Resurfacing of Highway 127 in Ontario Using a High Performance Double Chip Seal

Anton S. Kucharek, P.Eng., C.Chem.
Technical Services Manager
McAsphalt Industries Limited
Toronto, Ontario

J. Keith Davidson, P.Eng.
Technical Director
McAsphalt Industries Limited
Toronto, Ontario

Peter Linton
Manager of Pavement Products
Miller Paving Limited
Gormley, Ontario

Ted Phillips, CET, Ltd. Lic.
Geotechnical Engineering Supervisor
Ministry Of Transportation
Kingston, Ontario

ABSTRACT

Highway 127 is a two-lane roadway between Maynooth and Highway 60 in Eastern Ontario. The highway carries 1600 Average Annual Daily Traffic (AADT) with 8.5 percent commercial vehicles. Prior to 2006, the pavement surface consisted of moderate to severely oxidized hot-mix asphalt, with non-uniform, heterogeneous sections.

The Ministry of Transportation, Ontario (MTO) Eastern Region selected a double chip seal treatment for a 16.4 km section of this road as a way to improve surface characteristics but also as a holding strategy before having to proceed with full road rehabilitation. The contract called for a formal project-level design including aggregate-binder compatibility testing and surface treatment performance testing. The seal incorporated a CRS-2P emulsion with Ontario Provincial Standard Specification (OPSS) 304 Class 1 aggregate for the first lift and a 1/4-1/8" chip for the second lift. The project was completed by Miller Paving during August 2006.

The paper summarizes the stages of this project. It specifically outlines the laboratory work and presents several design methods incorporated, with emphasis on how project parameters led to adjustments in binder application rates. Finally, the paper summarizes the construction stage with emphasis on equipment calibration, materials application and process control, traffic control and logistical aspects.

RÉSUMÉ

La route 127 est une route à deux voies entre Maynooth et la route 60 dans l'est de l'Ontario. La route a un trafic moyen journalier annuel de 1600 véhicules avec 8,5 pour cent de véhicules commerciaux. Avant 2006, le revêtement de surface consistait en un enrobé bitumineux fortement oxydé avec des sections hétérogènes non uniformes.

Le Ministère des Transports de l'Ontario (MTO) de la région de l'est a choisi un enduit superficiel double pour une section de 16,4 km de cette route comme moyen d'amélioration des caractéristiques de surface mais aussi comme stratégie de maintien avant de procéder à une pleine réhabilitation de la route. Le contrat demandait un design normal de niveau de projet incluant les essais de compatibilité liant granulat et les essais de performance de l'enduit. L'enduit comprenait une émulsion CRS-2P selon la spécification 304 provinciale de l'Ontario et un granulat de classe 1 pour la première couche et une pierre ¼-1/8 '' pour la seconde couche. Le projet a été complété par Miller Paving en 2006.

L'exposé résume les étapes de ce projet. Il souligne spécifiquement le travail en laboratoire et présente plusieurs méthodes de design incorporées, avec emphase sur la façon dont les paramètres ont conduit aux ajustements dans les taux d'application du liant. Enfin, l'exposé résume les étapes de construction avec emphase sur la calibration de l'équipement, l'application des matériaux, le contrôle du procédé et du trafic et les aspect logistiques.

1.0 INTRODUCTION

Highway 127 is a two-lane highway located in Eastern Ontario. It extends between the Town of Maynooth at the southern end and Highway 60 just East of Whitney at the northern end. It is an important link between an area of Southeastern Ontario that encompasses Bancroft, Bellville and Kingston (via Highway 62) and the East-West corridor of Highway 60, located at the southern edge of Algonquin Park.

The road is experiencing high volumes of tourist traffic during the summer months with local heavy traffic year round, consisting mainly of logging trucks, aggregate hauling trucks and other construction vehicles. The total volume of traffic is 1600 Average Annual Daily Traffic (AADT) with approximately 8.5 percent heavy commercial vehicles. Location of the project is shown in Figure 1.

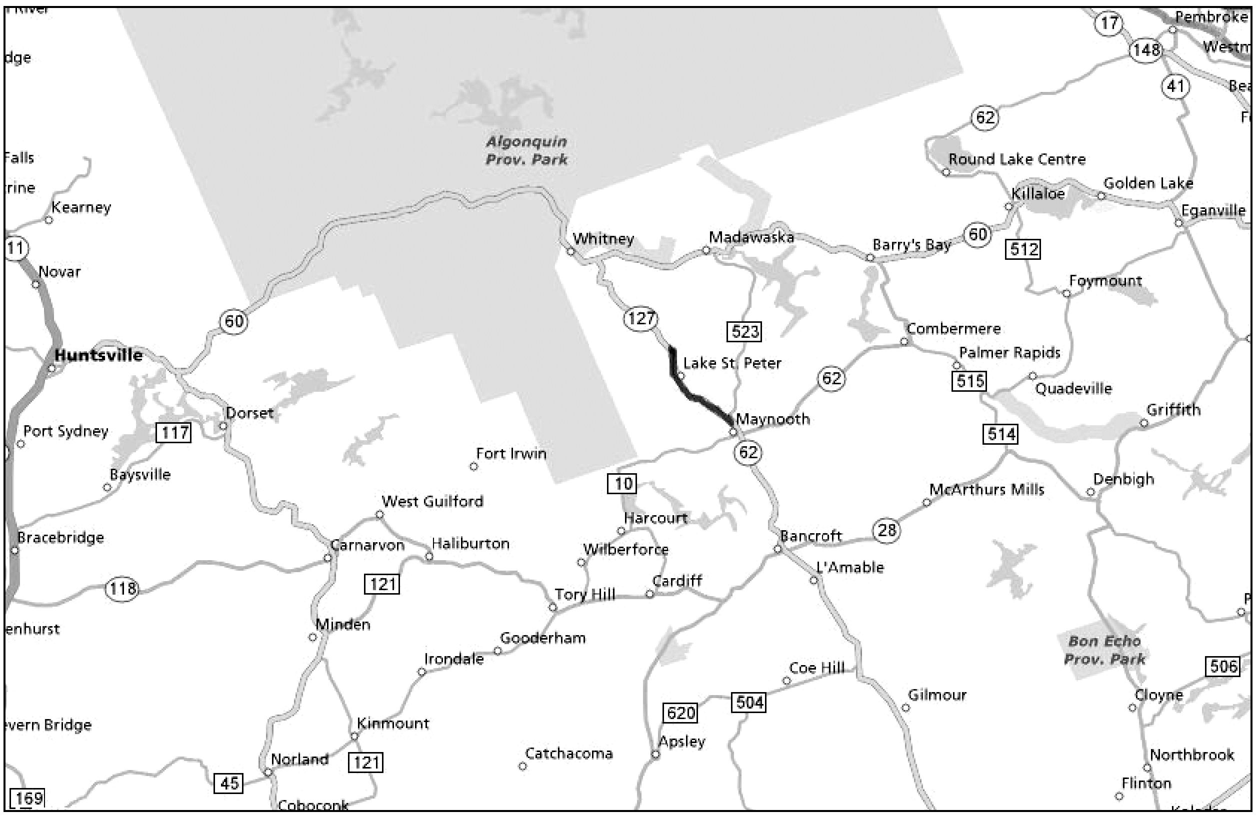


Figure 1. Location of the Resurfacing Project on Highway 127

The described section on Highway 127 was last resurfaced in 1992 when the old pavement was pulverized and then covered with a 50 mm lift of recycled hot-mix. This was the case for its entire length, except the first 1.6 km. The cold temperature performance of this hot-mix was its major shortcoming. It experienced frequent transverse cracks with slight severity throughout.

The first 1.6 km section north from Maynooth was part of a previous paving contract completed in 1990. The cracking in this section was more pronounced and the surface properties were showing more aging related distresses.

2.0 CHIP SEAL PROCESSES

2.1 Overview

One of the fundamental guidelines governing the concept of preventive maintenance has been "the right treatment on the right road and at the right time." Surface treatment applications for preventive maintenance have evolved tremendously over the last 20 to 30 years. The toolbox available to the engineer in charge of selecting a surface treatment contains a wide variety of processes and options. Ultimately, a careful analysis of each and every parameter that comes into play will determine the selection of the best-suited process for any existing situation.

Chip seals belong to a class of surface treatments commonly named "seal coatings." The terminology varies, however, with different geographical areas; in Australia the process is called "sprayed sealing", in South Africa it is known as "surfacing seal," while in the United Kingdom it is known as "surface dressing" [1]. The generally accepted terminology of "chip seals" will apply to most types of processes belonging to the seal coating family, with the possible exceptions of the graded-aggregate seals – known in some northern parts of Europe as Otta Seals.

