze-thaw cycles and exposure to the deicing salts during the in-service period of the pavement would also impact the aggregates and hence make it impossible to judge the quality of virgin aggregates based on the recuperated asphalt mix results. Several studies report the impact of these factors on aggregates and asphalt durability[29, 30]. A study titled "*Influence of freeze–thaw on the polishing resistance of coarse aggregates*" concluded that for some aggregates, the microtexture is negatively affected, and the skid resistance is consequently reduced as a result of freeze-thaw[31].

[29] Pittenger R., West T., Effects of Salt, and Trace Minerals for Bituminous Pavements - Literature Review, Information Gathering and Research Plan Development, Report, FHWA/LN/JHRP-95/2, 1995
[30] Dubberke W., Marks V.J., The Effect of Deicing Salt on Aggregate Durability, Transportation Research Record 1031, Transportation Research Board, National Research Council, Washington. D.C. 1985
[31] D. Wang, X. Chen, H. Stanjek, M. Oeser, B. Steinauers, Influence of freeze–thaw on the polishing resistance of coarse aggregates, Construction and Building Materials, Volume 64, 2014, Pages 192-200

Finally, during the extraction and recovery process, separating the asphalt cement (the bitumen) from the aggregate requires soaking the asphalt mix in a strong chemical solvent (typically trichloroethylene or N-Propyl bromide)[32]. The literature reports that most extraction and recovery methods will leave some asphalt cement on the aggregates[33], which could alter the PSV measurements.

In summary, I consider that comparing PSV_{2017} against the requirements for the virgin aggregates or the standards is invalid and irrelevant. The aggregate sample tested in 2017 is not, in any way, representative of the 2007 virgin quarried aggregates used in the SMA, nor of the 2008 sample tested by MTO. There is no scientific evidence that this test result could be used to predict the initial properties of the aggregates or to assess the current frictional characteristics of the pavement.

3.2 Comparison with 1992 data

Dr. Flintsch also compares the PSV value of the recovered aggregates (PSV_{2017}) to the one reported in Dufferin's data sheets from 1992 and writes: "*This result from the in-service RHVP pavement in December 2017 (PSV=45) is consistent with the results the MTO obtained from 1992(….)*". In my opinion, this comparison is not valid and irrelevant. It is a pure coincidence that the two values are identical. The PSV_{1992} was conducted on quarried aggregates. In contrast, the PSV_{2017} was conducted on aggregate recovered from an asphalt mix used as a surface course for ten years, with all the traffic and other factors explained in the previous paragraph. Dr. Flintsch then writes: "*The variation of PSV over time for a quarry is not uncommon as different rock seams are exploited over time,*" which is accurate and invalidates his comparison. This explains the difference between PSV_{1992} and PSV_{2007} (45 versus 52), but, in my opinion, the similarity between PSV_{1992} and PSV_{2017} is a pure accident.

The properties of natural aggregates vary depending on their source (deposits and quarries), mineral nature and production techniques[34]. Aggregates are produced from

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[32] Mikhailenko P., Baaj H., Survey of Current Asphalt Binder Extraction and Recovery Practices, 2017 Conference of the Transportation Association of Canada, St. John's, NL

[33] Mikhailenko P., Ateian P., Baaj H., Extraction and recovery of asphalt binder: a literature review, International Journal of Pavement Research and Technology, 13, 20–31, 2020

[34] Ordre des Géologues du Québec, Dircetive - Caractérisation des granulats et de leurs sources en vue de leur utilisation dans le béton, August 2017

various geological formations by different industrial processes of excavation, crushing, screening, washing, or mixing. The properties of the natural material used to produce the aggregates vary in space according to the petrology constrained by the stratification, the variations of facies, the structures, and other geological phenomena. In igneous or metamorphic massifs, the variations can happen in all directions, and it is often unsafe to consider that the characteristics observed in one place extend over a great distance[34]. Figure 8 shows a picture of an igneous quarry the in the Beauce Region in Québec. The picture shows the variability of the geological formations at an igneous quarry.

Figure 8. Picture of an igneous or metamorphic massif in Québec (Beauce)[34].

