Recent development in recycling binders for in-place cold recycling of bituminous aggregate

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ABSTRACT: Many millions of square metres of roadway have been rehabilitated using the in-place cold recycling process in Canada. The driving engine of in-place cold recycling is associated with the concept that existing pavements are sources of primary roadway materials. The existing pavement is reclaimed and transformed into a bituminous aggregate, treated with a recycling system, placed and compacted in-place. The nature of recycled mixtures differs significantly from hot mixtures. Hot mixtures are usually two-part systems, whereas, recycled mixes are multi-part systems including: aggregate, aged binder, recycling binder and possibly corrective aggregate and other additives. Additionally, water is added during recycling for coating and compaction. The air voids content of recycled mixtures is much greater than hot mixes. A small amount of recycling binder is added to bituminous aggregate; consequently, the build up of cohesion of recycled mixtures is highly dependent on the nature of recycling binder, the properties of aged binder, the addition of corrective aggregate and additives, if required, the curing conditions and the mixture densification. The selection of recycling system is based on the characteristics of bituminous aggregate, the expected interaction of recycling binder with aged bitumen and the site constrains/conditions. The paper proposes a classification of recycling techniques based on objectives, materials and recycling systems. It defines the performance of recycled work in accordance with material mechanistic properties and field constructability. It provides information on the parameters used to engineer recycled mixtures. Finally, it describes the field conditions that influence the performance of recycling material.

KEY WORDS: Recycling, bituminous aggregate, emulsion, aged bitumen, pozzolanic agent

1 INTRODUCTION

The process of in-place cold recycling of bituminous roadway is well established in Canada. Many millions of square metres of pavement have been rehabilitated using this process and the industry capacity to recycled bituminous pavement is among the highest in the world. Many Canadian road agencies use in-place recycling as a standard pavement rehabilitation method. The experience of using different versions of in-place cold recycling with respect to equipment and recycling binders is extensive.

The performance of in-place cold recycling observed over the last two decades has demonstrated that the benefits associated with recycling are technical, economical, and environmental. One of the main technical benefits of in-place recycling is related to the ability of the recycled material to mitigate reflective cracking, which implicitly provides added life to the rehabilitated pavement. In-place recycling also offers significant benefits related to the environment. In-place recycling technologies reuse all of the existing materials, allowing the preservation of aggregates and bitumen. The cold nature of the process reduces the consumption of energy and consequently reduces the green gas emission. Consequently, in-place recycling technologies are continuing to gain acceptance among Canadian road agencies.

1.1 Objectives of the paper

The objective of the paper is to provide current information on in-place recycling processes carried out in Canada. The concepts associated with the various techniques are defined and explained. The paper proposes a classification of recycling techniques based on objectives, materials and recycling systems. It defines the performance of recycled work in accordance with material mechanistic properties and field constructability. It provides information on the parameters used to engineer recycled mixtures. Finally, it describes the field conditions that influence the performance of recycling mat. The paper focuses on partial depth recycling with the addition of bitumen emulsion as a main component of the recycling system.

1.2 Definitions

For the purpose of this paper the following definitions are used:

- *Reclaimed material* refers to roadway material granulated in-place containing either 100 % bituminous aggregate or a combination of bituminous aggregate and underlying granular material.
- *Bituminous aggregate* refer to roadway material obtained from the sizing of a reclaimed bituminous material commonly referred to as RAP (Reclaimed Asphalt Pavement).
- *Recycling binder* refers to a hydrocarbon substance mainly composed of bitumen added to reclaimed material for the purpose of providing cohesion to the recycled mixture.
- *Recycling binder carrier* refers to the mean by which the viscosity of the recycling binder is reduced in order to be blended uniformly with the reclaimed material.
- *Recycling system* refers to an ensemble of components invariably including a recycling binder and possibly other additives/aggregates necessary to meet recycled work requirements.
- *Fluxing agent* refers to a hydrocarbon substance that may be added to the recycling binder for the purpose of fluxing and/or rejuvenating the aged bitumen.
- *Corrective aggregate* refers to an imported uncoated aggregate that may be blended with the reclaimed material for the purpose of correcting the mineral gradation of the bituminous aggregate or to lower the total binder/mineral aggregate ratio.