The generic chip sealing process consists of a calibrated application of one or multiple layers of asphalt binder, combined with a calibrated application of one or multiple layers of stone – not necessarily in this particular order. This definition allows for a wide variety of seal coating types. The most commonly known seal coating types are:

- Single chip seals
- Double chip seals
- Triple chip seals
- Racked-in seals
- Sandwich seals
- Inverted double or triple seals
- Fiber or geotextile reinforced seals
- Cape seals

All the above chip-sealing types have been described in detail by the existing literature [2,3] and their characteristics will not be further discussed in the present paper.

Regardless of the type of application, the benefits of applying a chip seal include the protection of the existing road surface from water ingress and from further oxidation, as well as improved macrotexture and general aspect of the pavement. Chip seals have no major contribution to structural improvement of the existing road, with the possible exception of isolated cases where fibre reinforced seals can mitigate reflective cracking to some degree. For this reason, chip seals have to be applied on roadways where the distresses are relatively low and are not of a structural nature.

An essential project selection step involves the assessment of the degree of distress of an existing roadway. Roads that present extensive alligator or cold temperature cracking, any rutting over 10 millimetres or any widespread structural failure will not be a suitable candidate for a chip sealing application. However, if any of the major distresses are localized and not very severe, they can be repaired as part of the surface preparation process, prior to a chip seal application. Repairing could include sealing cracks, removing and replacing sections of hot-mix, patching potholes and repairing defective profiles by re-levelling road sections. For best results, these operations should be done one season before the application of the chip seal [2].

2.2 Types of Double Seals

When mentioning the term “chip seal” to any road engineer in North America, the instant mental image it brings forth will be that of a single chip seal. This is because single seals represent the vast majority of seal coatings done on our continent. Double seals are less common, while other chip seal types are practically non-existent. By contrast, designers in other parts of the world will not hesitate to utilize the full array of available seal coating types. Each type has advantages and disadvantages over the others and each type will deliver specific benefits to a particular situation.

For example, double seals are more appropriate in situations where traffic is heavy, plough damage can be severe and the general stress on the seal is high. It is also desired where flying stones can present a hazard for vehicles. Racked-in seals are best suited for any situations where the risk of dislodging the stones is high, such as tight turning areas or steep grades. Sandwich seals are excellent for repairing raveled surfaces while inverted seals are best suited for very rich or flushed substrates. Cape seals are probably the best solution for situations where high shear could damage the treatment, such as severe ploughing or high-speed heavy traffic.

One must distinguish between two different systems called “double seals”. The “classic” double seal applied in North America essentially consists of two superimposed single chip seals. The McLeod design method [4] describes this process in detail, including the necessary design corrections that have to be applied to each lift (binder spray rates and aggregate spread rates). The aggregate size for the second lift is required to be roughly half the size of the bottom lift chip.

The “true” double chip seal consists also of two layers of binder and two layers of aggregate. It also respects the size relationship between the two aggregates used for the two lifts. However, the design principle for this application is different, as it is designed as one double system and not as a combination of singles. This approach is also valid during the construction stage. Unlike the classic double, this system will not utilize any rolling between the applications of the two lifts. The second lift of binder and chips will be applied immediately after the first and then everything will be rolled simultaneously. This allows a better aggregate packing and also increases the effectiveness of the cover chip to act as a lock-in stone for the larger bottom-lift chip. The result is a tightly packed treatment, very robust and with a finer macrotexture than a single chip seal.

3.0 PROJECT SELECTION AND EVALUATION

3.1 MTO Contract # 2006-4052

When the Ministry of Transportation, Ontario (MTO) Eastern Region decided that resurfacing of a section of Highway 127 was necessary, a number of possible options were analyzed. Previous experiences with chip sealing applications on main roads in Eastern Ontario were not always positive. The main risks associated with this type of process were windshield damage due to flying stones and plough damage to the road surface during the winter. In addition, public perception associated with anything that is not hot-mix is not always positive. There have been situations in the past where local residents have complained that they were getting “second class pavements” whenever a chip seal was applied close to their residence.

However, the section of highway in cause was a good candidate for a high performance seal coating. The road profile was in good shape, with no significant rutting or base failure problems. The hot-mix asphalt was old and oxidized, but capable of continued performance if further degradation was stopped or minimized. The main concern was the relatively high number of cold temperature transverse cracks.

The decision was made by the MTO to apply a seal coating on this section of highway, but in a different manner than in the past. Ministry engineers were aware of the great progress worldwide concerning cold process technologies and that in other parts of the world, chip seals perform very well under much more severe traffic conditions. As a result, a special provision to the Ontario Provincial Standard Specification (OPSS) 304 [5] was published to include a number of additional requirements concerning the design and execution of the project.

From the start, a single chip seal application did not appear to be the best suited seal type for this road. The main concern was the amount of snowploughing that this area experiences every winter. The careful evaluation of all the other road conditions - there are a number of parameters that have to be taken into account when selecting a chip seal application [6] – pointed toward a double chip seal as the best suited type for this application. Below is a summary of the key requirements of the MTO Contract #2006-4052 concerning the materials selection and seal coating design:

- The type of application has to be a double seal coating,
- The binder has to be a polymer-modified emulsion in compliance with OPSS 1103 [7],
- The aggregate will have to come from a Designated Sources for Materials (DSM) listed source for HL1 or Superpave FC1 stone,
- The gradation of the bottom chip will have to comply with OPSS 304 [5] Class 1,
- The gradation of the top chip will have to comply with ASTM D 448 [8] Type 9,
- Both aggregates have to originate from the same geological source and parent material,
- The aggregate emulsion compatibility will have to be verified using the EN-12272-3 test [9] "Determination of binder aggregate adhesivity by the Vialit plate shock test method,"
- The spray and spread rates will have to be determined by means of a recognized formal seal coating design methodology and the design will be sealed by a licensed Professional Engineer,
- Timing for the completion of the work can be no later than the end of the month of August,
- The contractor shall warrant the work for a period of 24 months against design and workmanship defects such as loss of aggregate, flushing, streaking and delamination.

This type of contract can be classified as an "output driven contract" and is part of the general MTO strategy of moving towards End Result Specifications (ERS). Basically this means that the agency will specify "where and when," but not "how," allowing the contractor to have greater input and control over the design and the construction methods. Such contracts divide the risk between the agency and the contractor and allow the contractor to warrant the work [2].

The MTO informed the local residents of the intended road resurfacing through a mail letter program. The mailings emphasized some of the basics of pavement maintenance and pavement preservation, described the principles of a seal coating and emphasized the cost savings associated with preventive maintenance.

An informal meeting was also held with the mayors and the road superintendents of the two affected municipalities to explain the process and its benefits. Communication proved to be well worth the effort, as the residents were informed and cooperated with the contractor during the execution of the project.

3.2 Evaluation of the Road Section

The existing substrate consisted of a hot-mix asphalt surface that was oxidized moderately in some sections and severely in some other sections. The section resurfaced in 1992 was fairly homogeneous, the only exception being a few locations that were recently repaired with new hot-mix patches (Figure 2a). The area of the patched sections was minimal, amounting less than 5 percent of the total project length. These patches were full width lane repairs, applied over some areas that showed alligator cracking, and were done in the spring of 2006. Other cracks were still present, such as transverse low temperature cracking (Figure 2b) and some longitudinal cracks related to foundation distresses. Alligator cracking was not present after completion of the hot-mix patching and there was no significant rutting.

The section overlaid in 1990 extended for the first 1.6 km from Maynooth northbound and displayed more surface oxidation and more pronounced cold temperature cracking. The double chip seal was initially planned only for the section that was resurfaced in 1992, but it was decided to extend the application southbound and cover the additional 1.6 km into Maynooth. This would produce a continuous and uniform surface for the highway and would also allow an interesting performance comparison for the seal coating, applied over two road sections with different degrees of distress.

