A TWENTY-YEAR PERFORMANCE REVIEW OF COLD IN-PLACE RECYCLING IN NORTH AMERICA

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ABSTRACT

Many millions square metres of pavement have been rehabilitated with Cold In-place Recycling in North America since it first started in the State of California in the late 1970s, with. approximately four million tonnes currently being recycled every year..

In many areas the primary cause of pavement distress and failure is thermal cracking. Before the utilization of Cold In-place Recycling, the only effective treatment for cracked pavements was the total removal of the bituminous concrete layers. Cold In-Place Recycling uses the in-place bituminous pavement as a source of materials. The existing bituminous concrete pavement is reclaimed, transformed into a bituminous aggregate, which is then mixed with a new binder and laid down in-place.

Cold In-place Recycling restores the longitudinal and transverse profile of the roadway. Recycled bituminous mixtures obtained from Cold In-place Recycling have mechanical properties that improve with time. They provide more fatigue resistance but less stiffness than regular standard hot bituminous mixtures at a young age. In addition, recycled bituminous mixtures offer improved mitigation of reflective cracking. This paper presents an overview of Cold In-place Recycling and a discussion of project selection, design practices, process equipment, construction procedures and the performance of recycled bituminous mixtures.

RÉSUMÉ

Plusieurs millions de mètres carrés de chaussée ont été réhabilités avec le recyclage à froid en place en Amérique du Nord depuis le début dans l'état de la Californie à la fin des années 70 : approximativement quatre millions de tonnes sont présentement recyclées chaque année.

Dans plusieurs régions, la première cause des dommages des chaussées et de la détérioration est la fissuration thermique. Avant l'utilisation du recyclage à froid en place, le seul traitement efficace pour les chaussées fissurées consistait à enlever complètement les couches de béton bitumineux. Le recyclage à froid en place utilise le revêtement bitumineux en place comme source de matériaux. Le revêtement bitumineux existant est recyclé, transformé en un granulat bitumineux, qui est ensuite mélangé avec un nouveau liant et posé en place.

Le recyclage à froid en place restaure le profil longitudinal et transversal de la route. Les enrobés bitumineux recyclés obtenus par le recyclage à froid en place possèdent des propriétés qui s'améliore avec le temps. Ils fournissent plus de résistance à la fatigue mais moins de rigidité que les enrobés bitumineux à chaud standard à bas âge. En outre, les enrobés bitumineux recyclés offrent une atténuation améliorée des fissures de réflexion. Cet exposé présente une vue générale sur le recyclage à froid en place et une discussion du choix des projets, des pratiques de conception, de l'équipement du procédé, des procédures de construction et de la performance des enrobés bitumineux recyclés.

1. INTRODUCTION

1.1 Background

Large scale recycling of existing bituminous pavement started in 1975. The petroleum crisis in the early seventies and the development of milling equipment for the road industry created a favourable environment for emerging large scale recycling technologies. The current concept of Cold In-place Recycling (CIR) of existing bituminous pavements dates back to the late 1970s [1]. The State of California was the first road agency to utilize this process. Many millions of square metres of pavement have been rehabilitated with this process since 1980 throughout the United States and Canada. It is estimated that approximately four millions tonnes of bituminous concrete are recycled every year using this process in North America.

The experience with CIR in North America is extensive and the benefits associated with this process are significant when compared with traditional pavement rehabilitation methods [1]. Cold In-place Recycling reduces the cost of pavement rehabilitation. With this process, the existing pavement geometry is preserved. Cold In-place 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, CIR has evolved into one of the fastest-growing pavement rehabilitation processes.

1.2 Objectives

The objective of this paper is to provide current information on how the CIR process is carried out in North America. The concepts associated with CIR are defined and explained. The CIR project selection criteria as well as the CIR project design practices are presented. Information on CIR equipment and the current construction procedures are provided. The performance of CIR in North America is discussed. Finally, experimental technologies associated with CIR are presented. This paper discusses Cold In-place Recycling as it is currently carried out in North America.

