Seal Coat Systems in Canada: performances and practice

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Paper prepared for presentation at the
“Soils and Materials – Investing in new materials, products and processes” session

at the 2005 Annual Conference of the
Transportation Association of Canada
Calgary, Alberta

ABSTRACT

Seal coat systems have been used in Canada and other countries for many decades. In fact, the development of the seal coat system is closely associated with the increased usage of the automobile as a means of transportation at the turn of the 20^{th} century. Today it is the most common type of roadway surfacing in Canada.

Seal coat is a thin wearing course made of superimposed layers of aggregate and bituminous binder. This type of treatment may be used to restore the surface characteristics of existing worn out roadway or to waterproof and preserve an existing roadway. They may be applied onto an existing bound material or an unbound road base.

This type of treatment forms an impervious thin overlay over an existing bound or unbound surface. Seal coat systems may be divided into two families of treatments: the *chip seal system* and *graded seal systems.* Chip seals combine the application of a layer of calibrated chips onto a layer of a cationic rapid setting bitumen emulsion while the graded seals are systems that combine the application of a dense graded or gap graded aggregate onto a layer of anionic high float type bitumen emulsion. Each system may be applied as a single application or a multiple application. Seal coat systems may be applied at spread rates that range from 14 kg/m^2 for a single chip seal applied onto an existing bituminous surface to 40 kg/m^2 for a double high float seal treatment applied onto an unbound granular base.

Many parameters such as the traffic and the existing surface conditions must be taken into account in the design of a specific seal coat system for a given roadway. Field adjustments are also very important; field conditions such as ambient temperature, the time of the year, the sun/cloud conditions must be taken into account as well. The success of this type of treatment is not only associated with the selection of an optimal design but also with the close attention to the local conditions during the field application.

This paper presents an overview of the seal coating technologies and a discussion on the state of the practice including, design practices, construction procedures of these surface treatments in Canada and abroad. In addition, the paper introduces new concepts related to the selection of seal coating systems as well as the emerging chip sealing systems now available in North America.

CONCEPTS

Surface treatments consisting of superimposed layers of bituminous binder and cover aggregate have been used for many decades. For the purpose of this paper, this type of treatment is referred to as seal coating. The development of seal coating systems is closely associated with the increased usage of the automobile as a means of transportation. Today, this is the most common type of surfacing system in Canada. It is estimated that approximately 40 million square meters of this treatment is placed every year in Canada. The usage of this type of treatment varies greatly from one province to another in Canada. This paper presents an overview of the systems available in North America and abroad, and a discussion on the state of the practice including, design practices, construction procedures and the performance of these surface treatments.

Definitions

Unfortunately, there is still no universally accepted nomenclature for this type of treatment of the surface of a roadway. In Canada and the United States, it is often referred to as *seal coats, chip seals* or simply *surface treatment*. In the United Kingdom, the term *surface dressing* is used. In Australia, the successive application of bituminous binder and cover aggregate is referred to as *sprayed sealing*. In South Africa, it is called *surfacing seals.* As indicated above, for the purpose of this paper the expression ***seal coating*** is used to designate the different families of processes that may be associated with the superimposed layers of bituminous binder and cover aggregates.

Reasons for seal coating roadways

This type of treatment may be used for the purpose of restoring the surface characteristics of roadway, texture and friction, as a preservation treatment, to stop ingress of water and oxidation of bituminous surfacing, or as a surfacing sealing system applied on top of a consolidated unbounded base material. However, it should be noted that seal coating systems do not have the ability to correct the profile of a roadway or the ability to strengthen the roadway structure.

Texture and friction: The texture and the friction properties of surfaces are dependent on the nature of the aggregate mosaic at the surface of the roadway. The aggregate mosaic is a function of both, the micro-texture and macro-texture of the surface of the road. The micro-texture is the texture of the aggregate, while the macro-texture is the overall texture of the surface. The micro-texture provides friction at all speeds, while the macro-texture provides surface drainage and it contributes to friction at higher speeds. Seal coating systems using a carefully selected aggregate can provide both micro-texture and macro-texture.

Ingress of water: Seal coating systems may be used to cover and protect the existing structure against the damage caused by the atmospheric elements. The membrane like binder can be effective in sealing binder-lean or oxidized surfaces as well as sealing minor non active cracks. As for any other preventive maintenance treatment, if applied before the appearance of any major structural deficiencies, seal coating systems will preserve the integrity of the roadway structure, delaying the requirements for major repairs, thus contributing to prolonging the life of the roadway.

Surfacing system: Seal coating of granular base material is a common practice in Canada. It is a cost effective surfacing system for low volume roads. Low volume roads often consist of layers of granular material placed on top of frost susceptible roadbed soils. Distortion caused by the differential frost heaving actions is common for this type of structure. Seal coating surfacing systems have membrane-like mechanical properties, which provide them with the ability to follow moderate distortion induced by differential frost heaving.

TYPE OF SEAL COATING SYSTEMS

Seal coating systems may be separated into two main families of systems: the one-sized aggregate systems are referred to as *chip seals* and the graded-aggregate systems are referred to as *graded seals.* Within each of these families of systems there are several types of systems that vary according to the number of layers of aggregate and binder. There are the single type systems which consist of a single application of binder and aggregate and there are the multiple systems which consist of one or many applications of binder and aggregate. Table 1 summarizes the type of systems available within each family of seal coating systems.