2 CLASSIFICATION OF RECYCLING TECHNIQUES

In-place cold recycling processes are pavement rehabilitation techniques for bituminous pavement that does not require heat while recycling the in-place material. The recycling techniques may be performed partial depth or full depth, which refers to the partial treatment of the bituminous surface layers or the full treatment of the bituminous surface layers plus some of the underlying granular material. Milling machines are generally used with the partial depth processes, while reclaiming machines are used with the full depth processes.

The recycling techniques are classified in accordance with three parameters which are: the objective of the treatment, the nature of the materials to be recycled and the recycling system. Accordingly, the recycling technique performed in Canada over the last twenty five years may be classified into five classes as described in Table 1. Bituminous binder treatments have been used extensively in Canada over the last 25 years, whereas the experience with hydraulic binders and composite binders is limited. The classification proposed in Table 1 is closely related to the classification included in French technical guide entitle “Guide technique: Retraitement en place à froid des anciennes chaussées” published in 2003.

Bituminous binder treatments are well suited to rehabilitate the roadway structure found in Canada, which typically consists of unbound granular material road base overlaid by bituminous materials. The objective of the treatments is to correct surface defects or to remediate structural weaknesses. The process may be partial-depth if the structure of the roadway is sound or full-depth when the roadway structure is inadequate. Recycled materials are composed of reclaimed bituminous aggregate with or without part of the underlying granular material. The total added residual binder may range from 0.8 % for the recycling of reclaimed bituminous aggregate to 4.0 % for the recycling of binder lean reclaimed materials. The usage of a pozzolanic agent such as cement or lime is generally beneficial to the mixture. Pozzolanic agents act as catalyst to accelerate the build up of cohesion of the materials recycled with cationic emulsions. The amount of pozzolanic agent use as catalyst is typically less than 30 % of the total amount of emulsion. Occasionally, corrective aggregate is added to the process to improve the mineral skeleton of the recycled mixture.

<table>
<tr><th colspan="2" rowspan="3">Type recycling treatment and characteristics</th><th colspan="3">Bituminous binder treatments</th><th>Hydraulic binder treatment</th><th>Composite binder treatment</th></tr>
<tr><th>Partial depth treatment</th><th>Partial or Full Depth Treatment</th><th colspan="2">Full depth treatment</th><th>Partial or Full Depth Treatment</th></tr>
<tr><th>I</th><th>II</th><th>III</th><th>IV</th><th>V</th></tr>
<tr><td rowspan="2">Objective</td><td>Type of rehabilitation</td><td colspan="2">Surface</td><td colspan="2">Structural</td><td>Surface or Structural</td></tr>
<tr><td>Principle</td><td>Recycling of bituminous surface layers</td><td colspan="2">Recycling of the full thickness of bituminous surface layers including some or a proportion of the underlying granular material</td><td colspan="2">Creation of a new pavement material using the in-situ material</td></tr>
<tr><td rowspan="2">In-place materials</td><td>Ratio of granular to bituminous treated materials</td><td>Bituminous material only</td><td>40 to 80 mm of bituminous material plus some underlying granular material</td><td colspan="2">75 to 150 mm of bituminous material and 75 to 150 mm of underlying granular material</td><td>Bituminous material with or without underlying granular material</td></tr>
<tr><td>Depth of treatment</td><td colspan="2">60 to 120 mm</td><td>125 to 200 mm</td><td>200 to 300 mm</td><td>75 to 300 mm</td></tr>
<tr><td rowspan="4">Recycling system</td><td rowspan="3">Binder, aggregate and additives</td><td>Bituminous or rejuvenating binder</td><td colspan="2">Bituminous binder</td><td rowspan="2">Cement or other pozzolanic binders</td><td rowspan="2">Blend of bituminous and hydraulic binders</td></tr>
<tr><td colspan="3">Pozzolanic agents may be added as catalyst to accelerate build up of cohesion</td></tr>
<tr><td colspan="5">Corrective aggregate may be added to improve characteristics of the recycled mixture</td></tr>
<tr><td>Added binder content</td><td>0.8 to 1.5 % residual binder</td><td>1.3 to 2.0 % residual binder</td><td>1.8 to 4.0 % residual binder</td><td>3.0 to 6.0 % hydraulic binder</td><td>1.5 to 7.0 % composite binder</td></tr>
</table>

Table 1: Suggested classification of roadway in-place cold recycling techniques

3.0 DEFINITION OF PERFORMANCE FOR RECYCLING WORK

The performance of recycling work is defined in accordance with the traditional mechanical properties of the recycled material, which are related to the long term performance of the roadway, while the constructability performance of the recycling work is associated with the properties of the recycled material during construction and shortly after.

