A review of in-place cold recycling/reclamation in Canada

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ABSTRACT

The current concept of in-place cold reclamation/recycling of bituminous pavement was introduced in Canada in 1983. It is estimated that more than 40 million square metres of pavement have been rehabilitated using an in-place cold reclamation/recycling method over the last twenty years in Canada.

The driving engine of in-place reclamation/recycling is associated with the concept that the existing pavement is the source of primary materials to create a new pavement material. The existing pavement materials are reclaimed and transformed into a sized material, which is then mixed with a bituminous binder and laid down in-place. The reclamation/recycling of the pavement is performed without heat and depending on the existing pavement conditions, the operation is performed using the Cold In-place Recycling process (CIR) or the Full Depth Reclamation/Stabilization process (FDR). The bituminous binder is either an emulsified bitumen or a foamed bitumen.

The environmental benefits associated with in-place cold reclamation/recycling are significant. There is nearly no transportation of pavement materials and the processes are performed without heat. The energy consumption for the production of in-place cold recycled material is approximately 20 % of the energy necessary to produce new hot bituminous materials for an equivalent quantity. As a result the emission of greenhouse gas is also greatly reduced.

The recycled mixtures have mechanical properties that differ significantly from those of standard hot bituminous mixtures. The voids in the mixture are high and as a result the stiffness of the recycled mixtures is typically lower than that of standard hot bituminous mixtures. The high void content of recycled mixtures offers an improved mitigation of reflective cracking**,** which before the introduction of in-place reclamation/recycling was one of the primary causes of pavement failure in Canada.

This paper outlines the concepts associated with in-place cold reclamation/recycling of bituminous pavements with a particular focus on project selection and design practices. The binder selection is discussed in detail as well as the equipment, construction procedures and performance of recycled mixtures.

1.0 INTRODUCTION

1.1 Background

The petroleum crisis in the early seventies and the development of milling/reclaiming equipment for the road industry created a favourable environment for emergence of large-scale reclaiming/recycling technologies. The current large-scale concept of in-place reclamation/recycling of existing bituminous pavements using a cold process was first developed in the USA and it was later introduced in Canada in 1983. It is estimated that more than 40 million square metres of pavement have been rehabilitated using a cold in-situ reclamation/recycling process over the last twenty years in Canada. It is estimated that in North America approximately five to ten million tonnes of bituminous concrete pavement are reclaimed/recycled every year using this pavement rehabilitation method.

The experience with in-place reclamation/recycling in Canada is extensive and the benefits associated with this process are significant when compared with traditional pavement rehabilitation methods. In-place reclamation/recycling reduces the cost of pavement rehabilitation. With this process, the existing pavement geometry is preserved. In-place reclamation/recycling reuses all of the existing materials, allowing the preservation of aggregates and bitumen. The cold nature of the process reduces the impact on the environment and preserves energy. These benefits have spurred the development of high production equipment. Consequently, in-place reclamation/recycling is constantly gaining acceptance among Canadian road agencies.

1.2 Objectives

The objective of this paper is to provide current information on how the cold in-situ reclamation/recycling processes are carried out in Canada. The concepts associated with these processes are defined and explained with a particular focus on project selection and design practices. Information on binder selection is presented in detail as well as the equipment and construction procedures. The performance of reclaimed/recycled pavement is discussed. Finally, recently published information on the environmental benefits of cold in-situ reclamation/recycling is presented.

1.3 Definitions

Cold in-situ reclamation/recycling processes are pavement rehabilitation techniques for bituminous pavement that does not require heat while reclaiming/recycling the in-place material. The processes may be divided into three different types of in-place reclamation/recycling processes as define hereafter.

Partial-depth reclamation/recycling process reuses only the existing bituminous concrete material. It is commonly referred to as Cold In-place Recycling or CIR. The end result is a mixture of reclaimed bituminous pavement and a new bituminous binder. Depth of recycling typically ranges from 65 to 125 mm. The work is carried out with a multi-functional recycling train. This process is generally performed on thicker bituminous pavements. The pavement structure is usually adequate and the pavement profiles may be moderately deformed. The pavement surface is moderately to severely cracked.