Type of application	***Seal coating systems***	
	Chipping	***Graded-aggregate***
Single application system	- Single chip seal	- Single graded seal
Multiple application systems	- Double chip seal - Triple chip seal - Racked-in chip seal - Sandwich seal - Sandwich seal double chipping - Inverted double chip seal - Cape seal	- Double graded seal
Proprietary application systems	- Fibre/geotextile reinforced seal coating systems	

Table 1 – Type of seal coating systems available in Canada and abroad

Single application systems: The single application system consists of a single application of binder followed by a single application of cover aggregate. It is referred to as *single chip seals* when a single size aggregate is used. Most single chip seals are placed on existing bound substrate. Single chip seals are usually sufficiently robust for many situations. *Single graded seals* may be used as a surfacing system on top of consolidated granular material or an existing bound substrate. However, the usage of this type of system has greatly diminished in certain part of Canada over the last few years. On one hand, single graded seals placed onto bound substrate tend to bleed because of the lack of space within the aggregate matrix, while on the other hand, single application systems placed on top of a granular material are usually not robust enough to withstand traffic even for low volume roads. Single application systems may be used as temporary measure to protect the structure from weather damage and site traffic during construction. They are also used as curing sealant for cement treated granular material.

Double seals: Double seals have two layers of aggregate and two applications of binder, the second layer of binder being placed between the two layers of aggregate. The double chip seals and the double graded seals are quite different from one another not only from the aggregate perspective but also from the binder application and the placement method. Double graded seals may be described as two singles seals applied independently on one another. In the case of the double chip seals, the two layers of binders and aggregates are designed as a system not as individual layers applied on top of one another as it is the case with the double graded seal. Double graded seals are applied on consolidated unbound granular material. Double chip seals are applied on a wide range of situations ranging from stabilized granular material to high volume roads. Double chip seals produce a marginally lower texture depth than other chip seal treatment using equivalent chipping. They are usually quieter and more robust.

Triple chip seals: Triple seals have three layers of aggregate and three applications of binder. The triple chip seals are extremely robust and may be used on a wide range of situations. The largest size chipping is applied as a first layer and it determines the thickness of the treatment. The subsequent layers serve to fill the gaps in between the chippings of the first layer. Similar to double chip seals the triple chip seal has a lower texture than other seal coating systems and they are also quieter. Triple seals are used in the United States.

Racked-in chip seals: Racked-in chip seals are also referred to as choke seals. It consists of one heavy layer of binder followed by two layers of cover aggregate. The second layer of chipping is smaller than the first layer and it fills the gaps within the matrix of the first layer of aggregate. The smaller chippings lock the larger chipping in position, thereby producing a stable matrix. It is used in Europe and Australia on roadways where traffic is heavy and/or fast.

Sandwich chip seals: The Sandwich chip seal system consists of a layer of coarse chippings applied onto the substrate first, then a layer of bituminous emulsion followed by the application of a single fine chipping. Sandwich chip seals are mainly used where the existing substrate is binder rich.

Sandwich seals double chipping: Similar to the traditional sandwich chip seals, the sandwich seal double chipping consist of a layer of coarse chippings applied onto the substrate first without any binder followed by the application in this case of a double chip seal with the smaller chipping applied at the top. This type of treatment is used in certain region of France as a treatment for highly heterogeneous substrates.

Inverted double chip seals: The inverted double chip seals are also similar to the sandwich seal. They consist of a layer of small chipping applied onto the substrate first without any binder followed by the application of a single coarser chip seal. This treatment is used in the United Kingdom on substrate of variable hardness due to extensive patching.

Cape seals: The Cape seal is a system that combines a single chip seal with a fine slurry seal. The slurry seal locks the large chipping in position, thereby producing a stable matrix. It provides a "knobby" type texture with excellent friction properties. Similar to double chip seals, Cape seal may be applied over a wide range of situations and they are usually quieter and more robust than other types of seal coating systems. Cape seals are commonly used because of the colour and the finished surfacing characteristics.

Fibre/geotextile reinforced seal coating systems: This type of seal coating system originated in Europe and it has been recently introduced in the United State market. A network of fibre or a geotextile fabric is incorporated within the binder prior to the application of the cover aggregate. This type of seal coating system has enhanced tensile properties, which provides the ability of the system to absorb stresses generated in the roadway surface. It is used on cracked roadways where mitigation of reflective cracking is important. It is often described as a *"stress absorbing membrane"* SAM. It is also used as a SAMI system (stress absorbing membrane interlayer).

PARAMETERS TO CONSIDER IN THE SELECTION AND DESIGN OF SEAL COATING SYSTEMS

The selection of an optimized system may be carried out in four basic steps. The first step is related to an evaluation of the parameters related to the environment and the roadway condition. The second step concerns the selection of the type of seal coat system, including the selection of the aggregate and the binder type. The third step consists of determining the binder spray rate in accordance with the aggregate characteristics. And finally the last step consists of correcting the design binder spray rate in accordance with the localized site conditions and timing of placement.