It is essential to consider both the long term and the constructability performance of recycling work in the selection of recycling system and the design of recycled material. The long term performance is related to mechanical properties of the material such as: *stiffness, fatigue resistance, reflective cracking mitigation, durability, rutting resistance and thermal cracking mitigation.* Whereas constructability performance of recycling work is associated with the: *workability*, *minimization of raveling, ease of compaction, increase smoothness, absence of post compaction and rapidity of the recycled material to build-up of cohesion.*

The characteristic of the bituminous aggregate, the weather conditions, the recycling binder system and the density achieved during compaction have significant but varying degree of influence on both the long term and the constructability performance of the recycling work. The nature, the amount and the distribution of the recycling binder within the bituminous aggregate has a strong influence the long term performance. Whereas, the type of binder carrier and the usage of certain additive such as cement influences the constructability performance.

4 ENGINEERING OF RECYCLED MATERIALS

The engineering of recycled material is a rational process by which, through a series of decisions, optimal solutions are selected to maximize the performance of the recycling work. The engineering work is carried out in three stages including a detailed analysis of the bituminous aggregate, the selection of the recycling system and the laboratory work. Site specific considerations such as weather during the work, thickness of treatment, etc. are also taken into account in the selection of the recycling system.

4.1 Reclaimed materials

Reclaimed materials may be composed of 100 % bituminous aggregate or a combination of bituminous aggregate and underlying granular material. The reclaimed materials may constitute up to 99 % of the new roadway recycled material. The following section provides information on the various characteristics of the bituminous aggregate that influence the performance of the recycled material including the gradations of both the bituminous aggregate and the mineral aggregate, the properties/amount of the aged binder contained in the bituminous aggregate.

4.1.1 Gradation of the bituminous aggregate vs. mineral aggregate

Bituminous aggregate is defined as reclaimed asphalt pavement (RAP) particle that has been sized to be recycled. It is an aggregation of mineral particles bound together by bitumen. Consequently, the gradation of a bituminous aggregate differs significantly from the gradation of the mineral particles aggregated within the bituminous aggregate.

The differences in gradation are considerable at the lower size of the gradation band. The bituminous aggregate particles passing the 75 μm sieve generally ranges between 0.5 to 1.0 %, while the mineral aggregate particles passing the 75 μm sieve may range from 5.0 up to 9.0 %. At the 4.75 mm sieve the difference between the two gradations is not as significant but remains considerable. The percentage passing the 4.75 mm sieve of the bituminous aggregate is generally between 30 and 50 %, while the value of the mineral aggregate may be between 50 and 70 %.

Finer bituminous aggregate are easier to place and compact compared to coarser gradations. The potential for segregation of large particle is reduced and the gradations are more conducive to achieve higher densities. The occurrence of excessive ravelling is also minimized. Yet, finer gradations are not necessarily preferable as they require more energy to produce which may impacts on production. Furthermore, it has been observed that segregation free and equally compacted materials, coarser or finer bituminous aggregate tend to homogenize within a short period of time after the completion of the work with warm weather and the kneading action of the traffic. The production of a finer bituminous aggregate may be preferable in the latter part of the summer when the occurrence of continuous warm weather is uncertain. Bituminous aggregate may be considered coarse when the maximum nominal size of the bituminous aggregate is between 1.25 and 1.5 times the maximum nominal size of the mineral aggregate. Bituminous aggregate may be considered fine when the maximum nominal size of the bituminous aggregate is 1.0 to 1.25 times the maximum nominal size of the mineral aggregate.

The mineral aggregate gradation of the recycled material has a direct influence on the mechanical properties of the mixture. Coarse mineral aggregate gradations are not commonly found unless an open graded mix is recycled, whereas sandy gradations are more common. In both cases, the usage of a corrective aggregate is required. Coarse gradations tend to ravel and the build up of cohesion is limited, while sandy gradations tend to produce tender mixes often susceptible to permanent deformations. Typical dense graded gradations provide excellent results. The sieve size used to assess the gradation of the mineral aggregate is the 4.75 mm. If the passing 4.75 mm sieve is between 45 than 65 % there is no requirement for corrective aggregate. Mineral gradation between 65 and 75 % passing at the 4.75 mm sieve may require corrective aggregate if the voids of the compacted mixture are less than 9 %. This is often associated with soft aged bitumen and/or high aged bitumen content in the bituminous aggregate. Mineral gradations above 75 % passing at the 4.75 mm sieve are considered sandy and a corrective aggregate is required to strengthen the mineral skeleton of the mixture.