Figure 2a. Recent Hot-Mix Patching

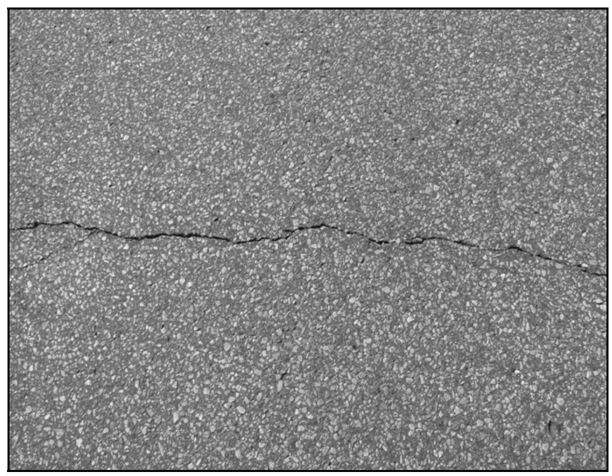


Figure 2b. Cracking in the Hot-Mix

Figure 2. Examples of the Substrate Conditions Prior to the Double Chip Seal

4.0 MATERIALS SELECTION AND DESIGN

4.1 Aggregate Selection and Properties

The aggregate selected for completion of this project came from the MRT Aggregates Inc., a quarry located approximately 22 kilometres North of Havelock, Ontario. The quarry is listed on the MTO's DSM list for hot-mix aggregate and the stone type is a meta-gabbro trap rock. The general physical properties are listed in Table 1.

Table 1. Physical Properties of Aggregate

Laboratory Test and Test Number	Result	OPSS 304 [5]
Wash Pass 75 mm Sieve, % maximum, LS-601 [10]	0.9	1.3
Absorption by mass, % maximum, LS-604 [11]	0.719	1.75
Flat and Elongated Particles, % maximum, LS-608 [12]	13.1	20
Petrographic Number (HL), maximum, LS-609 [13]	4.2	135
Unconfined Freeze Thaw loss, % maximum, LS-614 [14]	4.7	6
2 Faces Crushed Particles, % minimum, LS-617 [15]	100	60
Micro-Deval Abrasion loss,% maximum, LS-618 [16]	6.9	17

Note: OPSS is Ontario Provincial Standard Specification, LS is Laboratory Standard.

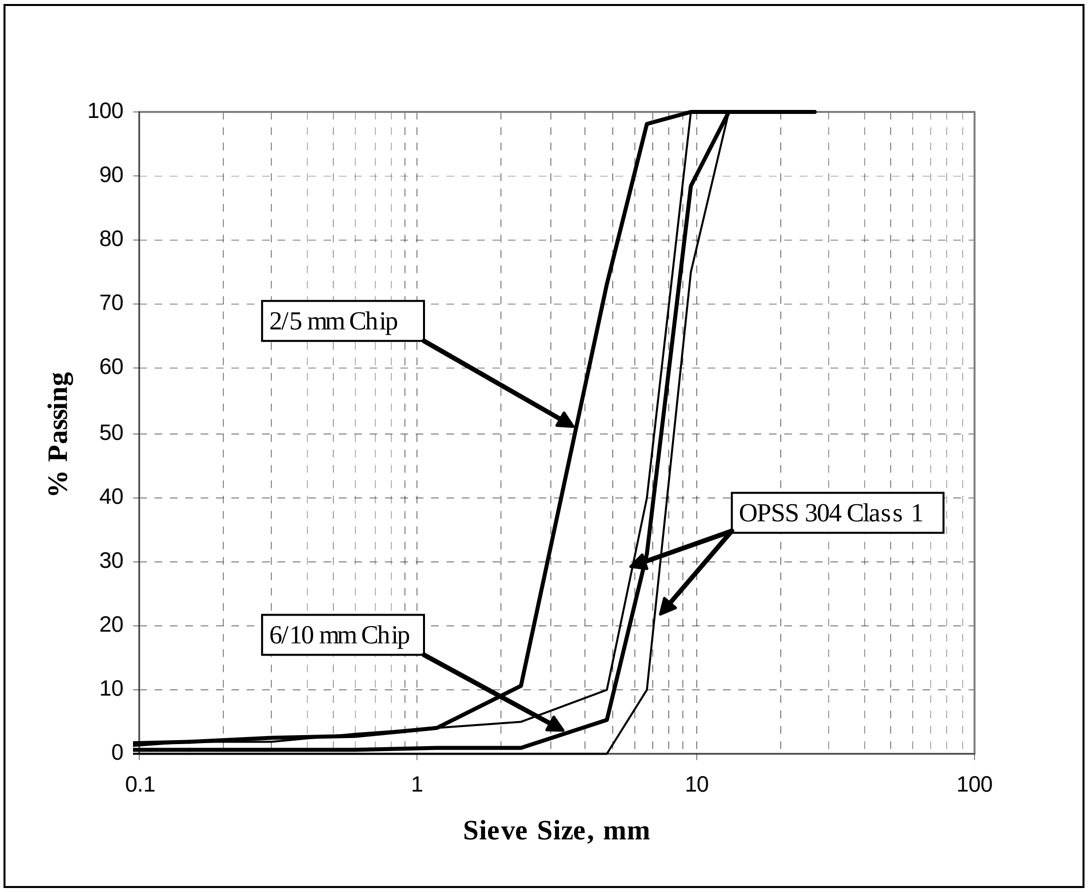
It became evident during the design stages of the double seal coating that it would be almost impossible for the aggregate quarry to prepare and supply an aggregate passing the ASTM D 448 [8] Type 9 gradation range in such a short timeframe. The closest available aggregate gradation to an ASTM D 448 Type 9 was a fine chip commonly called 1/4-1/8 inch chip. The chip was sampled and analyzed for suitability as the top layer of the double surface treatment. It essentially met all the requirements and proved to be the right size for providing good interlocking with the Class 1 stone. It was therefore decided to use this chip as a second layer application and the MTO agreed that the substitution would not have any detrimental effects. Therefore, the aggregate gradations used were a Class 1 (or 3/8 inch) chip for the bottom and a 1/4-1/8 inch chip for the top lift. Classifying these chips by a metric European system they would correspond to a 6/10 millimetre chip for the Class 1 and a 2/5 millimetre chip for the fine one.

The European grading system utilizes a small “d” and a large “D” for stone classification. Table 2 and Figure 3 show the average gradations for the two chips in tabular and in graphical form, respectively.

Table 2. Gradations for the 6/10 and 2/5 Millimetre Chips

Sieve Size, mm	Bottom Chip, % passing	Top Chip, % passing
16.0	100	100
13.2	100	100
9.5	88.4	100
6.7	31	98.2
4.75	5.23	73.3
2.36	0.9	10.7
1.18	-	3.9
0.600	-	2.9
0.300	-	2.4
0.150	-	2.0
0.075	0.48	1.6

For the design stage of any surface treatment, it is required to measure a number of aggregate properties other than the intrinsic stone properties. These properties are presented in Table 3 for both of the aggregate gradation curves.



Note: OPSS is Ontario Provincial Standard Specification.

Figure 3. Gradations for the 6/10 and 2/5 Millimetre Chips

Table 3. Physical Properties of the Two Gradation Bands

Laboratory Test	6/10 mm Chip	2/5 mm Chip
Average Least Dimension, mm	6.2	N/A
Median Dimension, mm	7.9	3.86
Flakiness Index, %	13.1	N/A
Loose Unit Weight, kg/m^3	1437	1406
Bulk Relative Density, LS-604 [11], kg/m^3	2.883	2.800
Absorption, LS-604 [11], %	0.657	0.630

Note: LS is Laboratory Standard (Ontario Ministry of Transportation).

To work as a pair of aggregates in a double chip seal system, the two aggregates had to meet a key condition: the median size of the top chip had to be between 30 and 50 percent of that of the bottom layer chip. This condition is required for achieving a proper interlocking between the aggregate and for accomplishing good packing between the lifts. In our case the ratio between the small and the large median sizes was 48.8 percent, which is excellent. This ratio has contributed greatly in accepting the 2/5 millimetre chip for usage although it does not strictly meet an ASTM D 448 [8] Type 9 gradation.

4.2 Binder Selection and Properties

The emulsion selected for this project was a CRS-2P emulsion as required by the MTO contract. The emulsion was designed and manufactured by McAsphalt Industries Limited. The base asphalt cement used was modified prior to emulsification with a thermoplastic Styrene-Butadene-Styrene (SBS) type elastomer. A number of different types of CRS-2P emulsion formulations have been considered and their breaking and curing characteristics have been assessed by using the Frosted Marble Cohesion test and DSR tests [17]. In the end, the emulsion selected has shown that it is capable of building at least 75 percent of its cohesion and its viscoelastic complex shear modulus within the first two hours, under normal curing conditions. This has been considered very important, as stone loss during the early construction stages is a major concern in cold climates. The properties of the CRS-2P emulsion as per OPSS 1103 [7] are shown in Table 4.