Table 3 is extracted from a document titled "*Predicting skid-resistance development in practice based on the correlation between polished stone value and mineralogy*"[35]. In this study, aggregate samples were obtained from five different quarries, and PSV testing was conducted in the lab using the same test equipment. The results demonstrate clearly that the PSV value can change significantly (a difference of 4 between the highest and lowest

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[35] Kuijper P.M., Predicting skid-resistance development in practice based on the correlation between polished stone value and mineralogy, Report no. 727235, Ministry of Infrastructure and Water Management of the Netherlands, August 9, 2017

value was observed for the first quarry), even when the materials are sampled from the quarry at the same time (i.e., same batch, same rock seam, same production method and equipment).

Table 3. Polished Stone Values for the different quarried materials[35]

Quarry	Polished stone value measurement 1	Polished stone value measurement 2	Polished stone value measurement 3	Mean	Standard deviation
Ellenberg	64	66	62	64	2.0
Langenthal	51	50	48	50	1.5
Dönstedt	54	57	56	55	1.5
Flechtingen	59	57	56	57	1.5
Mammendorf mix	54	54	53	54	1.5
Mammendorf red	55	56	53	55	1.5

In a study from New Zealand titled "*Does the polished stone value test assure skid resistance?*"[36], the authors discussed the effect of sampling and stone selection on PSV. Based on the literature, they state that the most significant source of uncertainty comes from sampling location and intervals. They report that considerable variability in PSV (absolute values and standard deviation) increased as sampling intervals increased[36]. In this study, the authors refer to short intervals (weeks or months) and not fifteen years (from 1992 to 2007).

The authors also reported that the crushing process is a primary source of variability of the PSV[36]. Table 4 demonstrates that significant variability may occur depending on the source of the sample (quarry face) and the degree of crushing.

Table 4. Effect of crushing process on PSV (adapted from Bean et al. [36])

Quarry face	Degree of crushing	
	Tertiary	Primary
A	49	56
B	54	61

[36] Bean D., Pidwerbesky B., Does the polished stone value test assure skid resistance?, Road and Transport Research, Vol. 3, No. 2, June 1994.

A media release published in 2000 in InfraStructures[37] reported that Demix Agrégats invested $12 million to modernize their aggregates crushing and processing facility in Varennes, which would allow them to extend the service life of the quarry and produce high-quality aggregates. This would indicate that the aggregate production in 1992 was done using the old facility and probably in different zones from the aggregates exploited in 2007 and 2008.

It is, therefore, reasonable to conclude that the aggregates produced in 2007 and used in the RHVP project are closer in quality to the aggregates tested in 2008 and are most likely quite different from the 1992 aggregates.

3.3 The Drop in Friction Between 2008 and 2014

In the last few sentences of paragraph 2.1.5, Dr. Flintsch's report discussed the drop in friction observed between 2008 and 2014 (approximately 20%). Dr. Flintsch describes this drop as "significant". In addition, he appears to connect this drop in friction to the PSV of 45 measured in 2017 on the aggregate sample recovered from the in-service pavement. I disagree with Dr. Flintsch on both points.

Dr. Flintsch considered that the drop in friction of 20%, over a six-year period is significant. I have examined the literature on this point and found that this drop is within the norm for paving projects with similar materials and service lives[36,38].

I have extensively discussed the validity of the 2017-PSV Test in section 3.1 of this report and concluded that the test is invalid and should not be used to evaluate the polishing resistance of the aggregates in 2007, or to explain the drop in friction on the RHVP.

Aggregates polishing is, in fact, a significant contributor to the loss of the skid resistance of pavements. As stated by Dr. Flintsch, the aggregate loses its microstructure because of the abrasive effect of traffic, and this is true for all natural aggregates. Therefore, it is reasonable to expect aggregates to polish during the pavement's service life. Aggregate polishing would happen faster when the traffic volume is higher than the anticipated design volume, which was the case for the RHVP[39]. However, I disagree with Dr. Flintsch

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[37] http://www.infrastructures.com/1000/demix.htm
[38] Lane B., Kennepohl G., Kazmierowski T., Raymond C, Tam K., Ten-Year Performance of a SMA Freeway Pavement in Ontario, Proceedings of the Canadain Technical Asphalt Association, 2007
[39] Red Hill Valley Parkway Detailed Safety Analysis, CIMA, November 2015 (HAM*702)

on relying on the PSV testing conducted in 2017 to explain the drop in friction or to conclude that the Aggregate is susceptible to polishing. The aggregate sample recovered from the in-service pavement in 2017 was significantly altered and is not representative of the virgin quarried aggregate used in the manufacturing of the SMA. It follows that the 2017-PSV Test result cannot be relied upon to create any connection with the drop in friction on the RHVP.