4.1.2 Properties of aged binder

The rheological properties of the aged bitumen contained in the bituminous aggregate are extremely important to assess to determine the type of recycling binder needed to optimize the performance of the recycling mixture. The rheological properties of bitumen change over time; this is referred to as binder aging. Binder aging is a process by which the maltene fraction of the bitumen is transformed through phenomenon such as oxidation, volatilization and others, which results in binder hardening.

The standard penetration test performed at 25°C is a useful rheological property that offers a rapid assessment of the aging of the binder. It is also indicative of the potential of the cold recycled mixture to resist permanent deformation. Furthermore, the penetration number provides information on the capability of the aged binder to contribute to the cohesion or the recycled mixture. Penetration numbers below 20 are considered low and indicative of hard bitumen whereas penetration numbers above 45 are high and indicative of very soft bitumen. Bitumen with penetration numbers between 20 and 30 are considered intermediate and penetration numbers between 30 and 45 are soft.

4.1.3 Bitumen aggregate binder content

The binder content is the third important characteristic to assess to determine the type recycling binder required to maximize the performance of the recycled mixture. The binder content gives information on the space occupied by the aged binder within the bitumen aggregate, thus, providing an indication on the amount of recycling binder that may be added to the mixture.

As for other dense graded type bituminous mixtures, the space available for the binder is limited even in the case of high void recycled mixtures. As a rule of thumb, whenever the total binder content is greater than 6.5 to 7.0 % the volume of binder may be such that the continuous phase of the mixture is no longer the mineral skeleton, but the binder.

Consequently, binder rich recycled mixtures are susceptible to permanent deformation during the service life of the roadway and during the placement of hot surfacing material. During the service life of the roadway, the occurrence of permanent deformation may be even more pronounced when the traffic is heavy and slow, and the recycled mixture is close to the surface. During the placement of the hot surfacing material, binder rich recycled mixtures may become unstable, which will invariably affect the quality of the surfacing mat.

Bitumen aggregate containing between 5.5 and 6.0 % before recycling will generally lead to the production of a binder rich recycled mixture. The usage corrective aggregate is often required to reduce the binder/mineral aggregate ratio and strengthen the mineral skeleton of the recycled mixture. It has been found that dense graded type corrective aggregates are preferable to chippings to effectively reduce the binder/aggregate ratio. Dense graded corrective aggregates offer more surface area for coating than chippings for equal quantities. The quantity of a dense graded corrective aggregate added to a recycled mixture is established in accordance with two parameters: the minimum addition of recycling binder and the desire maximum amount of binder in the recycled mixture, which is often selected to be below 6.5 %.

4.2 Recycling binder systems

Recycling mixtures are produced using a very small amount of new recycling binder. Thus, it is imperative to understand how the aged binder and the recycling binder interact with one another to select an optimized system. The following section explains the interaction of the aged binder with the recycling binder, it also describes the process by which a recycling binder may be selected and finally it provides information of the different recycling binder carrier systems available.

4.2.1 Interaction between aged bitumen and recycling binder

Recycled mixtures may be produced with the addition of only 1.0 % added residual bitumen, whereas comparable mixtures, produced using uncoated aggregates, require at least 4.0 to 5.0 % residual binder. Thus, it is accepted that the aged binder contained in the bituminous aggregate contributes to the build up of cohesion of the new recycled mixture.

The contribution of the old bitumen to the build up of cohesion of the new recycled mixture varies depending on a multitude of factors. The recycling process is performed using a cold process, consequently the blending of old and new binder depends on the fluxing characteristics of the recycling binder and weather condition which may accelerate or slow down that process. It is accepted that a portion of the aged bitumen remains inert while a portion combines with the added recycling binder to eventually produce a *new effective binder*. Field and laboratory observations are indicating that the portion of the aged bitumen that combines with the added recycling binder depends on the gradation of the bituminous aggregate, the bitumen content, the softness of the aged binder, the fluxing characteristics of the recycling binder, and the coating characteristics of the binder carrier.

