# Short Term Performance of an Innovative Cold In-Place Recycling Technology in Ontario

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## ABSTRACT

Cold In-place Recycling (CIR) is a pavement rehabilitation method that processes an existing asphalt pavement in situ, sizes it, mixes in additional asphalt cement, and lays it back down without off-site hauling and processing. The added asphalt cement is typically emulsified asphalt. An innovative development in CIR technology is the use of expanded asphalt, rather than emulsified asphalt to bind the mix.

The Ministry of Transportation Ontario (MTO) constructed a trial section of CIR with expanded asphalt on Highway 7, east of Perth, Ontario in July, 2003. The 5 km trial section of CIR with expanded asphalt was constructed adjacent to 7 km of conventional CIR. Placement resulted in a fairly smooth, hard, uniform surface suitable for temporary traffic, and provided a good platform for hot mix paving operations. The CIR with expanded asphalt placement progressed in a continuous and efficient manner, placing 5 km over a three-day period.

To evaluate this innovative technology, Falling Weight Deflectometer (FWD) testing was carried out immediately after construction and in the year following construction to compare the CIR and CIR with expanded asphalt technologies and to assess the change in strength of the pavement structure over time. Evaluation of pavement roughness and rutting was also carried out using MTO's Automatic Road Analyzer (ARAN). FWD and ARAN results for 2003 and 2004 indicate that the CIR and CIR with expanded asphalt pavements are performing similarly.

Cores were obtained of the CIR and CIR with expanded asphalt pavements and resilient modulus testing was carried out according to ASTM D4123-82, Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. Analysis of Variance showed the resilient modulus results for CIR and CIR with expanded asphalt to be statistically the same.

Based on short-term results, CIR with expanded asphalt appears to provide an acceptable in-place recycling rehabilitation strategy that provides an economic alternative to conventional CIR, reducing the curing time, and extending the construction season.

## INTRODUCTION

Cold In-place Recycling (CIR) is an established pavement rehabilitation method that has been found to mitigate reflective cracking, extending pavement life (*1*). CIR processes up to 125 mm of an existing Hot Mix Asphalt (HMA) pavement, sizes it, mixes in additional asphalt cement, and lays it back down without off-site hauling and processing. The added asphalt cement is typically emulsified asphalt, a blend of asphalt cement and water. The material is then profiled and compacted to form a binder course layer. A new HMA surface is placed after the emulsion has set and moisture and compaction requirements have been met.

A recent innovative development in CIR technology is the use of expanded (foamed) asphalt, rather than emulsified asphalt to bind the mix. In this new process, hot asphalt cement is pumped through an expansion chamber on the cold recycling unit, where a small amount (1 percent) of cold water is injected and immediately vaporizes. This creates thousands of tiny bubbles within the hot asphalt cement causing it to rapidly expand (foam). The expanded asphalt is then mixed with the processed reclaimed asphalt pavement. As with conventional CIR, the material is then profiled and compacted to form a binder course layer. This combination of CIR and expanded asphalt technologies results in a 100 percent recycled material.

With conventional CIR, the Ministry of Transportation Ontario (MTO) specifies a minimum 14-day curing period to allow the mix to set and moisture and compaction requirements to be met. Application of CIR is usually limited to the warmer, drier months. The major advantage of CIR with expanded asphalt is that a new HMA surface can be applied following a two-day curing period, if compaction requirements have been met. The process is less dependent on warm, dry weather for placement, which results in an extended construction season.

MTO constructed a trial section of CIR with expanded asphalt on Highway 7, east of Perth, Ontario in July, 2003. A 5 km trial section of CIR with expanded asphalt was constructed adjacent to 7 km of conventional CIR mix, giving MTO an excellent opportunity to observe the performance of each material. During construction, samples of both mixes were obtained and indirect tensile strength testing was carried out. Falling Weight Deflectometer (FWD) testing was carried out on the existing pavement prior to construction. FWD testing was repeated immediately following construction and one-year after construction, in order to determine the change in strength of the pavement structure and to allow comparison of the two technologies. Short-term evaluation of pavement roughness and rutting was carried out using MTO's Automatic Road Analyzer (ARAN). Resilient modulus testing was also carried out on 5 cores of each material.