Parameters related to the existing roadway and the environment

The parameters related to the roadway to be seal coated are related to its location, the existing surface conditions, the traffic counts, the traffic speed, the roadway layout, the substrate hardness and trafficked pathways within the roadway. The parameters related to the environment of the roadway to be seal coated are related to the local climatic conditions, the shade conditions and the timing of placement of the seal coating system.

Surface conditions: The evaluation of the surface conditions is critical for the selection of an optimized system. It is an assessment of the dryness/roughness/fatness of the surface and its homogeneity/heterogeneity characteristics. A smooth-rich surface will likely require a different seal coating system or a larger chip compared to a smooth-dry surface. Similarly, the design approach may be different for a smooth-dry surface compared to a rough-dry surface. Moreover, heterogeneous surfaces due to extensive patching may require a different seal coating system compared to homogeneous surfaces.

Road hardness: The road hardness is the assessment of the potential of the aggregate to indent the existing roadway surface. It is a property influenced by the surfacing material and the local climate. This is a critical property to accurately assess to select the correct size of aggregate. The UK and Australia have developed and standardized hardness probes and methods to measure this property. It should be noted that both the UK and Australia use with success seal coating systems in urban areas and on high volume roads. Generally, on soft substrate a larger aggregate is used while on a hard substrate a smaller aggregate is used. The binder spray rate is also adjusted accordingly.

Traffic categories: The evaluation of the volume of traffic per each lane of the roadway is critical for the success of the treatment. The traffic, especially the volume of heavy vehicles, embeds the aggregate into the binder and the substrate. In a certain manner, the traffic itself is part of the method of placement. The determination of the binder spray rate is closely associated with the traffic travelling in the lane. The binder rate may be different from one lane to another on the same roadway. The best example to illustrate this approach is the rate of binder required for a system applied on the travelling lanes of a four-lane roadway compared to the rate required for the passing lanes.

Traffic speed: The traffic speed may also be a factor to consider in the selection of the seal coat system. If the traffic is moving at a high speed, it increases the risk of having aggregate come loose. Multi-layer seal coating systems may be preferable on high speed roadways. For the purpose of the selection of a seal coating system the UK considers roadways as high speed, when the travelling speed is greater than 80 km/hr.

Roadway layout: Vehicles travelling on a roadway with a steep gradient and tight curves induce stresses in the surfacing differently than the same vehicle travelling on a straight and flat roadway. Similarly, additional stresses are transferred into the surfacing system of the roadway at intersections where traffic is stopping and turning. Considerations ought to be given to these factors in the selection of an optimized seal coating system.

Trafficked pathways: Roadway surfaces are not trafficked uniformly across their width. The embedment of the aggregate is greater in the wheel path compared to the centre of the roadway or in between the wheel path of a lane. Whenever practical, the usage of a higher binder rate is usually considered for the areas of a roadway that are less trafficked to compensate for the lack of kneading action provided by the traffic to embed the aggregate.

Climate and Timing of placement: The placement of seal coating system must be carried out in the summer months. Moreover, the success of a seal coat treatment is not only related to favourable climatic conditions during placement, but also, and very importantly, the following weeks after the placement of the system. This is particularly important to ensure the long term stability of the system. As indicated before, the traffic contributes to the embedment of the aggregate into the binder and the substrate. The embedment and the kneading action induced by the traffic, only occur if the temperature of the roadway is warm. If the aggregate of the seal coat system is not properly embedded into the substrate before the onset of the cold weather, snowplough damages can occur during the winter months. If work must be carried out at the end of the season, finer multi-layer type systems may be less at risk than a single seal with coarse aggregate. The usage of a premium binder may also reduce the possibility of snowplough damage. Increasing the binder rate may also be considered as a measure to prevent snowplough damage, but it also increases the risk of bleeding the following summer. It is important to carry out the placement of a seal coat system under good weather, yet it is probably just as important that a few weeks of good weather remains after the work is completed to allow the traffic to complete the embedment of the seal coat system.

Shade conditions: Seal coating systems applied on roadway surfaces constantly shaded by trees or other object tend to remain cooler than the areas exposed to sun. The embedment of the aggregate into the substrate/binder will be less in the shaded areas compared to the areas exposed to the sun. The rate of binder is normally increased in these areas to take into account the lack of warmth of the roadway surface due to shading.

Selection of the type of seal coat system

The selection of the type of seal coating system for a specific roadway depends on a number of factors. The usage of flow diagrams, a catalogue of systems or decision trees are common. Computer programs have been developed in France and in the UK to help with selection of optimized systems. The local experience is required to develop selection systems that accounts for the local conditions. For example, snow removal and snowplough damage is a very important factor to take into consideration in many parts of Canada and it needs specific attention, while in other counties the variation in the hardness of the substrate requires a more specific evaluation. It is the case in the southern US where the indentation of the aggregate into the substrate will be significant because of the long period of warm weather. Other factors such as reduction of initial aggregate loss or the pressure to open the road to traffic may influence the selection of an optimized system. Moreover, there may be reasons other than those included in standard selection process that may influence the final selection of an optimized system. Noise generation may be a factor to consider in the selection of the system. If noise is a factor the selection of a finer multi-layer system may be preferable, even though a single chip seal may be adequate.