Nevertheless, the softness of the aged binder is probably the most important factor to determine to evaluate the potential contribution of the old bitumen to the build up of cohesion of the new recycled mixture. Old hard binders with a penetration of less than 20 are nearly inert and the contribution to the cohesion of the new mixture may be limited without significant rejuvenation, whereas old but very soft binders with a penetration number of more than 45 are still active and the contribution to the cohesion of the new mixture may be significant. Furthermore, the fluxing characteristic of the recycling binder is also important factor to assess to determine the potential contribution of the old bitumen to the build up of cohesion of the new recycled mixture. Recycling binder containing a fluxing agent such as rejuvenating oils with good coating capability mixed with a fine graded bituminous aggregate in the warm summer months will create a new effective binder within the recycled mixture faster than a neat bitumen binder with minimum coating capability mixed with a coarse graded bituminous aggregate in the cooler month of the road construction season.

4.2.2 Selection of recycling binder

Bituminous aggregate may be recycled using different types of recycling binder. The parameter that differentiates the recycling binder from one another is related to the capacity of the added binder to restore the binding properties of the aged binder. The recycling binders are selected by either assuming that the aged bitumen is nearly inert or that the aged bitumen is still active. Detailed information on the characteristics of the bituminous aggregate and the conditions under which the recycling is planned to be carried out is required to determine the best approach in selecting the binder.

Recycling binder containing fluxing agent such as rejuvenating oils are designed to penetrate aged bitumen restoring some of their binding properties. The added binder requirement may be relatively low, but this type of recycling binder is relatively expensive. Furthermore, the build-up of cohesion of recycled mixtures blended with this type of binder may be relatively slow since it is related to a fluxing of the aged binder, which is time and temperature dependent. The selection of this type of recycling binder may be appropriate for a recycling operation planned for the warm period of the construction season of a bitumen aggregate containing a hard aged binder.

It is also possible to recycle bituminous aggregate containing hard aged bitumen using neat bitumen i.e. without any fluxing agent. The aged bitumen is considered inert and it is assumed that little binding is expected from the aged bitumen. The new binder requirement is generally greater in this case since the contribution of the old binder to the cohesion may be limited. The selection of this type of recycling binder may be appropriate for an operation planned for the cooler period of the construction season of a bitumen aggregate containing a hard aged binder.

Neat bitumen may be the preferred type of recycling binder to recycle bituminous aggregate containing very soft aged bitumen. In fact, it may be beneficial in certain cases to consider the usage of hard neat bitumen as the recycling binder, especially when the recycling operation is planned for the warmer months of the construction season. Recycling binders containing a fluxing agent are seldom used in this situation. Permanent deformation of this type of recycled mixture is often a controlling factor in the mixture design, thus, the usage of a recycling binder that contains a fluxing agent is not the preferred choice. Fluxing agents soften aged binder, thus increasing the permanent deformation potential of this type of recycling mixture.

4.2.3 Selection of recycling binder carrier

Recycling binder carrier refers to the process by which the viscosity of the recycling binder is reduced in order to be blended uniformly with the reclaimed material. Emulsification process of bitumen is the main type of binder carrier used for recycling bituminous aggregate.

Many options are available with the emulsification process including standard emulsions, modified emulsion and rejuvenating type emulsion. The standard emulsion may be cationic, anionic or anionic high float. The modified emulsion contains polymer. The rejuvenating type emulsion is composed of bitumen and fluxing agent in the form of rejuvenating maltene type oil. Medium and slow setting emulsions are used with recycling work.

Recycling work performed with polymer and non-polymer modified high float emulsions is common. The coating of high float emulsion added in small dosage within a dense graded material tends to be selective. The smaller particles of the bituminous aggregate are generally coated with a thick film of bitumen while the larger particles are partially or not coated. High float emulsions are always produced with a certain amount of fluxing agent to promote coating, consequently softening of aged bitumen. The added bitumen fluxes through the aged bitumen of the bitumen rich small fraction of the bituminous aggregate creating a mastic paste that binds the bituminous aggregate matrix together.

Recycling work using polymer and non-polymer cationic slow setting emulsions is becoming more and more prevalent in Canada. The coating characteristics of cationic slow setting emulsion are significantly different than those of high float emulsion. The thickness of the coating is thinner than the coating obtained with high float emulsions, but a larger portion of the smaller fraction of the bituminous aggregate is coated at an equivalent emulsion dosage. Cationic slow setting emulsion may be produced with or without any fluxing agent. As the added bitumen fluxes through the aged bitumen, a mortar like paste is created. In this case, the mortar is produced with a larger portion of the smaller fraction of the bituminous aggregate and the mortar is not as bitumen rich as the mortar obtained with the high float emulsions. It is often the preferred recycling binder when the portion of uncoated aggregate included in the recycled mixture is greater than 10%. Cationic emulsions allow the use of a small amount pozzolanic agent such as cement or lime to accelerate the build up of cohesion of the materials recycled.