1.3 Definitions

The CIR process is a pavement rehabilitation technique for bituminous pavement that does not require heat during the recycling process. Cold In-place Recycling may be either full-depth or partial-depth [1]. Full-depth CIR is commonly known as full-depth reclamation and stabilization. The work is performed with a pulverizer and the end result is a mixture of bituminous aggregate, base material and a bituminous binder. This process is performed at a depth ranging from 125 to 300 mm. Partial-depth CIR is a process that reuses only the existing bituminous concrete. Depth of recycling typically ranges from 65 to 125 mm. This process is generally performed on thicker, more uniform bituminous pavements. The work is carried out with multi-functional recycling equipment. This paper addresses only partial-depth CIR.

2. PROCESS DESCRIPTION

Cold In-place Recycling is based on the principle that the in-place bituminous pavement is a source of materials that may be used to build a new bituminous layer. Therefore, CIR includes all of the operations of a pavement material production line in one location. Cold In-place Recycling consists of several fundamental operations:

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

3. PROJECT SELECTION

Selection of suitable candidates for CIR requires a detailed field investigation. Field investigation requirements vary for each project, but generally the investigation includes a records review, a visual inspection and a pavement investigation [2].

3.1 Records Review

The records review includes an assessment of the construction/maintenance information as well as a review of past condition surveys. The construction/maintenance records assessed in conjunction with the past condition surveys provide valuable information to determine the performance of the pavement and its suitability as a candidate for Cold In-place Recycling. The construction/maintenance records may indicate that crack sealing activities were frequent, indicating that cracking is severe or that localized patching work was often required, indicating that the pavement structure is weak. . The information obtained from the construction/maintenance records and the past condition surveys allows assessment of the rate of pavement deterioration and the effectiveness of the maintenance activities.

3.2 Visual Inspection

The main objective of the visual inspection is to determine the mode and the severity of pavement distress. Although Cold In-place Recycling may be carried out on a wide range of deteriorating bituminous pavements, structurally sound and well-drained pavements are the best candidates [4, 5, 6, 7]. Cold In-place Recycling may be considered a potential rehabilitation technique wherever the following categories of pavement distress occurs:

• pavement cracking
  - age cracking
  - thermal cracking
  - fatigue cracking
  - reflective cracking

- permanent deformation
  - rutting due to unstable bituminous mixture
  - shoving
  - rough pavement
- loss of integrity in the existing bituminous pavement
  - raveling and potholing
  - stripping
  - flushing
  - loss of bond between bituminous layers.

Standard CIR may not be able to correct problems like rutting, shoving and flushing. These distresses may be indicative of an excess of bitumen in the existing mixture, hence additional bituminous binder, a requirement of standard CIR, may aggravate the situation. The addition of a corrective aggregate is needed to improve the gradation of the existing mixture and to reduce the ratio of total bitumen/mineral aggregate.

Photograph 1 – Well-drained structurally sound candidate for Cold In-place Recycling

3.3 Pavement Investigation

The pavement investigation provides additional information on the nature and the condition of the bituminous cover and the extent of the distresses identified during the visual inspection. The thickness of bituminous cover is established and the nature of the mixes to be recycled is determined. The roughness of the pavement is evaluated and an assessment is made of the presence of base and subgrade problems.

The information on the thickness of bituminous cover is necessary to establish if there is enough thickness to performed the CIR process and, given that there is enough thickness, the actual depth of the

CIR cut. The nature of the mixes to be recycled may have a significant impact on the mix design. The presence of a non-traditional bituminous mixture such as an Open Graded Mix, a Penetration MacAdam or a Sand Mix may have an impact on the mix design. Aggregate stripping or the presence of an exotic aggregate such as slag may also have an impact on the mix design. The presence of a non-traditional mixture is often the first indication that the usage of a corrective aggregate may be required. In some cases, the nature of the in-place mixtures to be recycled may require a specific type of binder to recycle the in-place mixtures.

When the pavement is severely deformed, CIR may require an additional corrective operation as described later in the section *Pavement Design*. Pavements with extensive base or subgrade problems are not good candidates for CIR. The investigation must also indicate if the pavement strength is sufficient to support the CIR equipment.