Table 4. CRS-2P Emulsion Properties

Laboratory Test and Test Number	Result	OPSS 1103 [7]
Viscosity, Saybolt Furol, 50ºC, SFs	290	75-400
Residue by Distilation, 204ºC, %	69.9	min. 65
Settlement, 24h, % mass	0.1	max. 1
Sieve Test, %	0.02	max. 0.2
Demulsibility, 35 ml DOSS 0.8%, %	69.1	min. 40
Oil Portion of Distillate, %	0.3	max. 3
Particle Charge	Positive	Positive
Penetration on Residue, 25ºC, dmm	129	100-250
Ash Content, %	0.16	max. 1
Elastic Recovery, 10ºC, %	67	min. 55

Note: OPSS is Ontario Provincial Standard Specification.

The emulsion was produced at the time the project started and was delivered at a temperature of 70 to 80ºC to the jobsite by tanker truck.

4.3 Aggregate–Emulsion Compatibility

4.3.1 Overview

It is known that cationic emulsions have better aggregate compatibility and build stronger interfacial bonds than anionic emulsions. This statement is generally true for most of the aggregate types and is a result of the chemical type of the emulsifiers used for producing cationic emulsions. However, testing for compatibility between aggregate and asphalt binder is probably the most important test for any bituminous process. If the chemical affinity between asphalt and stone is absent, or is less pronounced than that between aggregate and water, any further engineering becomes superfluous.

The general belief is that good aggregate–emulsion compatibility will be achieved if the stone and the emulsion will have opposite charges. This is intuitively true, however this approach is oversimplified. It is not always easy to determine the true surface that an aggregate will have while in contact with an asphalt. Surface charge of the same stone can vary from dry to wet, or with the presence of various impurities, such as dust, etc. A more correct statement might be that good aggregate-binder compatibility requires the formation of a strong chemical bond at the interface that will not be broken by water. This is an essential aspect of good compatibility but it is not yet sufficient: mechanical factors, aggregate absorption properties, microtexture, moisture content, dust films on the particles all come to play a role in creating a strong adhesive bond between aggregate and asphalt binder.

The MTO Contract #2006-4052 required that compatibility testing be measured by the Vialit adhesion test [9]. However, being in charge of the design and the material selection, the contractor believed that good compatibility was extremely important and chose to do additional tests to ensure performance. Overall, three different tests have been performed on the selected aggregate-emulsion pair: The Vialit Plate Shock, the ASTM D7000 Sweep Test, and a classical stripping test in the presence of water.

4.3.2 The Vialit Plate Shock Test Method

This test method was developed in France and is currently a standard EU test as EN 12272-3:2003 [9]. It encompasses more than one testing protocol and it is capable of measuring four different parameters: active "adhesivity," mechanical adhesion, wetting temperature and fragility temperature. We chose to utilize this test for determining the mechanical adhesion between the aggregate and the emulsion. In this test, the emulsion is placed at the bottom of a hard steel tray as a layer with a carefully controlled thickness. After pouring the emulsion, one hundred chips are manually placed uniformly across the area of the steel tray and are carefully embedded in the emulsion. The chips are used as received (without additional washing), are screened between the 9.5 and 4.75 mm sieves and then pre-conditioned for 24 hours in a refrigerator at 5ºC before embedding.

The specimens are then fully cured. We chose to cure them at ambient temperature in the laboratory over 3 to 4 days and avoided exposing them to force draft ovens or heat lamps. Once curing is complete (i.e. constant mass is achieved), each tray is placed upside down on a frame and receives three shocks from a 500 gram steel ball that is dropping from a height of 50 centimetres. The number of dislodged chips is then counted and the mechanism of failure is judged. If chips fail while fully stained with asphalt, the failure is judged as cohesive. If chips fail unstained or partially stained, the failure is deemed to be adhesive and a parameter called "Adhesivity Value" is calculated.

After performing this test on a sample of MRT Class 1 aggregate (screened between 9.5 and 4.75 mm) not one chip was dislodged from the three trays tested. This is an excellent result, translating into an Adhesivity Value of 100 percent. As a threshold, the European specification recommends a maximum of 20 chips out of 100 to be the absolute maximum allowable failure rate. Figure 4a shows a picture of the three Vialit specimens after the performance of the shock test.

4.3.3 The ASTM D 7000 Sweep Test

The Sweep Test is aimed at determining the capability of an emulsion to retain stone through a combination of adhesive and cohesive properties. Specimen preparation consists of spreading a precise amount of emulsion on an asphalt felt disk, then uniformly spreading the aggregate fraction collected between the 9.5 and 4.75 mm sieves. The spray and spread rates are defined by the test protocol and have no direct relation with field application rates. Specimens are compacted using a specially designed compactor and then cured. Once fully cured the specimens are brushed off with the fingertips to remove loose stone and then they are swept for 1 minute in a Hobart mixer, using a specially designed nylon brush. Weights are recorded prior to and after sweeping and the percent mass loss during sweeping is calculated.

Figure 4a. Vialit Plates after the Shock Test

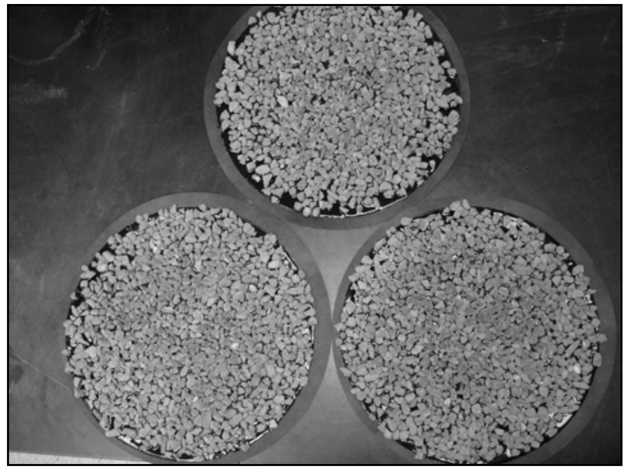


Figure 4b. Sweep Test Specimens after Sweeping

Figure 4. Vialit and Sweep Test Specimens after Completing the Tests

Performing the Sweep Test on a fraction of the coarse chip and the CRS-2P emulsion again produced very good results. The average sweep loss from three specimens was 0.72 percent by mass. There are yet no established pass/fail criteria for this procedure but a sweep loss of 0.72 percent is as good as we have seen during several years of performing this test. Picture 4b shows the specimens after performing the sweep.

4.3.4 OPSS 1153 Stripping Test

Both the Vialit and the Sweep test evaluate the aggregate-binder bond strength in a dry state. We found it absolutely necessary to ensure that the compatibility between the two components remains in the presence of water. As a result we decided to perform a classical stripping test on a sample of aggregate coated with the CRS-2P emulsion.

The method described in OPSS 1153 [18], Section 1153.03.01.01 is a quick, simple and effective stripping test. The coated specimens are boiled for 3 minutes in water with stirring and then the residual coating is evaluated visually. This test was performed on both the 6/10 and 2/5 millimetre chips. Retained coating was practically 100 percent for both aggregates, showing that the asphalt-stone bond remains strong also in the presence of water. Figure 5 shows the retained coating for the two size chips.

4.4 Chip Seal Design

4.4.1 Overview of Design Methods

A number of chip sealing design methods have been established worldwide. The most common method in North America is the McLeod method [4]. It was developed in the sixties by Dr. Norman McLeod and is based on a semi-empirical approach. Over the years it has been modified and adjusted to reflect changes in road conditions, traffic levels and in emulsion performance. Forty years later it still remains one of the most solid design methods and the starting point for a number of evolving design trends. Its major limitations lie with designing more complex seal coating systems such as sandwich seals, and racked-in seals.