The usage of rejuvenating type emulsions with partial-depth recycling work is not very common in Canada. A rejuvenating type emulsion is a blend of pure bitumen emulsion and emulsified rejuvenating maltene oil. The added bitumen provides cohesion to the recycled mixture, while the rejuvenating oil restores the bitumen characteristics of the aged bitumen. The effectiveness of the aged bitumen rejuvenation depends on a multitude of factors, but it tends to be related to the fluxing of the aged binder which is time and temperature dependent.

4.3 Field considerations

It is important to take into account the challenges associated with the job site and the field conditions to maximize the constructability performance of the recycling work. The field considerations may include the expected weather conditions during and after the recycling work, the thickness of treatment, the time pressure to place the surfacing mat, the type of traffic and the type of surfacing system.

The usage of a pozzolanic agent such as cement or lime accelerates the build up of cohesion of the materials recycled with cationic emulsions. It is beneficial to this type of recycling system whenever work is planned for the cooler months of the recycling season, the thickness of the treatment is greater than 100 mm or that it is imperative that the surfacing mat be placed on top to the recycled material in a short period of time. If the traffic is light and fast, kneading action of the recycled material may be limited, thus the usage of a neat bitumen recycling binder may be preferable. If on the other hand, the traffic is heavy and slow, and the work is carried out in the warmer months of the recycling season, more kneading action may be expected, thus the usage of a harsh mixture recycled with a smaller amount of recycling binder with some fluxing agent may be considered. If a thin surfacing system such as micro-surfacing or chip sealing is used to cover the recycled mat, it may be beneficial to plan the recycling work in the warmer months of the recycling season and the mat remained uncovered as long as possible to maximize the formation of the new effective binder before the placement of the overlay.

4.4 Recycling mixture design procedure

Recycling mixture design procedure is a process by which field conditions are simulated in the laboratory to evaluate the long term and the constructability performance of the recycled mixture. It is an interactive process that allows confirmation of the feasibility of the recycling work and to modify the previously selected recycling system, if required. Trial mixtures of reclaimed materials are prepared in the laboratory with varying recycling binder and water contents, but at a constant fluid content. The trial specimens are produced using a modified version of the Marshall method of compaction and a laboratory curing procedure to simulate both the compaction and curing of the recycled mixture occurring in the field. Laboratory testing is performed to determine performance-related parameters that are used to confirm the adequacy of the recycling system and to establish an optimal job-mix formula. The following section provides a brief description of performances-related parameters used to assess recycled mixtures, which are essentially air voids and water resistance.

4.4.1 Air voids

The air voids of the laboratory specimen are used to assess the ability of the recycled mixture to be compacted and to provide information on the potential risk of permanent deformation of the recycled mixture. The target laboratory air voids are between 9 and 11% for the Ontario laboratory curing and compaction procedure. Whenever the voids are less than 9% at the minimum added binder requirement it is common that a corrective aggregate is required to increase the voids. Voids below 9% are a sign of mixture tenderness, which may lead to rutting and/or shoving under heavy loading and warm weather. The density of recycled mixtures with voids above the 11% mark may easily be increased by adding more recycling binder or by using a softer recycling binder. Voids above 11% are a sign of mixture harshness, which may lead to excessive ravelling under unfavourable weather conditions and rapid light traffic.

4.4.2 Moisture sensitivity

Air voids of recycled mixtures are relatively high compared to dense graded hot bituminous mixture. Furthermore, the coating of the recycling binder tends to be selective. Consequently, recycled mixtures are less cohesive than dense graded hot bituminous mixtures. The adhesion of the recycling binder to the bituminous aggregate is critical, particularly during the time period that the new effective binder is forming. If adhesion is poor, rain may have a disastrous effect on the mixture, leading to ravelling. The evaluation of the moisture sensitivity of the recycled mixture is important and carried out using the retained stability method. If the retained stability is below 70 %, the usage of an additive such as cement or lime with a compatible recycling binder is often required.