4 Summary and Conclusions

This report examined the technical data available for the Aggregate from Varennes Quarry used in the SMA surface asphalt mix of the RHVP in 2007. The technical data included the results of a number of tests, such as Micro-Deval and Los Angeles Abrasion Tests, Petrographic Number, Physical and Morphological Analysis, Freeze-Thaw and Soundness Tests, both from the 2007 sample tested in Québec and the 2008 sample tested in Ontario by MTO. The data also included the results of the polishing test conducted in Québec (Cpp) and Ontario (PSV) in 2007 and 2008, respectively.

The careful examination of the technical data confirmed that the Aggregate met all the mandatory requirements of the OPS Specifications for FC-2 Aggregates and is fully adequate for use in surface courses of high-volume, high-speed highways in Ontario in 2007.

In conclusion, based on the technical data available in 2007 and the test results obtained by the MTO in 2008, I can confidently confirm that the coarse aggregate fraction used in the surface course of the RHVP had good technical properties in terms of durability, shape, petrography, and polishing resistance. The Aggregate could have been expected to provide a good functional performance and was suitable for use in the SMA surface asphalt mix of the RHVP in 2007.

This report also discussed Dr. Flintsch's analyses of the PSV values obtained for the Aggregates in 2017 and its connection with the drop in friction on the RHVP between 2008 and 2014. The 2017-PSV Test was conducted on a sample of recovered in-service aggregate. My analyses concluded the invalidity of this test. The recovered aggregate sample was significantly altered over the years and is not representative of the 2007 virgin quarried aggregates or the 2008 sample tested by MTO. It is also irrelevant to compare it to the PSV from 1992, as aggregate samples extracted from the same quarry fifteen years apart could be very different. In my view, the connection between the 2017-PSV Test result and the drop in friction on RHVP, or the properties of the virgin aggregates, is not a valid connection.

5 APPENDICES

5.1 Appendix 1 – QC Datasheet Demix 2007[40]

T-35
SHEET
Revision: 2006-05-21

QUALITY CONTROL - TECHNICAL DATA

From	DEMIX Varennes' Quarry	Material type : Crushed Traprock	Description: : 5-14mm classified
Date	: March 2007	FIRST LIFT (UNIQUE)	Codification : 9020

Production season	No. of Analysis	SIEVE ANALYSIS CSA A23.2-2A (% PASSING)																		Fineness modulus (1)
		112	80	56	40	31,5	28	20	16	14	12,5	10	5	2,5	1,25	630	315	160	80	
2006	91							100	99	93	82	60	8	2						
Standard deviation (δ)								0	1	3	5	8	3	1						
SPECIFICATIONS	Max. (%)							100		100		75	15	5						
	Min. (%)							100		90		45	0	0						