Parameters related to the aggregate

The aggregate parameters necessary for the determination of the binder spray rate in accordance with the aggregate characteristics are related to the *average least dimension* of the aggregate and the *voids in the loose aggregate*. The *average least dimension* represents the average of the thickness of all individual particles when the particles lie with their least dimension upwards. The aggregate flakiness and gradation are evaluated to determine the *average least dimension* of the aggregate. The *voids in the loose aggregate* provide an indication of the space available to fit the binder in between the aggregate particles. The aggregate loose unit weight along with the aggregate specific gravity is used to determine the *voids in the loose aggregate*.

Flakiness: The flakiness of the aggregate particle is evaluated by determining the percentage of flat particles within the aggregate. The preferred shape of the cover aggregate is cubical rather than flaky. Flaky particles tend to lie on their flat side in the wheel paths and tend to lie randomly in the less trafficked areas. An excessive amount of flaky particles in a seal coating system may cause the system to bleed in the wheel paths and to be more susceptible to snowplough damage and aggregate dislodgment in the less trafficked areas. The flakiness characteristic of the aggregate is determined using different methods; the Flakiness Index is however widely used. It is defined as the percentage of the aggregate particles having their least dimension less than 60% of the average size of the aggregate. The least dimension of an aggregate is defined as the minimum opening of a slot through which the aggregate can be passed. The tolerance limits for the flakiness of the aggregate are modulated in accordance with traffic but generally should be less than 30.

Gradation: Along with the shape, the gradation of the aggregate is assessed to determine the *average least dimension* of an aggregate. The *average least dimension* of an aggregate is influenced by the mean size of an aggregate. An aggregate is considered coarse if its gradation is positioned in the lower part of the gradation band, normal if it is positioned in the middle and fine if it is positioned in the upper part. Accordingly, the mean size of the aggregate varies from coarse to fine gradations within the same gradation band. The optimal binder spray rate for a single chip seal system may vary as much as ten percent between a coarse aggregate and a fine aggregate even when both chips comply with the same single-size gradation band. The impact of the aggregate gradation on the binder rate is less for the secondary layers of multi-layer chip seal systems.

Loose Unit Weight: The loose unit weight of an aggregate is used to determine the *voids in the loose aggregate* parameter. It is used along with the *average least dimension* parameter to determine the design binder spray rate specific to the aggregate. It is used to calculate the voids expected to remain between the aggregate particles after rolling. The loose unit weight of an aggregate depends on its gradation, shape and specific gravity. Graded aggregate may range from dense graded to gap graded. They tend to have a greater loose unit weight compared to chippings, thus, they provide less space for the binder. Dense graded aggregate are the least desirable type of aggregates for seal coating as they tend to provide less space for the binder. Consequently, dense graded seals may flush and/or ravel depending on the variation of the aggregate gradation.

Angularity: Even though, the angularity of the aggregate is not a factor considered in determining the design binder spray rate, it is important factor to take into account in the overall performance of the seal coating system. Closely knitted mosaics are more difficult to achieve with round particles compared to angular, crushed particles, therefore, round particles seal coating systems tend to be more prone to aggregate dislodgement cause by the rolling of the aggregate. Field experience has revealed that round particle chip seal systems tend to perform better than round particle graded seals providing the proper embedment of the chip has been achieved.

Parameters related to localized site conditions

As indicated before the selection of an optimized seal coating system for a specific roadway depends on a number of factors, which may vary within a site. Roadway parameters that influence the selection of an optimized seal coating system may vary within a site longitudinally and/or transversely. A steep gradient may be treated differently in an uphill direction compared to the downhill direction. The shaded areas may require additional binder compared to the non shaded areas within the same site. A job site may be divided into homogenous sections to account for the factors influencing the selection and the design of optimized systems.

SELECTION OF AGGREGATE AND BINDER

Aggregates

Aggregate type: As indicated in the section describing the various families of seal coating systems, there are three types of seal coating systems, which are differentiated with the type of aggregate used to build them. The one-sized aggregate systems are referred to as chip seals and the graded-aggregate systems are referred to as graded seals.

Each aggregate system may be described as follows:

- The one-sized aggregate systems are built using clean chippings. Chippings are defined as one-size aggregate if nearly all the aggregate particles are contained between two consecutive sieves that obey the general rule of $d \geq 0.6D$ where "d" represents the size of the smaller sieve, while "D" represents the size of the larger sieve. The common sizes of the chippings, expressed in d/D, are 2/4 mm, 2/6 mm, 4/6 mm, 6/10 mm and 10/14 mm. Coarser chippings (14/20 mm) are also used as the primary layer of triple chip seals.

- The graded-aggregate may be dense graded or gap graded. They are usually unwashed and the dust content may range between 1 to 8 percent. The nominal maximum size of the aggregate or the D value ranges from 10 mm to 16 mm. Coarser graded-aggregate such as 20 mm are occasionally used as the first layer of multi-layer systems.