5 CURING OF RECYCLED MAT

The build up of cohesion of recycled mixture occurs over two phases. The initial phase corresponds to the time period necessary for the recycling binder to form a continuous film of bitumen. The end of the first phase also corresponds to the beginning of the formation of the new effective binder, which is essentially associated with the second phase of the curing and further cohesion build up of recycled mixtures. The initial phase may be as short as a few days, while the second phase may last several months.

Bituminous aggregate is a unique material with respect to its reactivity with recycling binders. The aged bitumen electrically insulates the surface of the mineral aggregate, which virtually prevents any type of aggregate-binder interaction that may destabilize and break emulsions. Thus, the build up of cohesion, which is associated with the breaking of the emulsion, becomes highly dependent on the evacuation of water. The build up of cohesion is a gradual top to bottom process and the rate at which the recycled mat builds up cohesion is faster in the upper part compared to the bottom part.

The evacuation water and, accordingly, the build up of cohesion of the recycled mixture are strongly influenced by the ambient temperature and the atmospheric relative humidity. Warm and dry weather shortens the first phase of curing, while damp and cold weather has the opposite effect. The usage of a pozzolanic agent as a catalyst to help the breaking of a cationic emulsion is beneficial for recycling. It allows an effective break of the emulsion even in relatively unfavourable weather conditions, which is advantageous in the latter part of the construction season when the occurrence of favourable weather condition is uncertain. It also allows an effective break of the emulsion through the entire thickness of the mat, which is advantageous when the recycling treatment is relatively deep.

The pozzolanic agents are strongly alkaline (pH ~12) and the surface area offered for a small quantity of product is extremely high. The alkalinity of the agent destabilizes the acidic emulsions causing them to break even in the presence of water, thus, helping the recycling mixture to build up cohesion relatively independently from the evacuation of water.

6.0 COMPACTION OF RECYCLED MAT

Similarly to hot bituminous mixtures and granular material, the compaction operation of recycled materials serves to increase the density the mixture, thus enhancing the internal friction of the particles, which strengthens the mineral skeleton of the mixture. Other phenomena are also occurring during compaction of recycled mixtures. The mixture internal pressure created by the compaction laminates the bituminous aggregates together resulting in a rapid increase of cohesion. It is also suspected that the internal pressure between the particles forces the fluxing of the recycled binder with the aged binder.

The role of the water during the recycling operation is of prime importance. It has two functions: it helps the binder to coat the recycled material and it provides the mixture with an internal lubricant during compaction. Excessive water may cause the emulsion to only coat the finer particles. The lower water content that allows proper coating of the aggregate is preferred as it helps to speed up the evacuation of water. It is also indicative that heavy static and dynamic compaction is required to achieve the target densification of the mixture.

7.0 SUMMARY

Many millions of square metres of roadway are rehabilitated using in-place cold recycling techniques every year in Canada. The thriving of cold recycling is closely associated with the engineering strides that are made in this field every year in Canada and abroad.

Recycling techniques are classified into five distinctive classes of treatment in accordance with the *objective of the treatment*, the *nature of the reclaimed materials* to be recycled and the *recycling system*. The expected performance of the treatments is separated into roadway performance and constructability performance. This distinction is provided to help in the selection of recycling systems that optimized the outcome of recycling work including constructability challenges.

The parameters influencing the performance of the recycling mixture are defined. An emphasis is placed on the importance of characterising bituminous aggregate with respect to the aged bitumen and the mineral gradation of the reclaimed material to select optimal recycling systems. The interaction of recycling binders with aged binders is explained with a focus on the options available in terms of the selection process. Operational constraints that may affect the outcome of the recycling work are described and solutions are suggested to overcome potential job site difficulties. Finally, the laboratory mixture design procedure is briefly outlined with a description of the performance-related parameters that serve to primarily confirm the adequacy of the selected recycling system and secondly to determine the job mix formula. The parameters are the air voids and the moisture resistance of the mixture.

A description the parameters influencing the performance of the recycling matetrial as it relates to curing and compaction is included. Curing is the process by which the recycled material builds up cohesion and strength. It is influenced by a multitude of factors and it can be accelerated using pozzolanic agents. Recycled mixtures are harsh materials and difficult to compact. The role of water as well as the usage of heavy compaction is vital to obtain satisfactory densification of the recycled material. The internal pressure within the recycled material imposed by the densification process is beneficial and may initiate the curing process of recycled material.

The engineering of recycled roadways is becoming more sophisticated and more reliable, which reduces the risks associated with recycling and improves the performance of roadways rehabilitated using recycling strategies.

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