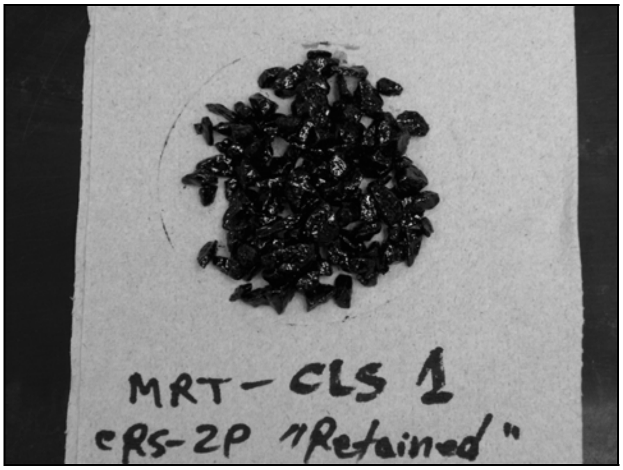


Figure 5a. Retained Coating - 6/10 mm

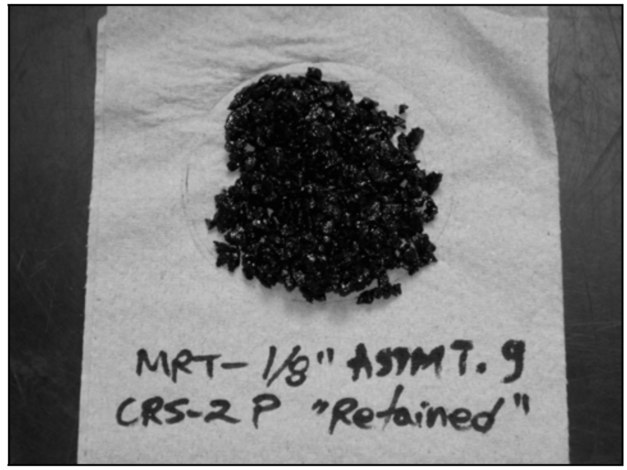


Figure 5b. Retained Coating – 2/5 mm

Figure 5. Retained Coating for the Two Sizes of Chips

Newer design methods have since been developed worldwide. The trend is that the newer methods are based on engineering principles and algorithms with associated software that facilitates the input of all the project parameters and the output of the design data. They not only calculate spray and spread rates for aggregate and binder, but also help selecting the optimum seal coating type for an existing project. The most important design methods are the United Kingdom (UK) Road Note 39 method [6], the Australian Austroads method [19], the French Alogen method [20] and the South African TRH3 method [21]. These methods are described in literature and we will not illustrate them in this paper.

The general design principle for all the designs follows approximately the same thought process. A basic spray and spread rate will be calculated based on aggregate size, roadway condition and traffic volumes. A first adjustment is then performed based on aggregate characteristics such as average least dimension, flakiness and size distribution. A second set of adjustments is then completed to account for surface condition (rich, dry, flushed, etc.), local conditions (grades, shade, etc.) and other project specifics.

For the double chip seal on Highway 127 we have utilized three design methods; the modified McLeod [4], the UK Road Note 39 [6] and the French Alogen [20]. After evaluating the outcome of each design method, values for aggregate spread rates and emulsion spray rates were selected based on our best judgment from the three design outputs.

4.4.2 Evaluation of the Road Conditions

The first step of a chip seal design involves determining the input parameters for the project. This requires surveying the road section, then identifying parameters such as traffic volume, speed, percent heavy vehicles, surface texture and hardness, climatic characteristics, grades, shade, ploughing, etc.

The whole 16.4 km length of the project was carefully mapped and recorded. Five major sections had different design input parameters and required a separate design. Each of the five sections is composed of a number of smaller sections scattered over the length of the project, with similar conditions. Table 5 summarizes the design conditions for each of the five sections.

Table 5. Design Parameters for Sections 1 to 5

Section 1 – 3 sections totalling 2900 m			
Traffic	50-100 CV/day/lane	Speed	80 km/h
Substrate Type	Bound	Homogeneity	Homogeneous
Hardness	Hard	Permeability	Somewhat permeable
Substrate Conditions	Lean & normal rough	Grade	Straight
Layout	Flat	Region	Cold
Shade	Somewhat shaded	Timing of Work	July/August
Snow Plough	Yes	Flying Chip Concern	Yes
Traffic Readiness	No	Noise Concern	No
Section 2 – 2 sections totalling 200 m			
Traffic	50-100 CV/day/lane	Speed	80 km/h
Substrate Type	Bound	Homogeneity	Homogeneous
Hardness	Hard	Permeability	Somewhat permeable
Substrate Conditions	No bleeding & smooth	Grade	Straight
Layout	Flat	Region	Cold
Shade	Somewhat shaded	Timing of Work	July/August
Snow Plough	Yes	Flying Chip Concern	Yes
Traffic Readiness	No	Noise Concern	No
Section 3 – 7 sections totalling 12350 m			
Traffic	50-100 CV/day/lane	Speed	80 km/h
Substrate Type	Bound	Homogeneity	Homogeneous
Hardness	Hard	Permeability	Somewhat permeable
Substrate Conditions	Lean & normal rough	Grade	Straight
Layout	Flat	Region	Cold
Shade	Normal	Timing of Work	July/August
Snow Plough	Yes	Flying Chip Concern	Yes
Traffic Readiness	No	Noise Concern	No
Section 4 – 5 sections totalling 700 m			
Traffic	50-100 CV/day/lane	Speed	80 km/h
Substrate Type	Bound	Homogeneity	Homogeneous
Hardness	Hard	Permeability	Somewhat permeable
Substrate Conditions	No bleeding & smooth	Grade	Straight
Layout	Flat	Region	Cold
Shade	Normal	Timing of Work	July/August
Snow Plough	Yes	Flying Chip Concern	Yes
Traffic Readiness	No	Noise Concern	No
Section 5 – 1 section totalling 250 m			
Traffic	50-100 CV/day/lane	Speed	80 km/h
Substrate Type	Bound	Homogeneity	Homogeneous
Hardness	Hard	Permeability	Somewhat permeable
Substrate Conditions	Lean & rough	Grade	Straight
Layout	Flat	Region	Cold
Shade	Normal	Timing of Work	July/August
Snow Plough	Yes	Flying Chip Concern	Yes
Traffic Readiness	No	Noise Concern	No

Surface roughness and hardness were determined by the empirical visual method, without the use of the Sand Patch Test or the Ball Penetration Test. A number of other input parameters were the same throughout the whole project, such as climate, timing of work, traffic, grade, etc. The variables that warranted design changes were the substrate condition and the shaded areas.

4.4.3 Completing the Designs

Designs were calculated by using the three design methods previously mentioned. For each of the five sections, the inputs for the materials used were the two chip sizes and the CRS-2P emulsion with a residue of 69 percent. The coverage factors for the aggregate were set at 95 percent for the bottom lift and 105 percent for the top lift. Table 6 lists the outcomes for the design methods selected, for each section.

Table 6. Design Outcomes for Sections 1 through 5

Section	Method	Spray Rate	Bottom Layer (Notes 1 and 2)	Top Layer
Section 1	French Alogen Method	Emulsion	1.15 l/m^2	1.45 l/m^2
		Aggregate	7-8 kg/m^2	4-5 kg/m^2
	UK Road Note 39 Method	Emulsion	1.3 l/m^2	
		Aggregate	9-13 kg/m^2	
	Modified McLeod Method	Emulsion	1.02 l/m^2	1.53 l/m^2
		Aggregate	17 kg/m^2	7 kg/m^2
Sections 2 and 3	French Alogen Method	Emulsion	1.10 l/m^2	1.40 l/m^2
		Aggregate	7-8 kg/m^2	4-5 kg/m^2
	UK Road Note 39 Method	Emulsion	1.2 l/m^2	
		Aggregate	9-13 kg/m^2	
	Modified McLeod Method	Emulsion	1.02 l/m^2	1.53 l/m^2
		Aggregate	17 kg/m^2	7 kg/m^2
Section 4	French Alogen Method	Emulsion	1.05 l/m^2	1.40 l/m^2
		Aggregate	7-8 kg/m^2	4-5 kg/m^2
	UK Road Note 39 Method	Emulsion	1.1 l/m^2	
		Aggregate	9-13 kg/m^2	
	Modified McLeod Method	Emulsion	1.02 l/m^2	1.53 l/m^2
		Aggregate	17 kg/m^2	7 kg/m^2
Section 5	French Alogen Method	Emulsion	1.15 l/m^2	1.40 l/m^2
		Aggregate	7-8 kg/m^2	4-5 kg/m^2
	UK Road Note 39 Method	Emulsion	1.3 l/m^2	
		Aggregate	9-13 kg/m^2	
	Modified McLeod Method	Emulsion	1.02 l/m^2	1.53 l/m^2
		Aggregate	17 kg/m^2	7 kg/m^2

Note 1: The French Alogen Method consistently recommended aggregate spread rates that were considered too low.

Note 2: The bottom layer aggregate spread rate recommended by the Modified McLeod Method was considered too high.

As a note, each of the three design methods recommends increasing the spray rate by some amount if the work is carried out during the late season, such as September, to compensate for the reduced curing time available and for the reduced embedment that the chip will experience before the winter.

From analyzing Table 6 it is evident that the total spray rates calculated by the three methods are very close, in the range of 2.5 to 2.6 litres per square metre. However, the distribution of the binder between the two layers varied with each method. The McLeod method yields an aggregate spread rate for the bottom layer that is obviously too high for a desired 95 percent coverage, showing its limitation when it comes to designing a modern double chip sealing system.