Full-depth reclamation/recycling process is commonly known as full-depth reclamation and stabilization or FDR/Stabilization. This process reuses the in-place bituminous cover as well as the part of the underlying granular material. The granular material accounts for at least 25 % of the mixture and the end result is a mixture of bituminous aggregate, unbound base material and a new bituminous binder. The depth of the treatment ranges from 125 to 250 mm. The full-depth reclamation and stabilization work is normally performed with reclaiming/stabilizing machines. Multi-functional recycling trains have also been used in a few cases. This process is commonly selected for pavements with thinner bituminous cover. The pavement structure of the typical candidates is often fatigue and the roadway surface is usually distorted and severely cracked.

The third type of reclamation/recycling process may also be defined as a partial-depth process. This process reuses the in-place bituminous cover as well as a small amount of the underlying granular material. The amount of the underlying granular material included in the mixture is generally less than 25 % of the mixture. Depth of recycling typically ranges from 65 to 125 mm. The work is carried out with a multi-functional recycling train. This process may be selected for pavement with thinner bituminous cover. The roadway surface of typical candidates may be moderately deformed and cracked, but the pavement structure is usually adequate.

2.0 PROCESS DESCRIPTION

Cold in-situ reclamation/recycling processes are based on the principle that the in-place pavement materials are a source of materials that may be used again to build a new bituminous layer. Therefore, all of the operations of a pavement material production line are included. Cold in-situ reclamation/recycling processes consist of several fundamental operations:

- reclamation of the existing pavement materials
- transformation of the reclaimed materials into a homogeneous calibrated material
- addition of an aggregate, if required
- addition of a new bituminous binder
- mixing of all the components
- placement of the new mixture
- compaction of the mixture
- curing of the mixture
- application of a wearing course.

3.0 PROJECT SELECTION

Selection of suitable candidates for cold in-situ reclamation/recycling processes require detailed engineering work. The engineering work may vary from one project to another, but generally it includes as a minimum a field investigation and a pavement structure assessment. The objectives of the engineering work are to determine:

- the suitability of the pavement for a cold in-situ reclamation/recycling process
- the selection of the in-place treatment
- the detailed design work in terms
    - pavement surface profile correction
    - material design
    - pavement design.

3.1 Suitability in the Pavement for an In-place Rehabilitation Method

The first objective of the engineering work is to determine if a given pavement may be suitable to be rehabilitated using an in-situ reclamation/recycling process in terms of physical, economical and technical feasibility.

3.1.1 Physical Feasibility

The physical feasibility is simply related to the physical environment of the pavement. The high performance recycling/reclamation equipment is commonly large and there are limitations on the maneuverability of certain pieces of equipment. Physical environment such as narrow residential streets or rural low volume roads may not be suitable for an in place pavement rehabilitation process. The performance of reclamation/recycling work in a small physical space may result in a lack of production, which will affect the pricing of the project. Or, the equipment associated with the selected process may be simply too large to fit into a confined urban space. Furthermore, the usage of large vibrating compaction equipment needed to increase the density of thick layers of recycled/reclaimed material in close proximity of residences may not be allowable.

The physical feasibility may also be related to the pavement sub-grade conditions. Low volume roads in rural environment are often structurally weak and they may not be capable of supporting heavy loads. The usage of large milling or paving equipment may not be suitable in certain cases, especially when the weak pavement has no or very narrow shoulders. The usage of equipment fitted with low-pressure tires such as reclaimers may be the only choice.

3.1.2 Economical Feasibility

The objective of the economical feasibility study of the project is to ensure that in-place pavement rehabilitation is economically viable in comparison to other technique that may be equivalent.

Rehabilitation Cost and Life-Cycled Cost

The rehabilitation cost and the life-cycled cost are important factors to take into account in the analysis. The method used to compare costs is relatively simple and it is still the predominant method used to compare the various rehabilitation strategies. On a small project, the cost associated with the mobilization of a multi-function recycling train may be disproportional to the actual cost of the rehabilitation. In such cases the traditional rehabilitation methods are usually more cost effective when compared to an in-place method. However, on mid-size and large projects, it is common that in-place rehabilitation methods are more cost effective than traditional methods.