Cleanliness: The cleanliness of the chipping is of the utmost importance for the success of any of the chip sealing systems. The presence of a thin layer of dust on dry chipping will prevent bonding between the chipping and the binder. Chipping is considered cleaned when the proportion of particles passing the 75 µm sieve is 1 per cent or less. In some cases, the specified maximum particles passing 75 µm may be as low as 0.3 %. The cleanliness requirements for graded-aggregate seal coating systems requirements are not as stringent. The anionic high float type emulsion used with this type of aggregate contains a wetting agent, which allows proper bonding. However, the development of aggregate/binder adhesion and strength may be slow, which limits the usage of this type of seal coating system to lower volume roads.

Aggregate selection for primary layer: The toughness of the primary layer of chippings (or chipping of a single chip seal system) is modulated in accordance with traffic loading. The chippings used for the primary layer are selected in accordance with traffic to provide friction as well as resistance to crushing and abrasion. For most chip sealing systems the chipping of the primary layer protrude at the surface to provide friction as well as crushing and abrasion resistance. The thickness of a chip seal system is closely related to size of the chipping used for the primary layer. In the case of an inverted double chip sealing system the objective of the primary layer is different, thus, the toughness of the primary layer of chip is not as critical. The first layer smaller chipping is applied to produce a more uniform surfacing of a roadway with variable hardness. Similarly, the first layer of a double graded-aggregate seal provides uniformity and also surface cohesion. In both cases, the inverted double chip seal and the double graded-aggregate seal, the aggregate of the primary layer are not protruding at the surface of the roadway.

Aggregate selection for secondary/tertiary layer: The role of the secondary/tertiary layer of a multi-layer chip sealing system is to lock the chipping of the primary layer in position. The toughness of the frictional properties of the chipping of the secondary layer is also important but not as critical as what is required for the chipping of the primary layer. The chippings are smaller and selected to fit within the interstices left within the chippings of the primary layer and pack around the larger chipping in position.

Aggregate size selection: The aggregate sizes for the seal coating systems are selected in accordance with both the traffic and the hardness of the existing roadway. On softer substrate and/or higher volume roads increased embedment is expected, thus, multi-layer chip seals with a larger primary layer chip may be required. In contrast, on harder substrate and/or lower volume roads less embedment is expected, therefore, small chippings single chip seals or multi-layer chip seals with a smaller primary layer chip may suffice.

Binder

Binder types: There are four families of binders that have been used over the years for seal coating: cutback bitumen, tar-bitumen blend binders, hot sprayed bitumen and bitumen emulsions. Yet, the implementation of more restraining health and safety regulations has spurred the development and the usage the bitumen emulsions. Bitumen emulsions are the preferred binders for seal coating in many industrial countries. There are mainly two types of emulsions used for seal coating; anionic high floats and cationic emulsions. The emulsions are further classified in accordance with their setting characteristics and their viscosity. Regardless of their type, emulsions may be modified with polymer or unmodified.

Anionic high floats emulsions: The anionic high float emulsions set as water evaporates and they are usually not chemical sensitive to the mineral nature of the aggregate. The build up of cohesion and adhesion of anionic high float seal coating systems may be considered medium setting to slow. Therefore, it is possible to include a wetting agent in the manufacturing of high float emulsions to facilitate the coating of large particles even in the presence of dust. Anionic high float emulsions are mainly used with graded-aggregate seal coating systems. The setting and viscosity characteristics of high float emulsions are selected in accordance with the gradation of the aggregate. Slower setting high floats with lower viscosity is preferred for dense graded aggregates while faster setting with higher viscosity high float emulsions is preferred for gap graded aggregates.

Cationic emulsions: Contrary to anionic emulsions, the setting of cationic emulsion is strongly affected by the chemical nature of the aggregate, which destabilizes cationic emulsions causing them to break and set rapidly. Thus, gain in strength of cationic seal coat systems is more rapid than with anionic type systems. Consequently, cationic emulsions seal coating systems are preferred where and when the success of the treatment is highly dependent on the rapid gain of strength of the system, which is essentially associated with the build up cohesion of the systems and the build up of adhesion of the binder with the aggregate. The surface area of the aggregate influences the setting of cationic emulsions. Therefore, the presence of high surface particles, dust, may cause the emulsion to destabilize in an uncontrolled manner, which may in return, prevent the binder to build up adhesion with large particles. Fast setting and high viscosity cationic emulsions are the preferred binders for dust free chippings used to produce the various types of chip sealing systems.

Modified bitumen emulsions: Bitumen emulsions, anionic or cationic, may be modified by the addition of polymers to enhance their adhesion and cohesion properties. Compared to unmodified emulsions, polymer-modified emulsions are not as thermally susceptible. They also provide both, better early adhesion to the aggregate and better long term durability as binder film thickness increases. Polymer-modified emulsions are particularly suitable for high volume roads and/or where snowploughing may be considered aggressive.