4. PROJECT DESIGN

The project design involves two distinctive design activities: bituminous mixture design and pavement design.

4.1 Bituminous Mixture Design

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

4.1.1 Field Sampling

Using the information gathered during the field investigation, the CIR project is divided into relatively homogeneous sections. A representative sample (approximately 50 kg) of the in-place bituminous material is extracted from the pavement in each section. Samples are extracted from the pavement with coring machines and crushed in the laboratory to reproduce the CIR equipment crushing operation [9].

4.1.2 Material Testing

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

- gradation of the bituminous aggregate before and after the bitumen extraction
    - fine aggregate content
- characterization of the aged bitumen
    - penetration
    - absolute viscosity
    - content
    - softening point [4]
    - asphaltene content [4].

Along with the field investigation, the test results are used to determine if addition of corrective aggregate is required in the process. The selection of the type of emulsion is also based on the results of these tests. The field samples may be examined for evidence of binder stripping from the aggregate to determine if an antistripping agent is required [10].

4.1.3 Additive Selection

Corrective Aggregate

Corrective aggregate may be required to strengthen the mineral skeleton of the mixture and/or to lower the binder content. The corrective aggregate is usually selected to adjust the existing gradation of the mineral aggregate to a shape similar to that of a dense graded material [1,2,3,4,8,11].

Bitumen Emulsion

Only a very small amount of new bitumen can be added to a bituminous aggregate before the new material becomes too rich and unstable. Consequently, the success of a CIR project is highly dependent on the performance of a relatively small amount of virgin bitumen.

The selection of a bitumen emulsion is based on the following characteristics [1]:

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

4.1.4 Laboratory Mixture Design

A sequence of tests is performed on trial mixtures of bituminous aggregate with varying emulsion and water contents. The results obtained from these tests provide the necessary information to select an optimum emulsion and the water content for proper mix density, air voids and stability. The typical emulsion content for standard CIR ranges from 1.5 to 2.2 % and the typical water content ranges from 2.3 to 3.0 %.

The role of the water during the CIR operation is of prime importance. It has two functions: it helps the emulsion to coat the bituminous aggregate and it provides the mixture with an internal lubricant during compaction [3]. Excessive water may inhibit compaction and also cause the emulsion to coat only the fines. The lowest water content that allows proper coating of the aggregate is preferred to reduce the drying time before compaction [10].

If a corrective aggregate is required, the trial mixtures may also be carried out with different types and amounts of aggregate. A corrective aggregate representing more than 20 % of the recycled mixture may not be economically viable. Generally, when rutting, shoving or flushing is present, it may indicate that the in-place mixture is too rich in bitumen, in that case the addition of a corrective aggregate is often required to reduce the ratio of bitumen/aggregate.

The adhesion of the binder to the bituminous aggregate is critical, particularly in the first few days after the CIR operation. If adhesion is poor, rain may have a disastrous effect on the mixture, leading to raveling. In addition, the evaluation of the moisture sensitivity of the selected mixture is also recommended. If the new mixture is sensitive to moisture, use of a different emulsion or an antistripping agent may be required [13].

The mixture design methods currently used are modified versions of Marshall and Hveem methods of compaction. These modified methods of compaction, when applied to cold mixes, give an acceptable 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 environmental conditions in the field at that time [9].

4.1.5 Pavement Design

The expected life of a pavement rehabilitated using the Cold In-place 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, pavement profile, minimum depth of treatment, traffic and selection of surfacing course or courses.

4.1.6 Structural Design

Currently, there is not a universally accepted structural coefficient for CIR. The structural capacity of CIR recycled material is dependent on the nature of the in-place bituminous material, 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 recycled material. The most commonly used value for standard CIR work is 0.30 [7].

4.1.7 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:

- profiling the road with a milling machine if the thickness of the bituminous pavement is sufficient
- adding either virgin aggregate or bituminous aggregate from an external source
- correcting the profile with additional wearing course material.