Disruption to Traffic

More and more road agencies will take into account other economical factors in their decision making such as disruption to traffic. Roadwork has an impact on the normal flow of traffic in the form of traffic delays or increases of traffic on alternate routes. The economical impact of the disruption to traffic may be evaluated in relation to the occupancy of the roadway during the rehabilitation work and the construction traffic. The road occupancy associated with an in-place process has the advantage of being shorter than the road occupancy associated with a traditional pavement rehabilitation method. The nature of the in-place rehabilitation method and the performance of the reclamation/recycling equipment allows to process more materials in a shorter period of time than with a traditional rehabilitation methods. Furthermore, construction traffic, mainly the trucking of materials in and out of the work site is greatly reduced when an in-place method is used. Traditional pavement rehabilitation methods are based on material removal and replacement or on the addition of more pavement materials on top of the existing pavement. In addition to road occupancy truck traffic will accentuate the impact of the roadwork on the flow of traffic.

Disposal of Unwanted Pavement Materials

Disposal of unwanted pavement materials is becoming less and less a factor in Canada. Pavement materials are recycled in one form or another, but very often pavement materials are down graded to fill materials or to unbound granular materials. In-place reclamation is performed on a regular basis, where the bituminous layers are granulated in-place, mixed with the underlying granular material, graded and compacted. The higher valued bituminous material is down graded to the value of granular material. In other cases bituminous materials are recycled through a hot mix plant facility. In this case the bituminous material is hauled away from the site and returned as new hot mix. The trucking involved is costly in comparison to simply reusing the reclaimed materials in place.

3.1.3 Technical Feasibility

The range of application for in-place reclamation/recycling is substantial. The performance of recycling equipment is very high and well suited for most bituminous pavement encountered in Canada. However, the nature of certain types of in-place materials may limit the usage of reclamation/recycling techniques. The size of the larger mineral particles encountered within the pavement materials to be recycled should be less than 60 mm for 95 % of the materials to be recycled with no particles greater than 80 mm. The presence of large mineral particles significantly hinders the placement and finishing of reclaimed/recycled materials.

The weather conditions are also important to take into account when evaluating the technical feasibility of using an in-place cold reclamation/recycling technique for pavement rehabilitation. The cold reclaimed/recycled techniques will perform best when they are carried out in the warmer months of the year. On one hand water is used to help maximize compaction, on the other hand water must be expelled to maximize the build up of cohesion in the newly produced in-place materials. Dry and warm weather conditions are more suitable for the performance of in-place cold reclamation/recycling operations as they favour the departure of water from the in-place mixture.

3.2 Selection of the In-place Treatment

In-place cold reclamation/recycling techniques may be considered as potential rehabilitation techniques for a wide variety of pavement distresses. The selection of an in-place process is based on the objective pursued, the thickness and the nature of the bituminous cover and the roughness of the pavement surface.

The objectives of the reclamation/recycling of the pavement may range from structural improvement of a structurally weak low volume traffic roadway to a surface rehabilitation of a structurally adequate roadway carrying a significant amount of traffic. Structural improvement of weak pavement is usually associated with a thin bituminous surfacing, while surface rehabilitation of a structurally sound pavement is normally coupled with the presence of at least two layers of hot bituminous materials. The deformation of the pavement surface is often related to the strength of the pavement and the thickness of the bituminous cover. Structurally weak pavements with thin bituminous layer are often severely deformed, while structurally sound pavement with thick bituminous surfacing may be in better conditions with respect to the pavement surface profiles. The severity of the deformation of the surface of the pavement is often associated with pavements that are structurally weak with a thin bituminous cover thin.

Structurally weak, thin bituminous cover and severely deformed pavement are recycled/reclaimed in-place using the full-depth reclamation/recycling process. Conversely, structurally sound, thick bituminous cover and relatively smooth pavement are recycled/reclaimed in-place using partial-depth reclamation/recycling process. However, the selection of an in-place process may not be that clear in all cases as described hereafter.

Severely deformed pavement may still be recycled using the partial-depth process providing that an additional corrective operation is carried out such as a cut and fill evaluation of the roadway to ensure that the material to be recycled is well distributed throughout the project. Supplemental aggregates may also be used in this case. Profiling the roadway ahead of the partial-depth operation has been performed as well to correct the profile of the roadway. Thin bituminous covered pavement may also be recycled using a partial-depth process providing the pavement profile is not severely deformed. In this case a small amount of underlying granular material is incorporated into the new bituminous mixture.