Binder/aggregate adhesion properties: The initial test in determining the adhesion properties of a binder/aggregate system consists of making sure that the emulsion has the ability to coat the aggregate. A simple coating/boiling test is performed to verify the compatibility of the emulsion with the aggregate. The binder/aggregate compatibility test may be performed for both graded-aggregate seals and chip seals. However, other adhesion property tests such as the Vialit test or the Sweep test are specific to chips seals or graded-aggregate seals using gap graded aggregate. The adhesion properties of the binder/aggregate system over the life of the treatment are verified using the Vialit test. The Vialit test replicates the ability of the binder of a chip sealing system to retain chips under different environmental conditioning. The active adhesion property is verified by performing the test with specimens prepared with wet aggregates. Wet conditioning of the specimens before testing is used to verify the passive adhesive properties of the binder/aggregate system. Performing the test after freezing the specimens may also be performed to verify the adhesion properties of binder/aggregate system subjected to freeze/thaw cycles.

Rate of adhesion/cohesion build up: The rate at which seal coating systems build up strength may also be verified to determine the suitability of the systems for usage on roadways where early return to traffic is important. The recently developed sweep test provides excellent information in this regard. The test simulates potential aggregate loss caused by the brushing action of a sweeper on the surface of freshly place seal coating system.

SPREAD RATE OF AGGREGATE AND BINDER

Rate of spread of aggregate

The spread rate of the aggregate is determined using empirical methods based on field trials or by methods based on the aggregate properties such as the *average least dimension*, the *voids in the loose aggregate* and the *bulk specific gravity* of the aggregate. The method based on the aggregate properties has been developed specifically for chip seals systems. The aggregate spread rates for graded-aggregate seals are determined by trial and error based on coverage of the binder. The selected coverage varies from one system to another and from one layer to another.

Some cover aggregate gets thrown to the side of the roadway by the traffic. The amount of traffic whip-off varies from one type of system to another and also from one layer to another, plus traffic speed. For the single treatments, single chip seals or the single graded-aggregate seals, the coverage is usually 100% + 5% whip-off for the single chip seals to 100% + 10% whip-off for the single graded-aggregate seal. The lower layer chips of multi-layer systems are usually applied at coverage equal or less than 100% of the surface to provide space to place the smaller upper chips within the chips of the lower layer. Again, the typical coverage varies from one system to another and is also associated with the number of binder applications. For example, the racked-in system has only one layer of binder and two layers of chips; the first layer may be set at 100% - 25% and the second layer may be set at 100% - 20%. The whip-off aggregate may be relatively high compared to a double chip seal, where the first layer may be set at 100% - 5% and the second layer is set at 100% +10%. Even though, there is less coverage with the racked-in system compared to the double system, the whip-off aggregate is greater because of the total surface of the binder available.

Rate of spray of binder

The success of a seal coating operation is highly dependent in the approach taken to establish the rate of spray of binder. The spray rate of binder is commonly determined in three stages consisting of: establishing a basic spray rate of binder for the selected system using the information available for the site; then corrections are applied to the basic spray rate based on the aggregate properties; and, finally correction factors are applied to the spray rate of the binder for localised adjustment within the site.

Basic spray rate: Basic spray rate is established using the information specific to both, the site and the selected seal coating system. The information specific to the site includes: the existing surface conditions, the traffic count, the traffic speed, the roadway layout, the substrate hardness and trafficked pathways within the roadway, local climatic conditions, the shade conditions and the timing of placement of the seal coating system. The information specific to the selected seal coating system is related to the number of aggregate layers and the size of the aggregate selected. The UK approach and the French approach in establishing binder basic spray are quite similar. Comprehensive tables have been published and even computer software has been developed to determine basic binder spray rates. The North American approach still relies on the experience of the localized agency. The basic spray rate designs are provided in tables, but in a much more generalized manner compared to the UK/French approach that specifies the parameters to evaluate so a basic spray rate design can be obtained.

Corrections related to the aggregate shape and gradation: Once the aggregate becomes available the spray rate of binder may be corrected in accordance with the flakiness of the aggregate and its gradation. The optimum binder spray rate is established in relation to the voids available within the aggregate mosaic. After embedment of the aggregate mosaic, the optimum volume of residual binder should represent approximately 70 % of the voids available within the mosaic. In the trafficked areas such as the wheel paths, correction factors based on the *average least dimension* of the aggregate are applied to the basic spread rate. However, in the less trafficked areas of the roadway where aggregate particles may not lay flat or be fully embedded in the binder/substrate a higher binder rate may be considered. This is particularly critical to account for potential of snowplough damage. In the State of Minnesota, correction factors based on an average of the aggregate *mean dimension* and its *average least dimension* is applied to the basic spray rate.

Localised site corrections: Localised correction factors are applied to specific areas along the site to account for specific conditions, which are mainly shade, sharp curves, steep gradients, intersections, local traffic and substrate changing conditions. The localized site corrections are either applied ahead of time if the information is available or as the work progresses on site. When more than one layer of binder is applied, the correction factors are usually applied to the last layer of binder except for the substrate changing conditions. In this latter case the correction factors are applied to the first layer of binder.

SITE PREPARATION AND SCHEDULING OF WORK

Substrate repairs

The effectiveness of any seal coating operation is closely associated with the site preparatory work. The purpose of the preparatory work is to obtain a substrate as uniform as possible. Ideally, the preparatory work should be carried out well before the seal coating operation occurs to let the traffic knead the surface.

Surface deformations: Substrate repairs are often necessary prior to the placement of any seal coating systems when surface deformations exceed 30 mm. The repairs are usually performed using bituminous materials specifically formulated for this application.