Cold In-place Recycling 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].

4.1.8 Minimum Depth of Milling and Mitigation of Cracking

A minimum depth of milling is required to mitigate reflective cracking. As a rule of thumb, whenever the depth of the CIR cut is at least 100 mm or 70 % of the full depth of bituminous pavement, the potential occurrence of reflective cracking is greatly reduced [7]. Paved shoulder should also be recycled to prevent propagation of shoulder cracks into adjacent CIR treated lanes [7].

4.1.9 Traffic

When CIR was first introduced many road agencies recommended that CIR not be used on pavement carrying more than 5000 AADT (Annual Average Daily Traffic). The knowledge of the performance Cold In-place Recycled materials has greatly improved in the last decade and CIR project have been successfully carried out on roadways carrying traffic volume well in excess of that limit. Limits on traffic volume for CIR have been removed by most road agencies. An appropriate pavement design must be completed and it is still recommended to evaluate rutting potential of recycled mixture when the volume of heavy traffic is high [4,5,9,10,14].

4.1.10 Surfacing Course Selection

The final operation of the CIR process is the placement of a surfacing course [2,3,4,8,13,15]. 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 CIR in North America. Chip seals, slurry surfacing and open graded emulsion mixes have also been used successfully as surfacing materials for CIR.

5. EQUIPMENT AND CONSTRUCTION PROCEDURES

5.1 Recycling Equipment

A wide variety of recycling equipment is available to perform CIR; they differ from one another by how the following operations are regrouped or separated:

- reclamation of the existing bituminous concrete pavement
- transformation of the reclaimed pavement into a calibrated bituminous aggregate
- addition of an emulsion and mixing of all the components
- placement of the new mixture.

Photograph 2 - Single-unit recycling train with placement using a standard paver

Recycling 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 bituminous concrete pavement 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.