Thicker bituminous pavement may also be reclaimed using the full-depth process if the objective of the reclamation/recycling operation is to optimize the structural gain that the in-place materials can offer. High performance reclaimers will cut through thick bituminous layers. The limiting factor in this case is the compaction effort needed to adequately increase the density of a recycled material placed in a thickness of more than 200 mm. Compaction of thick layers of recycled material may require the usage of heavy single drum vibratory rollers and even pad foot roller to ensure compaction is achieved at the bottom of the layer.

In-place cold reclamation/recycling techniques are diverse and can adapt to a wide variety of applications. The recycling machines are designed to process the in-place material partial-depth, partial-depth with some underlying granular material or full-depth of the pavement. However, the selection of the right process is influenced by a multitude of factors and there are many cases where each process may be appropriate.

3.3 Detailed Project Design Work

The detailed project design work involves three distinctive design activities: surface grade and slope, bituminous mixture design and pavement design.

3.3.1 Pavement Profiles

Using the information gathered during the field investigation, the longitudinal and transverse profiles of the pavement surface are assessed. When the profile of the pavement surface is severely defective, the following corrective operations may be envisaged:

- establishing a cut & fill plan to use the excess material for the high areas in the low areas to even the distribution of recycled material throughout the project
- profiling the road with a milling machine if the thickness of the bituminous pavement is sufficient or pulverizing and reshaping the roadway before the stabilization operation
- adding either virgin aggregate or bituminous aggregate from an external source
- correcting the profile with additional wearing course material.

Recycling/Reclaiming work may be used to enlarge an existing pavement platform. The recycled mixture is simply laid down at a wider width than the original platform.

3.3.2 Bituminous Mixture Design

The bituminous mixture design is carried out in four stages: field sampling, materials testing, additive selection and laboratory mixture design.

Field Sampling

Using the information gathered during the field investigation, the reclamation/recycling project is divided into relatively homogeneous sections. A representative sample of the in-place material is extracted from the pavement in each section. Samples are extracted from the pavement with coring machines or dry cut saws and crushed in the laboratory to reproduce the equipment sizing operation.

Material Testing

The laboratory work conducted on the bituminous aggregate field sampling may include the following tests:

- gradation of the mineral aggregate before and after the bitumen extraction
    - fines content
    - ratio fine aggregate and coarse aggregate
- characterization of the aged bitumen
    - penetration
    - content.

The tests results are used to determine if addition of corrective aggregate is required in the process. The selection of the type of binder is also based on the results of these tests.

Binder Selection

A small amount of new bitumen is added to the recycled, consequently, the success of a reclamation/recycling project is highly dependent on the performance of a relatively small amount of new bitumen. The new bituminous binder may be a rejuvenating emulsion, an emulsion of unmodified bitumen, a polymer-modified bitumen and a foamed bitumen.

The selection of bituminous binder is based on the following characteristics:

- softening ability of the old bitumen

- coating capability of both the bituminous aggregate and the virgin aggregate
- cohesion build up and adhesion development at an early age to allow traffic and to resist rainfalls
- insensitivity to small variations in binder content.

Laboratory Mixture Design

A sequence of tests is performed on trial mixtures of recycled/reclaimed materials with varying binder and water contents. The results obtained from these tests provide the necessary information to select an optimum range of binder and water content for proper mix density, air voids and stability. The typical added residual bitumen for standard partial-depth in-place recycling ranges from 0.8 to 1.6 % and from 2.2 to 3.2 % for the full-depth process.

The role of the water during the reclamation/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 inhibit compaction and also cause an emulsion to coat only the fines. The lower water content that allows proper coating of the aggregate is preferred as it helps to reduce the drying time.

If a corrective aggregate is required, the trial mixtures may also be carried out with different types and amounts of aggregate. The nature and the amount of corrective aggregate will vary in accordance with the existing material conditions and the nature of the added binder. Corrective aggregates such as filler, continuously graded aggregate or single-size aggregate may be used to correct the material conditions of the in-place materials. Filler may be used to supplement a clean aggregate gradation processed using the full-depth process. The addition of filler may also be associated with a foamed binder. A continuously graded aggregate may be used to lower the binder content ratio in a bitumen rich material. Single-sized aggregate may be used to strengthen the mineral skeleton of sandy type mixture to be recycled.