4.4.4 Final Design Selection

From the three design methods studied, the French Alogen method produced what seemed to be the best-balanced results and also somewhat the most intuitive. It is also the only method of the three that explicitly takes into account the ploughing that occurs on a chip sealed road. Based on a careful analysis of each of the three design outputs, a final recommended spray and spread was selected for each of the five sections. The summary of the selected design parameters and the design per individual section as received by the working crew are summarized in Tables 7 and 8.

Table 7. Recommended Design Parameters for all Five Sections

Cond. No.	Type	Layer	Binder	Spray Rate				Chippings	Spread Rate (% Coverage)
				Designed		Recommended			
1	DCS	Bottom	CRS-2P	1.15	l/m^2	**1.20**	**l/m^2**	OPSS 304 Class 1	10.5 kg/m^2 (95%)
		Top	CRS-2P	1.45	l/m^2	**1.40**	**l/m^2**	2/5 mm	7 kg/m^2 (105%)
2	DCS	Bottom	CRS-2P	1.10	l/m^2	**1.10**	**l/m^2**	OPSS 304 Class 1	10.5 kg/m^2 (95%)
		Top	CRS-2P	1.40	l/m^2	**1.40**	**l/m^2**	2/5 mm	7 kg/m^2 (105%)
3	DCS	Bottom	CRS-2P	1.10	l/m^2	**1.10**	**l/m^2**	OPSS 304 Class 1	10.5 kg/m^2 (95%)
		Top	CRS-2P	1.40	l/m^2	**1.40**	**l/m^2**	2/5 mm	7 kg/m^2 (105%)
4	DCS	Bottom	CRS-2P	1.05	l/m^2	**1.05**	**l/m^2**	OPSS 304 Class 1	10.5 kg/m^2 (95%)
		Top	CRS-2P	1.40	l/m^2	**1.40**	**l/m^2**	2/5 mm	7 kg/m^2 (105%)
5	DCS	Bottom	CRS-2P	1.15	l/m^2	**1.15**	**l/m^2**	OPSS 304 Class 1	10.5 kg/m^2 (95%)
		Top	CRS-2P	1.40	l/m^2	**1.40**	**l/m^2**	2/5 mm	7 kg/m^2 (105%)

Note: DCS stands for Double Chip Seal.
OPSS is Ontario Provincial Standard Specification.

Table 8. Recommended Design Parameters per Individual Section

Sect.	Stations			Distance (m)		Design Cond.
	Start	to	End			
1	00+000	to	01+800	1800	m	1
2	01+800	to	01+900	100	m	2
3	01+900	to	02+100	200	m	1
4	02+100	to	02+200	100	m	2
5	02+200	to	03+100	900	m	1
6	03+100	to	05+600	2500	m	3
7	05+600	to	05+650	50	m	4
8	05+650	to	10+900	5250	m	3
9	10+900	to	11+150	250	m	5
10	11+150	to	11+300	150	m	3
11	11+300	to	11+600	300	m	4
12	11+600	to	11+650	50	m	3
13	11+650	to	11+700	50	m	4
14	11+700	to	11+850	150	m	3
15	11+850	to	12+100	250	m	4
16	12+100	to	16+100	4000	m	3
17	16+100	to	16+150	50	m	4
18	16+150	to	16+400	250	m	3

5.0 PLACEMENT OF THE DOUBLE SEAL

The work was completed during the second part of August 2006, just about as late in the season as the contract allowed. Any delays would have jeopardized the outcome of the application, as the risk of failure increases with the shortening of the warm weather period that the seal coating will experience after placement. In our climate, the timing of the work becomes especially important as it is not uncommon for the months of September and October to be cold and damp. The weather during the execution of the double chip seal on Highway 127 was seasonally warm, with temperatures between 20 and 25 degrees Celsius and no rain.

The contractor mobilized the following equipment for the job: two Etnyre distributors with computer controlled application; one Etnyre computer controlled chip spreader with variable width for the application of the bottom 6/10 millimetre chip, one Etnyre fixed-width chip spreader for the top 2/5 millimetre chip, two Dynapac pneumatic rollers, one Dynapac steel grade roller, and one broom. About one week prior to the start of the job, the distributors were re-calibrated using the ASTM D 2995 [22] procedure. Calibration checks for the distributors were performed after the application of each section, usually between 1.2 and 1.6 kilometres.

The chip spreaders were also re-calibrated one week prior to the start of the job, using ASTM D 5624 [23]. The aggregates were stockpiled within half a kilometre of the highway. The monitoring of the aggregate distribution was performed by loading each aggregate truck with four buckets of a 2.5-yard loader, as no scale was available in the yard or close-by.

The roadway was swept each morning prior to starting the application. Each chip spreader had to follow its distributor very closely, as the CRS-2P emulsion breaks very quickly. The two lifts were applied simultaneously with one distributor/chipper combination laying the first application followed closely by the second distributor/chipper combination applying the second layer (Figure 6a). The two applications were kept approximately 100 metres apart. Visual monitoring of the Class 1 stone along with the computer-controlled spreader enabled us to maintain the 95 percent coverage desired for the bottom lift.

The rolling was performed following the second application with the two pneumatic rubber rollers and then the steel grade roller (Figure 6b). The grade roller, although not necessary, had no ill effects and did help with chip embedment. The rolling pattern for the pneumatic rollers consisted in “up and back” twice totalling a minimum of three passes on the mat. The steel roller went “up and back” once, completing one pass as the mat was approximately 4.25 metres wide and the roller width is 2.1 metres. Vibratory mode on the steel roller was set to “off.”

Traffic control was set up as per the Ontario Traffic Manual (OTM) [24] for a two-lane highway. A designated construction zone was declared and speed limits were reduced from 80 to 60 kilometres per hour. Paid duty Ontario Provincial Police (OPP) officers were employed to enforce the designated speed zone. Maximum road closures were two kilometres long, as per the OTM. They were shortened as necessary, for intersections or other local conditions.

The entire 16.4 kilometres of the two-lane Highway 127 was double seal coated during four working days, averaging eight working hours per day. The roadway was swept approximately one week after completion, just prior to painting the road lines. Because of the size of the top chips, windshield damage was not considered to be a high risk, even prior to the final sweeping of the road.

The finished application looked uniform and tightly packed. Its macrotexture was finer than that of a single, but still more open than one of a dense graded hot-mix. The colouration of the treatment is quite dark due to the dark colour of the trap rock, belonging to the basaltic aggregate family. The dense and dark aspect of the seal coat gives it the look of a microsurfacing application to some degree.

Figure 6a. Applying Second Layer of Chips

Fig 6b. Rollers used for Compaction

Figure 6. Placement and Rolling of the Double Chip Seal

6.0 IN-SERVICE PERFORMANCE

It is still a bit early to call the double chip seal on Highway 127 a complete success, as it has not yet lived through a full season. However, it has survived the first winter rather well, with minimal plough damage and some minor spots that could require some localized repair. It still has to pass a full summer, however the aspect of the double seal today suggests that risk of flushing is minimal. The texture looks excellent and it provides a comfortable ride with good skid resistance (Figure 7a). The stone retention capability of the binder is greatly increased by the presence of the polymer in its structure (Figure 7b).