(1) From article 2.1 of CSA A23.1 definition

PHYSICAL AND MECANICAL PROPERTIES OF AGGREGATES

DESCRIPTION	TEST METHOD	RESULTS	SPECIFICATIONS NQ 2560-114	SPECIFICATIONS CSA A23.1/ Others	Executed by	DATE
Physical properties			*Class "1"*			
Micro-Deval (Degradation by abrasion)	LC 21-070	2%	≤ 15%	Mtl town ≤ 15%	DEMIX Aggregates	2007-03-05
Micro-Deval (Degradation by abrasion)	CSA A23.2-29A	1.3%		Freeze-thaw exposure ≤ 17%	DEMIX Aggregates	2007-03-05
Los Angeles (Impact & Abrasion loss)	LC 21-400	13.6%	≤ 35%		DEMIX Aggregates	2007-03-05
Los Angeles (Degradation by Impact & Abrasion)	CSA A23.2-16A	14.5%		Freeze-thaw exposure ≤ 50%	DEMIX Aggregates	2007-03-05
Los Angeles (Degradation by Impact & Abrasion)	CSA A23.2-16A	14.5%		Mtl town ≤ 30%	DEMIX Aggregates	2007-03-05
MgSO4 soundness loss	CSA A23.2-9A	0.1%		Freeze-thaw exposure ≤ 12%	LVM Fondatec	2006-01-30
Mechanical properties			*Class "1"*			
Fracturated particules %	LC 21-100	100%	100%		DEMIX Aggregates	2007-03-05
Flat particles %	CSA A23.2-13A-B	18.0%	≤ 25%		DEMIX Aggregates	2007-03-05
Elongated particles %	CSA A23.2-13A-B	12.0%	≤ 40%		DEMIX Aggregates	2007-03-05
Flat and Elongated particles %	CSA A23.2-13A-B	1.8%	N/A		DEMIX Aggregates	2007-03-05
Other properties						
Material finer than 80 µm	CSA A23.2-5A	0.8%	≤ 1,5%		DEMIX Aggregates	2007-03-05
Relative Density: Bulk / SSD / Apparent	LC 21-067 / CSA A23.2-12A	2.504/2.622/2.550			DEMIX Aggregates	2007-03-05
Relative Density: Bulk / SSD / Apparent	LC 21-067 / CSA A23.2-12A	0.72%			DEMIX Aggregates	2007-03-05
Bulk density Compact / Loose	NQ 2560-060 / CSA A23.2-10A	1422 / 1301 Kg/m³			DEMIX Aggregates	2007-03-05
Air Voids (%)	NQ 2560-060	43.0% / 47.9%			DEMIX Aggregates	2007-03-05
Unconfined freeze-thaw test	CSA A23.2-24A	0.6%		Freeze-thaw exposure ≤ 6%	LVM-Fondatec	2006-01-30
Petrographic examination	CSA A23.2-15A	100			LVM-Fondatec	2005-02-07
Polishing-by-Projection Coefficient (Cpp)	LC 21-102	0.49	Min. 0,45 *		MTQ Central Lab.	2005-05-27
Alkali-Aggregate Reaction	CSA A23.2-14A	0,022%	≤ 0,04%		LVM-Fondatec	2004-11-08

Prepared by: *Benoit Tremblay*
Technician

Approuved by: *Yves Séguin*
Quality Manager

Signature: C.E.T.

[40] GOL*4871 attaching GOL*4873

5.2 Appendix 2 – Test results on the Aggregate conducted by MTO in 2008[41]

Table 1
Laboratory Test Results
Demix Agrégats
Varennes, Quebec

Laboratory Test		
Lab Sample No.	08-B-9010	08-B-9009
Field Sample No.	-	-
Date Sampled	July 17, 2008	July 17, 2008
Type of Material	SP 12.5 FC2	screenings
Rock Type	syenite (trachytic phonolite)	syenite (trachytic phonolite)
Granular PN	100	-
HL + Conc PN	100	-
Absorption, %	0.551	1.051
Bulk Relative Density	2.518	2.568
Loss by Washing, %	0.78	-
Crushed, %	100	-
Flats & Elongated, %, 4:1	2.8	-
Flats & Elongated, %, 5:1	0.3	-
Micro-Deval Abrasion, %	2.7	9.4
Polished Stone Value	52	-
Aggregate Abrasion Value	2.3	-
Freeze-Thaw, %	1.6	-
Thin Section Description	feldspar, nepheline, albite	-
Pass 75 µm, %	-	1.4
Plasticity Index	-	N.P.
Los Angeles Abrasion, %	17	-
Fine Aggregate Angularity Method 'A', % (Superpave Consensus Test)	-	47.8
Sand Equivalent	-	97
Gradation, % Passing		
16.0 mm	98.7	
13.2 mm	89.8	
9.5 mm	51.4	
4.75 mm	5.5	100
2.36 mm		51.6
1.18 mm		22.6
0.600 mm		10.7
0.300 mm		5.4
0.150 mm		2.7
0.075 mm		1.4

SAS/RGG/jlp
3162-2-0-1
December 4, 2008

41 MTO*45

5.3 Appendix 2 – Aggregate Datasheet from 1992 provided to MTO in 2007[42]

Table 1
Laboratory Test Data
Demix Agrégats
Varennes, Quebec

	92-B-40015
Petrographic Number (H.L.)	103
Petrographic Number (Gran.)	100
Magnesium Sulphate Soundness, %	0
Los Angeles Abrasion, %	15
Absorption, %	0.53
Relative Density	2.529
Polished Stone Value	45
Aggregate Abrasion Value	2.5
Flat & Elongated Particles, %	13
Wash pass 75 µm Sieve, %	0.9
Micro-Deval Abrasion, %	3.5

Petrographic Rock Type Description:
Syenite (Trachyitic Phonolite)

CAR/RGG/jlp
3162-2-0-1
December 13, 2007
Enclosure

[42] MTO*43

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