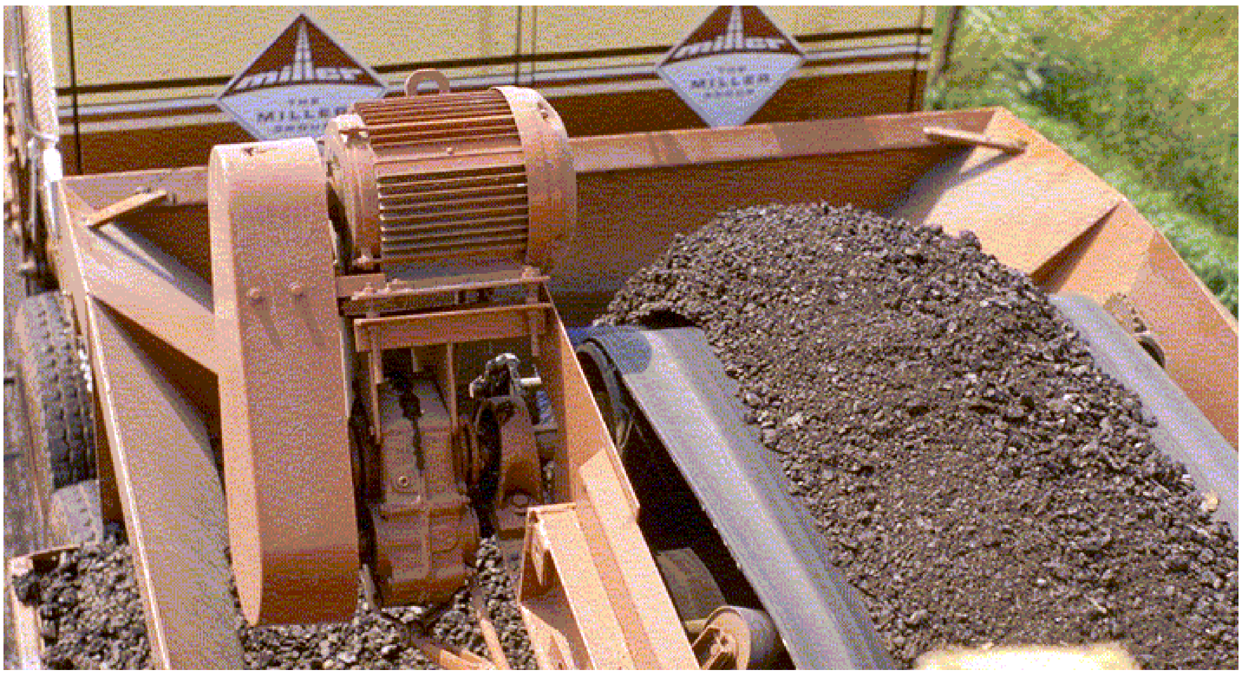
Photograph 3 - Two-unit recycling train

Photograph 4 - Multi-unit recycling train

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 others combining reclamation, sizing and mixing operations.

5.2 Gradation of the Bituminous Aggregate

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 [3]. 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. If segregation occurs, a reduction of the maximum particle size of the bituminous aggregate may be required [13].



Photograph 5 – Bituminous aggregate

5.3 Grade and Slope Control

To maximize the surface roughness correction capabilities of the CIR 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 Design*.

5.4 Segregation Control

The CIR mixtures are coarse and their workability is not as good as that of standard hot bituminous mixtures. Segregation is often difficult to control and is a major concern with CIR. Standard paving equipment is often the source of systematic segregation which occurs at the center of the screed of the paver [8]. The central gear unit that drives the augers creates a discontinuity in the flow of material and causes systematic segregation. Auger systems driven at the outer ends are very effective in preventing segregation. When such a system is installed on a mix-paver, segregation is virtually eliminated.

Photograph 6 – Segregated mat vs segregation free mat

5.5 Mixing

Mixing of the additives with bituminous aggregate may occur in the cutting drum and/or in a pugmill. Corrective aggregates are usually introduced ahead of the milling machine and mixed in with the bituminous aggregate within the cutting drum. The emulsion 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. Mixing systems controlled by weight are preferable, as they are more accurate.

5.6 Compaction

A successful CIR operation is highly dependent on the compaction of the mixture. Placement of the recycled mixture requires more compaction energy than does placement of standard hot bituminous mixtures. A CIR mixture tends to fluff which indicates that internal friction between the particles is high [3,10]. The use of one heavy pneumatic roller combined with one large double drum vibrating roller is typically 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 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 [8]. Hence, the mixture requires aeration prior to compaction to let some of the water escape. When the moisture content is adequate, compaction may start as the emulsion begins to break. The compaction operation may be delayed twenty minutes to one hour after the CIR mixture is placed [3,8,10]. The field optimum total water content for compaction ranges between 2.3 and 3.0 %.

Secondary rolling within a few days following the CIR operation is possible and occasionally necessary to reach the required compaction. When the density is low and/or when compaction by traffic has occurred, secondary rolling may be necessary. It may be carried out only when excess water has escaped from the mat.

The minimum compaction requirement most commonly used is 96 % of the density of the Marshall field compacted specimen. The compacted mixture internal void content ranges between 12 and 15 % [1,5,16]. During the first few months of service, a decrease of the void content of up to 0.5 % may be anticipated [4].

5.7 Field Adjustments

Field adjustments are carried out on a continuous basis during a CIR operation to account for the variability of the field conditions [8]. Field adjustments of the emulsion 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 mat. When the emulsion content is adjusted, an equal and opposite adjustment is made in the water content and vice versa.

The field adjustments of the water and of the emulsion content are based on the appearance of the mat after the initial rolling. Additional emulsion may be required if the mat remains brown or is prone to raveling. Emulsion content may be reduced in the following cases :

- the mat is very black and shiny and no raveling is apparent
- pushing or rutting of the recycled mixture occurs under traffic
- bleeding or flushing arises.

When the material looks wet and cannot be compacted, the water content may have to be reduced. Water may be added when the mixture looks dry, when the mixture does not show uniform coating and when the compacted mat ravels.