Cracking: Fatigued areas are usually repaired by simply removing and replacing these areas. Thermal cracking and longitudinal cracks are sealed using crack-sealant material. Non active surface cracks usually do not necessitate any treatment.

Surface defects: Pot holes are repaired using solvent free bituminous material. Streaking of the existing seal coat and snow plough damage may be repaired using a single seal coat system.

Bleeding: Spreading dust free chips on the defective areas during warm weather may repair bleeding areas. The gradation of the chips is selected in accordance with the possible indentation of the chips. The usage of pre-heated dust free chips has been done successfully as well. The usage of sandwich chip seal adapted for this application is also a viable option. However, in certain cases the removal of the bleeding material may be the only effective solution.

Timing of placement

The timing of placement is critical for the success of seal coating work. It is particularly important to schedule the work for the higher volume roads during the warmest months of the construction season. The effectiveness of the treatment is related to the good weather during the work but also after the work is completed. On higher volume roads, seal coating systems are usually slightly leaner to avoid bleeding and the build up of strength of the system is highly dependant of the embedment of the aggregate in the binder/substrate. Conversely, seal coating systems placed on lower volume roads requires more binder and their effectiveness is less dependant on the kneading action of the traffic. Nevertheless, it is important to start the seal coating work as weather permits in the early part of the construction season to limit as much as possible late season work.

EQUIPMENT

Binder Distributor

The binder distributor, also called sprayer is used to apply the binder onto the roadway. The success of any type of seal coating work is closely related to the accuracy of binder placement that the sprayer can provide. Binder distributors include a storage tank and a spray bar usually mounted on a truck chassis. The storage tank is insulated and equipped with a heated system to maintain the binder at the proper spraying temperature. The spray bar is mounted at the rear of the truck chassis and it is fitted with spray nozzles evenly spaced at usually 100 mm intervals. It is common that the spray bay may be extended from 2.5 m to 9.0 m. Binder distributor are equipped with programmable logic control (PLC) systems to maintain the rate of binder application constant regardless of the speed of the machine.

Aggregate Spreader

The aggregate spreader or chipping spreader is used to place, at a specific rate, a uniform aggregate cover onto the roadway. Aggregate spreaders are either self-propelled or attached to the dump truck tail gate. Some self-propelled aggregate spreaders have the capability of placing the aggregate onto the roadway at variable width up to 7.5 m. The self-propelled spreader pulls the supply trucks. The aggregate is placed into a receiving hopper and it is conveyed towards the front of the machine to a system that drops the aggregate from a constant low height onto the roadway.

Combination Units

These machines combine both the spraying of the binder and the placement of the aggregate within one chassis. The combination units were developed in Europe initially for localised repairs.

Rollers

Pneumatic rollers are used to initiate the aggregate embedment into the binder and the substrate. The weight per wheel may range from 1.5 to 3.0 tonnes. Smooth drum rollers fitted with rubber liners have also been used successfully on roadways with good transverse profile. This type of roller is always used in association with pneumatic rollers.

Sweepers

Sweepers are used to prepare and clean the substrate before the placement of the seal coating system and they are also used after the placement to evacuate the excess aggregate. There are two types of sweeper used: the rotary sweeper for the rural areas and the pick-up sweepers typically used in the urban settings.

PLACEMENT OPERATIONS

Traffic control

Seal coating system are generally placed with minimal impairment to traffic and the traffic is managed as per the local relevant regulations for traffic control for road work. However, the aggregate mosaic of a freshly placed seal coat may be fragile for several hours after the completion of the work. Vehicles rolling at high speed may unduly dislodge aggregates during the first few hours after the placement of the seal coat. Therefore, in addition to the regulations, specific reduce speed signage may be imposed to avoid flying chips. Speed enforcement may be necessary to ensure that the traffic adheres to the speed limitations.

Sweeping

Roadway surfaces are generally swept before the placement of the seal coat to ensure bonding. Yet, on higher volume roads, sweeping may not always be necessary since the traffic itself tends to keep the roadway free of debris. Thermoplastic roadway marking may prevent bonding and it is mechanically remove before the placement of the seal coat.

Spraying of binder

Weather conditions: The success of a seal coating operation is highly dependant on the weather condition while spraying the binder and the aggregate. Bitumen emulsion break slowly in cold or damp conditions as well as when the humidity is high. Evidently, the performance of seal coating work in rainy conditions must be avoided. Air temperature of 10ºC in the shade and rising is commonly used as guideline for seal coating.

Equipment readiness: Prior to the spraying of the binder various settings are checked such as the temperature of the binder, the condition of the spray bar (filters, nozzles, height, etc.) and the parameter introduced in the PLC system. The coordination with the aggregate spreading operation is imperative as it is important to place the aggregate onto the binder with minimal waiting time.

Joints: Seal coat joints are fragile and it is important to take particular care in their execution. Double coverage of the substrate with the binder at the transverse joint will result in localised flushing, thus, procedures are commonly in place to avoid overlap even for a few centimetres. Conversely, overlaps are necessary at the joint between two adjacent passes to maintain the set binder spray rate at the joint. The overlap distance is determined in accordance with the settings of the spray bar, which includes the spacing of the nozzles from one another, the spray bar nozzle alignment in relation to the spray bar and from one another, the spray bar height in relation to the ground and the spray fan angle. The location of the joint for multilayer systems is offset from one layer to another.