The adhesion of the binder to the bituminous aggregate is critical, particularly in the first few days after the operation. If adhesion is poor, rain may have a disastrous effect on the mixture, leading to raveling. The evaluation of the moisture sensitivity of the selected mixture is recommended. If the new mixture is sensitive to moisture, use of a different binder or anti-stripping additive such as cement or lime may be required.

The laboratory mixture design methods currently used give an initial job-mix formula for the fieldwork. The final job-mix formula is confirmed and adjusted in the field following an evaluation of the mixture qualities, which includes workability, coating, plasticity, ease of compaction and the weather conditions in the field at that time.

3.3.3 Pavement Design

The expected life of a pavement rehabilitated using an in-place cold reclamation/recycling process is related to the depth of the treatment and the type and thickness of the subsequent surfacing course. The pavement design must consider the following elements: structural design, minimum depth of treatment, traffic and selection of surfacing course or courses.

Structural Design

Currently, there is not a universally accepted structural coefficient for in-place recycling. The structural capacity of reprocessed material is dependent on the nature of the in-place materials, the added binder and the curing/fluxing time. The US road agencies assume AASHTO layer coefficients between 0.20 and 0.44 depending on the type and amount of additive added to the in-place material. The most commonly used value for standard partial-depth and full-depth work is 0.30. In Ontario, the Granular Base Equivalency (GBE) value for in-place reclamation/recycling work varies between 1.5 and 1.8.

Depth of Process

A minimum depth of process is required to mitigate reflective cracking in the case of the partial-depth process. As a rule of thumb, whenever the depth of the cut is at least 100 mm or 70 % of the full depth of bituminous pavement, the potential occurrence of reflective cracking is greatly reduced. Paved shoulder should also be recycled to prevent propagation of shoulder cracks into adjacent CIR treated lanes.

In the case of the full-depth process, the type of material may be a limiting factor. The depth of the process should be limited to the layers of material containing mineral particle smaller than 60 mm. The ability of compacting thick layer of material may also limit the thickness at which the process may be performed.

Traffic

When in-place cold recycling/reclamation was first introduced in Canada many road agencies recommended that recycling/reclamation not be used on pavement carrying more than 5000 AADT. The knowledge of the performance of recycled materials has greatly improved in the last decade and recycling/reclaiming processes have been successfully carried out on roadways carrying traffic volume well in excess of that limit. Limits on traffic volume for recycling have been removed by most road agencies.

Surfacing Course Selection

The final operation of the recycling/reclamation process is the placement of a surfacing course. The pavement structural design assumptions predicate the selection of the surfacing course. The surfacing course provides sealing and, when required, pavement reinforcement. Currently, the selection of the surfacing course is determined by local experience. Bituminous concrete surfacing is the most commonly selected surfacing materials for recycled/reclaimed pavement in Canada.

4.0 EQUIPMENT AND CONSTRUCTION PROCEDURES

4.1 Partial-depth Reclamation/Recycling Equipment

A wide variety of equipment is available to perform partial-depth recycling/reclamation work; they differ from one another by how the following operations are regrouped or separated:

- reclamation of the existing in-place material
- transformation of the in-place material into a calibrated material
- addition of an bituminous binder and mixing of all the components
- placement of the new mixture.

Equipment grouping all of these operations into one single unit as well as multi-unit recycling trains are available. The single unit recycling equipment reclaims, sizes and mixes in the additives in the cutting drum while the placement operation is performed with a standard screed attached to the back of the unit. In the case of a multi-unit recycling train, the reclamation of the existing material is performed by a standard milling machine, the sizing is accomplished by a mobile screen/crusher unit, the mixing is done with a mobile pugmill and the placement is carried out with a standard paver.

Other versions may include a mix-paver instead of the mobile pugmill and standard paver. A down cut milling machine may replace the standard up cut milling machine and mobile screen/crusher. Units grouping the sizing and the mixing functions are also available as well as combining reclamation, sizing and mixing operations.

4.2 Gradation of the In-place Material

The intent of sizing is to separate the aggregate particles from one another at the bitumen/aggregate interface. To break up the bituminous pavement to achieve adequate sizing, the largest particle of the bituminous aggregate may not be less than 1.5 times the largest mineral aggregate in the existing in-place mixture. The typical largest size aggregate in existing bituminous concrete is 25 mm. Therefore, a specification that the gradation of the bituminous aggregate must be “100 % passing the 37 mm sieve” is widely used for partial-depth work. In the case of the full-depth work the maximum particle size of the reclaimed material is commonly limited to 50 mm. Material containing larger particles may still be reclaimed and stabilized, but at least 90 % should be smaller than 60 mm with no particle greater than 80 mm.