5.8 Curing

A certain time period is necessary to allow the recycled mixture to cure and build up some internal cohesion before being covered with a wearing course. A time period of 14 days is typically specified. A low moisture content may be a criterion to evaluate the curing of the mixture. However, such a criterion may be misleading because the moisture content is increased by rain. The material may have built up adequate internal cohesion, but rainfalls may have maintained the moisture content at a high level, incorrectly suggesting that the mixture has not sufficiently cured. As a rule of thumb, whenever a complete core can be extracted from the mat relatively easily, the material has built up enough internal cohesion to be covered.

Photograph 7 – Cured recycled mat

5.9 Weather Limitations

The weather limitations for CIR are not as stringent as those of other emulsion applications. Cold In-place Recycling 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 CIR 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. When the air temperature is less than 10°C, early cohesion may be enhanced by increasing the emulsion content in the recycled mixture or by using a solvent rich emulsion capable of softening the aged bitumen.

6. PERFORMANCE OF COLD IN-PLACE RECYCLING

6.1 Rejuvenating Effect of the Added Emulsion

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 CIR [8,17]. 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 emulsion 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 emulsion. A solvent rich emulsion 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 emulsion with minimum coating capability mixed with a coarse graded bituminous aggregate in the cooler months 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 [1,4].

6.2 Added Binder Performance

Three categories of emulsion are available for CIR. The emulsion may be a standard emulsion, a modified bitumen emulsion or a rejuvenating type emulsion. 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 CIR.

The usage of polymer and non-polymer modified high float emulsions is common. The gel structure provided by the high float emulsion residue allows a thicker film of bitumen to build around the bituminous aggregate particles. Therefore, the coating of high float 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 [10].

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 from 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 CIR 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 [7].

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 [9]. Furthermore, because of the enhanced characteristics of polymer-modified emulsion, CIR may be carried out on higher volume roads [3].

6.3 Properties of Recycled Mixtures and Structural Impact

6.3.1 Modulus and Fatigue

Modulus and fatigue life of recycled 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 [4,18,7]. This phenomenon may be associated with the fluxing of the virgin bitumen with the aged bitumen as well as with the decrease in air voids [17].

The modulus obtained with recycled mixtures is dependent on many variables including the method of measurement. The value of the modulus is a function of time of loading and the temperature at which it is measured. In France, modulus values ranging from 3000 to 5000 MPa have been measured after 48 months of service. The tests were performed at 10° C with a loading duration of 0.01 sec. [19].

Modulus ranging from 3100 to 5500 MPa have been measured in the State of Oregon [17]. The fatigue life measured after 48 months of service has reached values of up to 250,000 cycles [19]. 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, CIR 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 mixture similar to those of virgin emulsion mixes rather than dense graded hot bituminous mixtures [19]. Virgin emulsion mixtures are known to provide more fatigue resistance but less stiffness than regular dense graded hot bituminous mixtures [21]. Field performances of recycled mixtures confirm the similarity between virgin emulsion mixtures and the cold recycled mixtures.

6.3.2 Pavement Deflection

The average deflections before and after CIR have been compared and have been found to be equivalent or smaller after CIR [4,6,22]. The deflection results indicate that the structural strength for standard CIR may be assumed to be at least equivalent to the in-place material prior to CIR. It has also been observed that there is less variation in the individual deflection results after the CIR than prior to CIR operation [4].

6.4 Reflective Cracking

Cold In-place Recycling is considered the most effective process to mitigate reflective cracking in a cold environment [9,16]. 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 [23].

The primary cause of pavement distress and failure in the Regional Municipality of Ottawa-Carleton (RMOC) in Ontario is thermal cracking [24]. In RMOC, 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 CIR 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 CIR pavement is 11 cracks per kilometre per year.

6.5 Economics

Cold In-place Recycling is a cost effective rehabilitation alternative to traditional methods. Based on the life cycle cost of pavement rehabilitation, the State of Oregon has reported that the annual cost of CIR projects may vary from 37 to 82 % of the cost of the 50 mm hot bituminous overlay alternative [17]. In the Regional Municipality of Ottawa-Carleton, the annual cost for the CIR rehabilitation method (75 mm of CIR + 40 mm of a hot bituminous wearing course) is approximately 55 % of the standard hot bituminous overlay method (40 mm of a hot bituminous correction course + 40 mm of hot bituminous wearing course) [24].