Figure 7a. Macrotexture of the Double Seal

Figure 7b. Enhanced Stone Retention

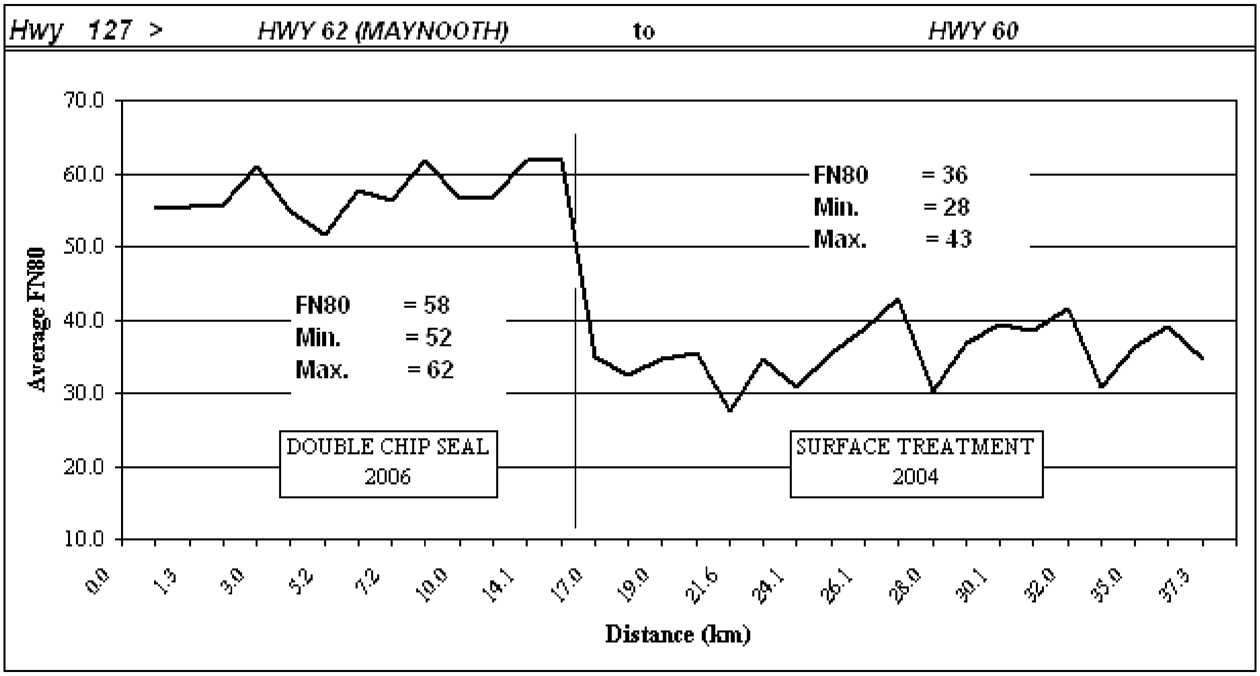
Figure 7. Seal Texture and Stone Retention Capability from Polymer Modified Asphalt

6.1 Skid Resistance Measurements

During the month of October 2006, MTO performed skid resistance measurements along the whole length of Highway 127 between Maynooth and Highway 60. Measurements were done at 80 kilometres per hour in both the northbound and southbound lanes. The outside air temperature during testing was 14ºC. The section adjacent to the new double chip seal was resurfaced in 2004 and consisted of a “classic” double chip seal – two superimposed singles. The bottom layer consisted of an OPSS 304 Class 3 and the top was a Class 1 application. The aggregate used was limestone and the emulsion CRS-2P.

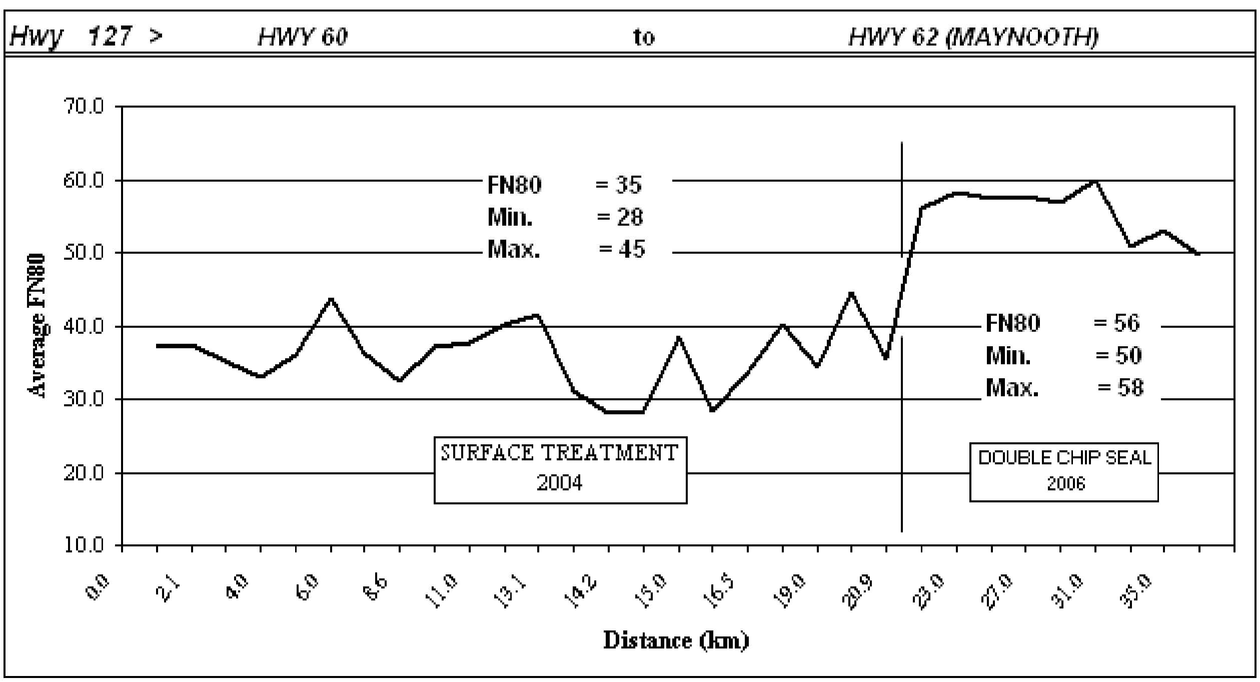
As shown in Figures 8 and 9, the friction numbers recorded on the 2004 chip seal, in the northern part of Highway 127, show good skid performance typical of surface treatments using carbonate aggregate, however, the friction numbers recorded on the southern 2006 double seal are outstanding. The main reasons for this excellent skid performance lie in the usage of the premium aggregate, as opposed to the carbonate aggregate. Also, the finished macrotexture on a true double seal is not produced only by the top aggregate but by an interlocking of the coarse chip and the finer chip.

The skid resistance measurement completed in October 2006 on the new double chip seal has produced average friction numbers of 58 in the northbound lane and 56 in the southbound lane. By comparison, average friction numbers on the adjacent 2004 surface treatment were 36 in the northbound lane and 35 in the southbound lane.



Note: FN80 is the locked wheel Friction Number recorded at 80 km/hr.

Figure 8. Average Friction Number for Highway 127 Northbound Lane



Note: FN80 is the locked wheel Friction Number recorded at 80 km/hr.

Figure 9. Average Friction Number for Highway 127 Southbound Lane

6.2 Performance after the First Winter

The entire length of the double chip seal was inspected during the month of April 2007 and its general performance so far is considered very good. Some of the distresses that have been noticed after the first winter are discussed in the following paragraphs.

Minor plough damage can be seen in some higher elevation spots, such as close to bridge joints where the plough blade bounces, or on high spots (Figure 10a). The number of places where plough damage was observed is low. Also, there is some delamination damage in one or two areas. An examination led us to believe that it was also caused by snowploughs and it occurred at the centreline where adhesion of the emulsion over the old painted centre line was reduced (Figure 10b).

Some old cracks have shown through the double seal, but this was not a surprise as it is a non fibre-modified chip seal (Figure 10a). Most of the observable reflective cracking is located at the southern end, over the 1990 section of 1.6 km that was in rougher shape. The vast majority of the transverse cracks have not reflected through the seal coating. Chip seals are usually more flexible than other surface treatments, such as microsurfacing or slurry seal and are usually capable to bridging cracks better. It will be interesting to monitor some of the cracks that have reappeared, to determine if any healing will occur during the hot summer months.

One observation from the MTO Contracts Office is that applying and maintaining zone striping is more difficult. A follow-up application of road markings on the double seal was done during a warm spell in January 2007. Another comment was that it took more de-icing material to maintain the de-icing standard required on such a highway during the first winter. Both these statements are valid not only for the 2006 double chip seal on Highway 127 but also have been previously noticed on other chip sealed roads.