4.3 Grade and Slope Correction

To maximize the surface profile correction capabilities of the partial-depth recycling/reclaiming operation, grade and transverse slope control devices are required to control both the cutting drum and the paving screed. A material storage capability as well as a means of adding material in the process are required to regulate the flow of material to the paving operation. When the profile of the pavement surface is severely defective, an additional corrective operation may be considered as described previously in the section *Pavement Profile*.

The material obtained from the full-depth recycling/reclaiming operation is commonly placed using a motor grader. The correction capability of the longitudinal and transverse profile of the roadway is excellent with respect to the longer wavelength defect on the roadway. The operation is usually carried out into two separate operations: the first operation consists of granulation operation and reshaping of the roadway and the second operation consists of binder mixing and final profiling of the roadway. The full-depth operation offers more flexibility in reshaping the roadway when compared to the partial-depth reclaiming/recycling operation with respect to the long wavelength defect and thick material placement (>100 mm). However, in the case of the correction of shorter wavelength defect and thin material placement (<100 mm) the traditional paver may correct the surface defect more effectively. Paver fitted with high density screeds have been used to place recycled/reclaimed material at thicknesses greater than 100 mm successfully. Even in this case the best results are obtained when the placement of the reclaimed material of the first operation of the full-depth process is carried out using a motor grader.

4.4 Mixing

Mixing of the additives with in-place material occurs in the cutting drum and/or in a pugmill. Corrective aggregates are usually introduced ahead of the milling machine or reclaiming machine and mixed in with the in-place material within the cutting drum. The bituminous binder may be mixed with the aggregate either in the cutting drum or with a twin shaft pugmill. Mixing with a pugmill is controlled by weight while cutting drum mixing is controlled by volume.

4.5 Compaction

A successful recycling/reclaiming operation is highly dependent on the compaction of the mixture. Placement of the new mixture requires more compaction energy than does placement of standard hot bituminous mixtures. A newly stabilized mixture tends to bulk up which indicates that internal friction between the particles is high. The use of one heavy pneumatic roller combined with one large single drum vibrating roller is commonly used. The rolling patterns to achieve compaction are established on test sections. Nuclear gauges are used to monitor the moisture content as well as the density of the mixture during the compaction operation.

The mixture moisture content is critical for compaction. On one hand, if there is not enough water, the mixture is harsh and will not compact. On the other hand, if there is too much water, the mixture will also not compact because of excess fluids and no air voids. In some cases, the water required for mixing may be in excess of what is required for compaction.

The minimum compaction requirement most commonly used is 96 to 98 % of the density of the bulk relative density of the mixture depending on the laboratory testing method or 97 % of the target density established in test section. The compacted mixture internal void content ranges between 12 and 15 % typically.

4.6 Field Adjustments

Field adjustments are carried out on a continuous basis during a partial-depth reclamation/recycling operation to account for the variability of the field and weather conditions. Field adjustments of the binder content and of the water content do not exceed ± 10% of the job mix formula. Even though the adjustments are relatively minor, they are very important to obtain uniform performance of the recycled mat. Field adjustments of the binder are not frequent in the case of a full-depth reclamation operation, however, as for the partial-depth operation the water content of the mixture is adjusted on a continuous basis to account for the field and weather conditions.

4.7 Curing

A certain time period is necessary to allow the newly produced mixture to cure and build up some internal cohesion before being covered with a wearing course. A time period of 2 to14 days is typically specified depending on the binder used. Foamed bitumen and solvent-less emulsions will cure faster than binder containing a solvent or a rejuvenating agent.

4.8 Weather Limitations

The weather limitations for cold recycling/reclamation are not as stringent as those of other emulsion applications. Recycling/reclaiming work has been performed in light rainy condition with success. Light rain will not affect the process providing that the moisture content of the bituminous aggregate is monitored and adjusted. Air temperature will affect the recycling/reclamation process more than rain. Low air temperature will influence the breaking and the curing of the emulsion, and it also affects the viscosity of the aged bitumen contained in the bituminous aggregate. At lower air temperatures, the early cohesion of the recycled mixture may be insufficient resulting in excessive raveling.