7. NEW TECHNOLOGIES

7.1 Compaction Equipment

7.1.1 Heavy Single Vibratory Roller

Recycled mixtures are placed in lifts ranging from 65 to 125 mm, which, in terms of compaction, are considered thick. Adequate compaction of recycled material is now and then difficult to obtain with conventional hot bituminous compaction equipment. Recycled materials are commonly difficult to compact. The internal friction between the particles is high because of the gradation and shape of the bituminous aggregate. It is also suspected that the presence of aged bitumen at the surface of the particle may prevent the sliding of the particle on one another during compaction.

As for any other types of granular material the density obtained is maximized one-third down the thickness of the lift. Density measurements performed on CIR cores extracted from 3 to 5 year-old CIR pavements indicates that the density for the bottom half of may be between 1.5 to 2.5 % lower than the top half of the core. It is suspected that this difference between the density at the bottom of the lift and the top of the lift is even greater when the thickness of the mat increases. Even though the average compaction CIR lifts meet the current specification, it may still be possible to increase density of recycled material by using more compaction energy to further compact the bottom of the CIR lift. As a result of greater density at the bottom of the CIR lift, both the cohesion of the recycled material and the strength of the CIR mat will increase.

Photograph 8 – Modified large single drum vibratory roller fitted to compact cold recycled material

The heavy double drum vibratory rollers are commonly used with Cold In-place Recycling. The largest double drum vibratory roller used with CIR provides 41.1 kg/cm of static linear loading with a maximum centrifugal force of 187 kN at high amplitude and low frequency. Trials are currently carried out with modified single drum vibratory roller that can provide at least 250 kN of centrifugal force at high amplitude and low frequency. Field observations indicate that the high impact provided by the drum of single drum roller pushes the recycled material downwards better than double drum vibratory rollers. One "big blow" at 250 kN appears to transfer more compaction energy within the recycled mixture than two "smaller blow" at 187 kN provided by a large double drum roller. The initial trials are also indicating that the static linear loading should not be drastically increased over 40 kg/cm. Freshly compacted recycled mat (24 hours) tends to be fragile and can be damaged by heavy drums. The exact size of modified single drum vibratory roller remains to be determined, but it appears from the initial trials that this type of roller is better suited for Cold In-place Recycling.

7.1.2 High-Density Screeds

The smoothness of the CIR mat is influenced by two operations: the placement, which is performed with a paver and the compaction of the recycled material, which is accomplished using pneumatic and vibratory rollers. The paver functions are to spread and to smoothen the recycled material while the function of the rollers is strictly to increase the density of the recycled material.

In their capacity of compacting the recycled material, rollers do not smoothen the CIR mat. In actual fact, the rollers will reproduce in great part the defects of the profile of the planed surface underlying the recycled material. This is even more accentuated with CIR due to the fact that pre-compaction of the recycled material is low (no more than 75 % behind the paver) and the thickness of the CIR mat is greater than 75 mm.

The smoothness of the CIR mat may be greatly improved if the pre-compaction of the recycled mixture behind the screed was increased. High-Density Screeds have been developed to provide greater pre-compaction. The level of pre-compaction obtained with a High-Density Screed can be substantially higher than the level of pre-compaction obtained with a conventional screed. High-Density Screeds are fitted with tamper/pressure bars that push the material downwards while being smoothened through the screed.