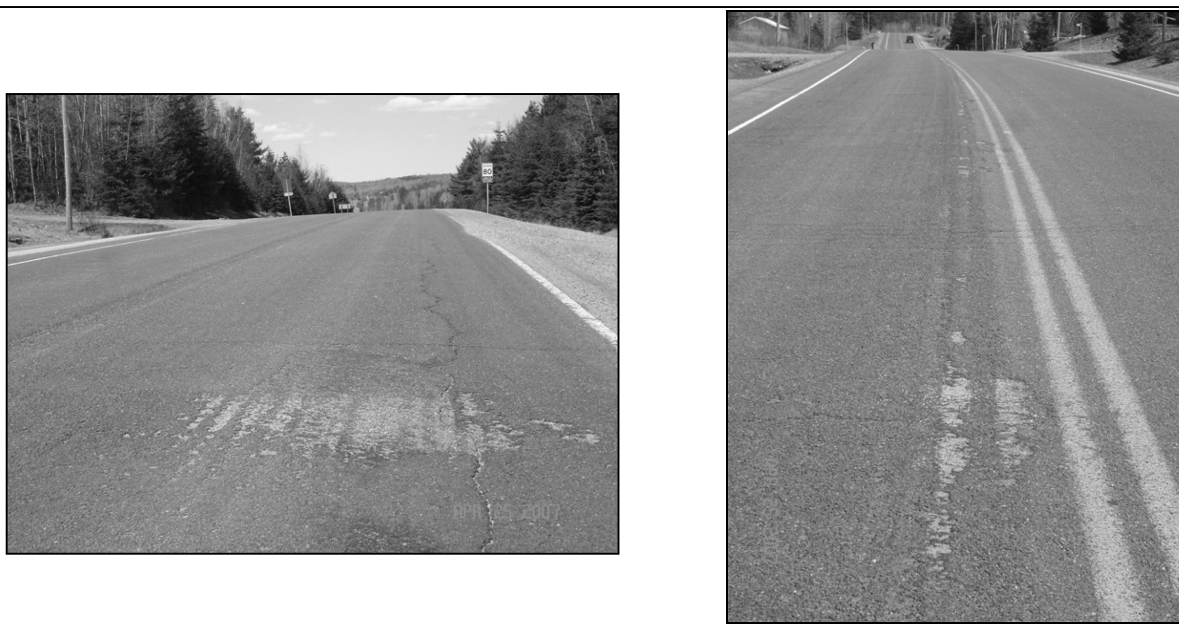


Figure 10a. Plough Damage and Longitudinal Crack **Figure 10b. Plough Damage at Centreline**

Figure 10. Distresses Observed After the First Winter in Service

7.0 SUMMARY

The resurfacing work completed on Highway 127 in Eastern Ontario in the summer of 2006 was a new approach to surface treatment in Ontario (Figure 11). It represented a departure from the “that’s how we always did it” philosophy, still too widespread in North America in regard to seal coatings. Instead, the desire was to adopt a project selection and design based on good engineering principles, strict material selection and control and best practices with respect to the field application.

The contract requirements were more complex than in the past - requiring that the aggregate be of high quality with strict mineralogical and size requirements. It also required proof that the aggregate and emulsion have good compatibility and demanded that a Vialit adhesion performance test be completed (although not for approval purposes). The need for a formal design for the seal coating, prepared by a licensed engineer was also stipulated in the contract.

Material selection was very strict. Aggregate quality prevailed over proximity. Emulsion selection was done after carefully assessing breaking and curing characteristics. Instead of one adhesion test, required by the contract, it was chosen to perform three separate procedures, two aimed directly at chip seal performance and one targeting stripping resistance in water.

The project selection was in itself a key step for assuring a high quality outcome. Based on the local traffic, environmental conditions and the type of roadway and substrate, a double seal was the best-suited chip seal type. The double seal selected was a “true” double seal, where both lifts are compacted simultaneously and not the “classic” double where the system is effectively composed of two singles. The entire road length was inspected and all sections with different input parameters have been identified. Subsequently, designs were completed separately for each section. Three different design methods were used to determine spray and spread rates, using separate input parameters for each of the five sections. Results from every design were analyzed and optimum spray and spread rate was determined.

Figure 11. Sections of Highway 127 after Project was Completed

The project was completed in August 2006. Best practices were emphasized during the construction of the double seal. Equipment was thoroughly calibrated and calibrations were verified periodically. Surface preparation was observed carefully and binder spray rates were adjusted according to the design for each section. The two lifts of the double seal were applied in close sequence, without compaction in-between the first and the second application. Compaction was done using two pneumatic rollers, followed by a steel roller. Traffic control was strictly enforced with paid OPP officers on duty. Skid resistance numbers measured during October 2006 were excellent.

The approach to this project was strongly influenced by seal coating work done overseas, especially in the UK, France, Australia and New Zealand. These countries have utilized seal coatings with a much higher degree of success and are finding this application type suitable for much higher traffic levels than North America. It is also true that the methodology relies on stricter control of materials and on more in-depth engineering design and execution for the seal coatings. We will continue to monitor the behaviour of the double chip seal on Highway 127 and with that, will continue to improve our in-depth understanding of the seal coating process, especially associated with the prediction of its long term performance.

REFERENCES

[1] Davidson JK, Houston G, Linton P, Croteau JM. “An Overview of the Design of Emulsion Based Seal Coating Systems Available in Canada and Abroad”, Proceedings, Canadian Technical Asphalt Association, 50, 363-377 (2005).

[2] Gransberg D, James DMB. Chip Seal Best Practices, National Cooperative Highway Research Program (NCHRP) Synthesis 342, Transportation Research Board, National Research Council, National Academies, Washington, D.C. (2005).

[3] “Bitumen emulsions: General Information”, Syndicat des fabricants d'émulsions routières de bitume, Paris, France; 118-147 (1991).

[4] McLeod NW. “A General Method of Design for Seal Coats and Surface Treatments”, Proceedings, Association of Asphalt Paving Technologists, 38, 537-630 (1969).

[5] “Construction Specification for Single and Double Surface Treatments”, OPSS 304, Ontario Provincial Standard Specification, Ontario Ministry of Transportation, Downsview, Ontario (2006).

[6] Nicholls JC et al. “Design Guide for Road Surface Dressing”, Road Note 39, Fifth Edition, Transportation Research Laboratory Limited, Crowthorne, United Kingdom (2002).

[7] “Material Specification for Emulsified Asphalt”, OPSS 1103, Ontario Provincial Standard Specification, Ontario Ministry of Transportation, Downsview, Ontario (2006).

[8] ASTM International (ASTM) D 448-03a, “Standard Classification for Sizes of Aggregate for Road and Bridge Construction”, Annual Book of ASTM Standards, Road and Paving Materials; Vehicle-Pavement Systems, 04-03, West Conshohocken, Pennsylvania (2007).

[9] EN 12272-3:2003, Surface Dressing – test Method – Part 3: “Determination of Binder Aggregate Adhesivity by the Vialit Plate Shock Test Method“, European Committee for Standardization, Bruxelles (2003).

[10] “Method of Test for Materials Finer than 75 μm Sieve in Mineral Aggregates by Washing”, Test Method LS-601, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[11] "Method of Test for Relative Density and Absorption of Coarse Aggregate", Test Method LS-604, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[12] "Method of Test for Determination of Flat and Elongated Particles in Coarse Aggregate", Test Method LS-608, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[13] "Procedure for Petrographic Analysis of Coarse Aggregate", Test Method LS-609, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[14] "Method of Test for Freezing-and-Thawing of Coarse Aggregate", Test Method LS-614, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[15] "Method of Test for Determination of Percent Particles with Two or More Crushed Faces and Uncrushed Particles in Processed Coarse Aggregate", Test Method LS-617, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[16] "Method of Test for the Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus", Test Method LS-618, Laboratory Testing Manual, Ministry of Transportation, Ontario (2006).

[17] Kucharek AS, Davidson JK, Croteau JM. "Chip Sealing Systems: Improving Early Age Chip Retention", Proceedings, 10th International Conference on Asphalt Pavements, International Society for Asphalt Pavement (ISAP), Quebec City, Canada (2006).

[18] "Material Specification for Emulsified Asphalt Patching Material", OPSS 1153, Ontario Provincial Standard Specification, Ontario Ministry of Transportation, Downsview, Ontario (2006).

[19] "Austroads Provisional Sprayed Seal Design Method, Revision 2000", Sprayed Seal Design Project Group, Austroads Incorporated, Sydney NSW Australia (2000).

[20] "Enduits superficiels d'usure: Guide technique", Ministère de l'Aménagement du territoire, de l'Équipement et des Transports, Paris, France (1995).

[21] "Draft Technical recommendation for Highways 3, (TRH3) Surfacing Seals for Rural and Urban Roads" Committee of State Road Authorities, Department of Transport for CSRA, South Africa (1998).

[22] ASTM International (ASTM) D 2995-99, "Standard Practice for Estimating Application Rate of Bituminous Distributors", Annual Book of ASTM Standards, Road and Paving Materials; Vehicle-Pavement Systems, 04-03, West Conshohocken, Pennsylvannia (2007).

[23] ASTM International (ASTM) D 5624-02, "Standard Test Method for Determining the Transverse-Aggregate Spread Rate for Surface Treatment Applications", Annual Book of ASTM Standards, Road and Paving Materials; Vehicle-Pavement Systems, 04-03, West Conshohocken, Pennsylvannia (2007).

[24] Ontario Ministry of Transportation. Ontario Traffic Manual: Book 7 - Temporary Conditions, Ontario Ministry of Transportation, Downsview, Ontario (2001).