5.0 PERFORMANCE OF RECYCLING/RECLAMING WORK

5.1 Binding Effect of the Added Bituminous Agent

The most commonly accepted understanding of the rejuvenating effect occurring in the recycled mixture is based on two opposing ideas proposed in the early development of cold recycling. One concept was based on the assumption that the aged bitumen was inert and the bituminous aggregate treated as a black aggregate. The other concept assumed that the aged bitumen was still active and that addition of a rejuvenating agent restored the aged bitumen to its original characteristics.

Field observations and laboratory work indicate that both processes are occurring. A portion of the aged bitumen remains inert and a portion combines with the added virgin bitumen contained in the binder to eventually produce a “new effective binder”. The portion of the aged bitumen that combines with the added virgin bitumen depends on the gradation of the bituminous aggregate, the bitumen content, the softness of both the aged and the virgin bitumen, and the coating characteristics of the added binder. A solvent rich binder 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 solvent-less binder with minimum coating capability mixed with a coarse graded bituminous aggregate in the cooler month of the road construction season.

The “new effective binder” rejuvenating concept supports the observations, which indicate that the mechanical performance of recycled mixtures improves during the first few months of service. These first few months of service probably represent the time period during which the added virgin bitumen is fluxing through and mixing with the aged bitumen.

5.2 Added Binder Performance

Four categories of binder are available for partial-depth and full-depth recycling/reclamation work. The binder may be a standard emulsion, a modified bitumen emulsion, a rejuvenating type emulsion or a foamed bitumen. The standard emulsion may be cationic, anionic or anionic high float. The modified bitumen emulsion contains polymer. The rejuvenating type emulsion is composed of bitumen and rejuvenating maltene type oil. Medium and slow setting emulsions are used with recycling/reclaiming work. With respect to foamed bitumen, the half-life of the foam is usually more than 10 seconds to allow proper mixing and the bitumen used in Ontario are mostly PG 58-28.

The usage of polymer and non-polymer modified high float emulsions is common. The gel structure provided by the high float emulsion residue allows to build a thicker film of bitumen around the bituminous aggregate particles. Therefore, the coating of high floats emulsion added in small dosage within a dense graded material tends to be selective. The bitumen rich smaller particles of the bituminous aggregate are generally coated with a thick film of bitumen while the larger particles are partially or not coated. The added bitumen fluxes through the aged bitumen of the bitumen rich small fraction of the bituminous aggregate creating a mortar like paste that binds the aggregate matrix together.

The usage of polymer and non-polymer cationic slow setting emulsions is also relatively common. 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. As the added bitumen fluxes through the aged bitumen, a mortar like paste is created. However, 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.

The usage of rejuvenating type emulsions with partial-depth recycling/reclaiming work is not very common, at least in North America. 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 mainly time and temperature related.

The polymer-modified emulsions provide higher early strength in cohesion and adhesion. The polymer also allows the usage of softer bitumen, which flux through and rejuvenate the aged bitumen more effectively, without the permanent deformation associated with emulsions made with unmodified soft bitumen.

5.3 Properties of Recycled/Reclaimed Mixtures and Structural Impact

5.3.1 Modulus and Fatigue

Modulus and fatigue life of recycled/reclaimed mixtures will increase during the first two years of service. The increase is the greatest in the first few months (3 to 5 months), after that period the modulus and the fatigue life will still increase but at a reduced rate. This phenomenon may be associated with the fluxing of the virgin bitumen with the aged bitumen as well as the decrease in air voids.

Modulus ranging from 3100 to 5500 MPa have been measured in the State of Oregon. The fatigue life measured after 48 months of service has reached values up to 250,000 cycles. These modulus and fatigue values were obtained in accordance with the diametral modulus and fatigue test (ASTM D4123). The tests were conducted at 23°C with a loading duration of 0.1 sec., a pulse frequency of 1 Hz and a pulse magnitude of 100 microstrain ($\mu\varepsilon$).

With similar air voids, recycled/reclaimed mixtures have significantly greater fatigue lives than standard hot bituminous mixtures. The creation of a mortar like paste with the bitumen rich smaller fraction of the bituminous aggregate appears to provide mechanical properties to the recycled/reclaimed mixture similar to those of virgin emulsion mixes rather than dense graded hot bituminous mixtures. Virgin emulsion mixtures are known to provide more fatigue resistance but less stiffness than regular dense graded hot bituminous mixtures. Field performances of recycled mixtures confirm the similarity between virgin emulsion mixtures and the cold recycled/reclaimed mixtures.