Placement of cover aggregate

As indicated above the placement of the cover aggregate follows closely the spraying of the binder to facilitate the coating of the aggregate. The lapse of time between the placement of the binder and the placement of the aggregate is as short possible. Lapse of time between 20 and 40 seconds are adhered to with fast setting emulsion and/or to reduce the potential of the binder running into low areas of a deformed roadway surface.

The aggregate spread rate for the lower layer of multilayer seal coat systems must be maintained closely. Excessive placement of aggregate will impede the placement of the subsequent layers and as a result the locking up function of the aggregate from the subsequent layers may not be achieved.

Embedment of aggregate

Pneumatic tire rollers provide the initial aggregate embedment into the binder and the substrate. Pneumatic tire rollers are well suited for this type of application as it applies uniform pressure onto the aggregate without crushing even on deformed roadways. The subsequent traffic completes the embedment, yet, on low volume roads the traffic may not be sufficient to fully embed the aggregate. Thus, the initial rolling provided by the pneumatic rollers becomes even more important.

Rolling procedures are established in accordance with the characteristics of the seal coating system. Intermediate rolling is necessary for certain multilayer systems while for others the rolling is performed after the placement of all the layers. Intermediate rolling is advisable for the initial embedment of the chips of the lower layer of a racked-in system, while it is advisable not to roll the first layer of chips before the second layer of a double chip seal has been applied. In this latter case, intermediate rolling may impede the binding and the locking up function of the second layer of chips.

Removal of surplus aggregate

The aggregate surplus is common and it includes the aggregates that lay loose on top of the mosaic and the aggregate that were strip out of the mosaic by the traffic. The aggregate surplus is removed as quickly as possible to facilitate the embedment of the aggregate by the traffic and to avoid the danger related to the flying aggregate. Mechanical sweepers are used to remove the surplus aggregate as soon as the newly place seal coat is stable enough which may range from a few hours to one or two days after.

Quality control

The success of a seal coating operation is closely associated with the calibration of the equipment, the quality control of the components and the control of the spread rate of the binder and the aggregate.

Calibration of equipment: The purpose of the equipment calibration is to ensure that the placement of the binder and the aggregate are uniform and at the rate expected in both directions: longitudinally and transversely. Calibration procedures are performed prior to the onset of the seal coating campaign and calibration checks are performed on a routine bases.

Binder distributors: The calibration procedure for binder distributors consists of ensuring that the settings of the distributor are adjusted properly. The settings include:

- the angle of the nozzles in relation to the within the spray bar and at the end of the spray bar to obtain equal coverage with each spray fan
- the height of the spray bar to ensure proper overlapping between the fans
- the temperature of the binder to ensure the pressure in the spray bar is maintained regardless of the viscosity of the binder
- the PLC system parameters to ensure that the spray rate of the binder is maintained regardless of the speed of the distributor.

The calibration is verified by spraying the binder onto retrievable devices/containers placed on the ground in a manner to obtain representative values of the spray rates in the longitudinal and transverse profiles. Many agencies consider the calibration of a distributor to be satisfactory when the measured values of the spray rate obtained from retrievable devices/containers are within 5 % of the target spray rate by weight.

Aggregate spreaders: Similar to binder distributors, the calibration of the aggregate spreader is verified and adjusted by spreading the aggregate onto retrievable devices/containers placed on the ground. The devices/containers are placed in a manner that representative values of the spread rate can be established by small increment in the transverse profile of the roadway. The procedure provides information that is used to adjust the opening of the gates of the aggregate spreader. Many agencies consider the calibration of an aggregate to be satisfactory when the measured values of the spread rate obtained from retrievable devices/containers are within 10 % of the target spread rate by weight.

Calibration checks: The calibration checks for both the binder distributor and the aggregate spreader consist of establishing the average spread rate of the binder/aggregate by relating the area covered to the amount of binder/aggregate placed.

Control of components: The control of the components consists of verifying that the binder and the aggregate delivered to the site meet their respective material specifications.

SUMMARY

Seal coating systems offer quick, efficient and cost effective ways of maintaining roadways in regards to surface texture and friction, and to stopping both the ingress of water and the oxidation of the existing bituminous surfaces. As illustrated in this paper, there are many types seal coating systems available to practitioners ranging from the traditional single chip seals to fibre reinforced multi-application type seal coating systems. Therefore, many possibilities are offered to practitioners for a wide the range of roadway conditions. Nevertheless, as indicated in the paper, the success of seal coating work is closely connected to the careful assessment of a certain number of well defined parameters related to the roadway environment and condition. Practitioners commonly use a decision tree approach to select optimized seal coating system. Furthermore, the meticulous selection of the aggregate and the binder has an impact on the outcome and the performance of the seal coating. Strict guidelines are followed to design appropriate spread rates for both, the binder and the aggregate. Finally, the paper clearly identifies the importance of performing the placement of any type of seal coating in accordance with a set of well defined procedures regarding the site preparation, the equipment characteristics and calibration, the workmanship and the quality control of the components.

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