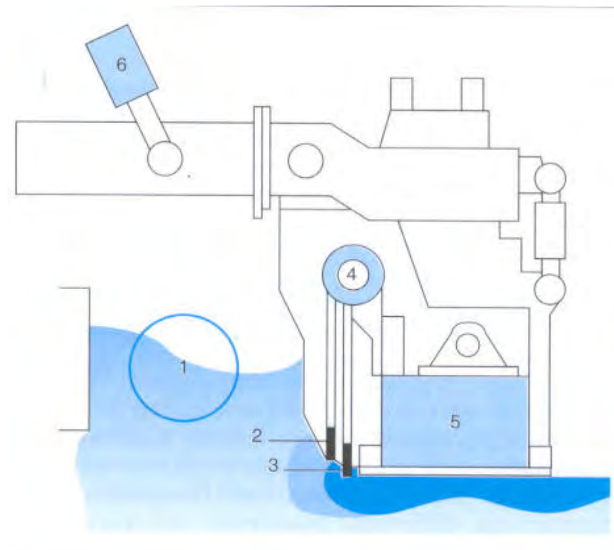


Figure 1 - High Density Screed

The use of High-Density Screeds is particularly advantageous whenever the pavement is deformed and the thickness of the mat is greater than 75 mm, which is nearly always the case with CIR candidates. The differential settlement related to the compaction operation is reduced and the smoothness of the mat is increased. The use of High-Density Screeds may allow CIR to be performed in thickness greater that the current limit of 125 mm. The usage of High-Density Screeds with CIR is very recent and the results are very encouraging.

7.2 Mixture Formulation: Usage of the Superpave Gyratory Compactor

There are a number of different laboratory mixture design procedures currently used to establish job mix formula for Cold In-place recycling. Some are modified versions of the Marshall method and others are related to the Hveem method of compaction. Currently, there is an effort to consolidate all these various methods into a standard mixture design procedure. At the request of the various stakeholders associated with CIR, the American Society for Testing and Materials (ASTM) has formed a task group under the D04-27 subcommittee on Cold Mixes to address this issue. The objective of the task group is to develop a standard method of compaction in order to obtain realistic physical properties in the laboratory that will duplicate what is achieved in the field.

Photograph 9 – High-Density Screed

The use of the Superpave gyratory compactor is becoming the standard to formulate hot bituminous mixtures throughout North America. As this compactor is becoming a standard apparatus in road material laboratories, the task group has decided to investigate the possibility of using the gyratory compactor as a starting point to consolidated CIR mixture design procedure. A number of studies have been performed to explore the use of this compactor for cold recycled mixtures. There are a number of outstanding issues such as how the gyratory compactor can simulate the effect of:

- the lift thickness
- the type of bitumen emulsion and water
- the curing phenomenon and build up of cohesion.

Progress is being made on these and other issues and in the near future a standardized method of designing cold in-place recycled mixes can be developed and used throughout the industry.

7.3 New Additives

7.3.1 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 [13]. The State of Oregon has started using lime in a dry form with emulsion in 1989 and in a slurry form in 1994 [13]. Cement is used on CIR 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 [13]. The modulus for the CIR mixtures including 1.0 % lime was 28% higher than the regular CIR mixtures after five months of service. Furthermore, the Index of Retained Resilient Modulus, a water susceptibility indicator, was 42 % higher for the CIR mixture treated with 1.0 % lime when compared with the value of the untreated mixture.

7.3.2 Solvent Rich Emulsion

The usage of solvent rich emulsion is relatively recent. The solvent rich emulsion may contain up to 15 % solvent in residual bitumen of the emulsion. The solvent appears to work as a fluxing agent. It accelerates the combination of the added virgin bitumen with the aged bitumen of the bituminous aggregate. The usage of this type of emulsion in cold weather is providing promising results.

8. CONCLUSION

Cold In-place Recycling may be considered a well-proven pavement rehabilitation technology. It is a recognized viable engineering and economic alternative to traditional rehabilitation methods for a wide range of traffic and pavement distress situations [4,9].

Cold In-place Recycling provides numerous important advantages in pavement rehabilitation which include the following [1,2,3,5,9,12,16]:

- 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 pavement 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.

Photograph 10 – Rural Cold In-place Recycling mat prior to placement of wearing course

Photograph 11 – Urban Cold In-place Recycling mat prior to placement of wearing course

Continual developments are being made in both the pavement engineering and the materials engineering fields to standardize and catalogue the various parameters for designing, testing and constructing Cold In-place Recycled pavements.

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