5.4 Reflective Cracking

Cold In-place Recycling is considered the most effective process to mitigate reflective cracking in a cold environment. In the Province of Quebec, a 70 mm recycled mixture overlay capped with a chip seal has been compared with a 60 mm standard hot bituminous overlay. The recycled mixture is capped with a chip seal. Both mixtures were applied onto a severely cracked pavement. The monitoring of the crack reflection indicates that after three years of service only a few cracks have reflected through the recycled mixture while 50 % of the original cracks have reflected through in the hot mixture section.

The primary cause of pavement distress and failure in the Municipality of Ottawa in Ontario is thermal cracking. In the Municipality of Ottawa, a pavement usually requires rehabilitation when the cracking frequency is approximately 155 to 170 cracks per kilometre. Standard hot bituminous mixture overlay may reach a cracking frequency requiring rehabilitation after 10 years of service. Based on the same cracking frequency criteria, it is estimated that rehabilitation of a partial-depth recycled pavement may not be required until after 14 years of service. The average rate of transverse cracking propagation for a hot bituminous overlay is estimated to be 16 cracks per kilometre per year while the average propagation of cracks through a recycled pavement is 11 cracks per kilometre per year.

5.5 Economics

Cold In-place Recycling is a cost effective rehabilitation alternative to traditional methods. Based on the life cycle cost of pavement rehabilitation in the Municipality of Ottawa, the annual cost for the recycled rehabilitation method (75 mm of CIR + 40 mm of a hot bituminous wearing course) is approximately 80 % of the standard hot bituminous overlay method (40 mm of a hot bituminous correction course + 40 mm of hot bituminous wearing course). In Quebec, the number reported was 70 % of the traditional rehabilitation method.

5.6 New Additives

5.6.1 Usage of Cement or Lime with Bitumen Emulsion

Further improvements in recycled mixture properties are possible. The use of cement or lime in conjunction with bitumen emulsion provides higher early strengths and greater resistance to water damage. Cement is used on partial-depth projects in the province of Quebec whenever the resistance to water damage is considered insufficient.

Diametral resilient modulus ASTM D 4123 tests have been performed on lime treated and untreated recycled mixtures. The modulus for the CIR mixtures including 1.0 % lime was 28 % higher than the regular recycled/reclaimed mixtures after five months of service. Furthermore, the Index of Retained Resilient Modulus, a water susceptibility indicator, was 42 % higher for the recycled/reclaimed mixture treated with 1.0 % lime when compared with the value of the untreated mixture.

6.0 CONCLUSION

Cold in-situ recycling/reclamation of pavement may be considered well-proven pavement rehabilitation methods. They are recognized viable engineering and economic alternatives to traditional rehabilitation methods for a wide range of traffic and pavement distress situations.

Cold in-situ recycling/reclamation of pavement provides numerous important advantages in pavement rehabilitation which include the following:

- conserves energy
  - process is carried out in-place and haulage of materials is reduced
  - no fuel for heating material is required
- conserves pavement materials
  - existing pavement material is reused
- preserves the environment
  - disposal of pavement materials is eliminated
  - air pollutants are reduced because of less haulage of materials and no heating of materials
- provides life cycle cost savings as well as initial cost saving
  - public investment in pavement is preserved
- allows the work to be executed with minimal disturbance to traffic
- controls and mitigates reflective cracking
  - when the entire thickness of bituminous cover is milled, reflective cracking is eliminated
- improves pavement surface smoothness and cross slope
- provides excellent performance under heavy traffic
  - post compaction is minimal even with high initial air voids in the recycled mixture
- allows to rebuild a wide range of distressed pavement which can not be simply overlaid
- homogenizes and improves the mechanistic characteristics of the treated layers
  - favourable deflection values are obtained
  - improved cohesion is reached with time
- avoids the need to raise the surface elevation of the pavement.

Continual developments are being made in both the pavement engineering and materials engineering fields to standardize and catalogue the various parameters designing, testing and constructing cold in-situ recycled/reclaimed pavements.

7.0 REFERENCES

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