This paper outlines the pavement design considerations that lead to the selection of CIR as the pavement rehabilitation strategy on Highway 7. The Contractor's change proposal from CIR to CIR with expanded asphalt is outlined, along with MTO's warranty requirements. A summary of construction issues and results of Quality Control (QC) and Quality Assurance (QA) testing are presented. Finally, results of an Analysis Of Variance (ANOVA) for the FWD, ARAN and resilient modulus test data are presented.

## PAVEMENT DESIGN

The project is located on Highway 7, from Innisville westerly to the town of Perth, Ontario, for a distance of 15.4 km (Figure 1). This section of Highway 7 is classified as a rural arterial undivided King's Highway, with a posted speed of 80 km/hr and a projected 2004 Annual Average Daily Traffic (AADT) of 9,000 with 8 percent commercial vehicles.

Highway 7 was originally constructed in 1957, with widening and resurfacing carried out in 1967. A pavement investigation carried out in 1985, showed an average HMA thickness of 207 mm. In 1985, 30 mm of the surface course was milled off prior to resurfacing with 80 mm HMA, resulting in an average HMA thickness of 255 mm. The resurfacing consisted of 40 mm of recycled surface course over 40 mm of open graded binder course.

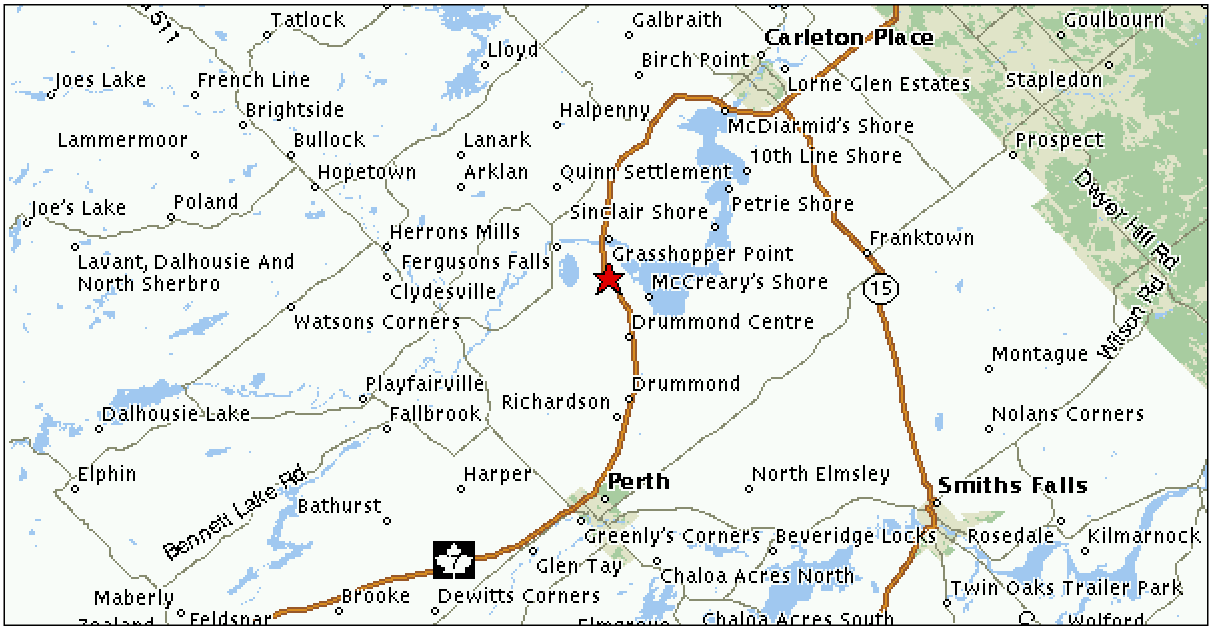


**Figure 1. Contract limits on Highway 7 from Innisville Westerly to Town of Perth, Ontario**

## Existing Pavement Condition

From the west limits of Perth easterly for 11.5 km, the existing pavement had severe, cupped full depth transverse cracks at 3-5 m intervals, localized severe rutting in both wheel paths, longitudinal cracking in the wheel paths, intermittent centreline cracking, and alligator cracking at the intersection of transverse and longitudinal cracks. The severe wheel track rutting was not widespread. This section of Highway 7 had a 1995 average Pavement Condition Rating (PCR) of 55 out of 100, with an average Ride Comfort Rating (RCR) of 6.2 out of 10.

For the easterly remainder of the project the pavement was in much better condition with well-sealed transverse cracks at 10-20 m intervals and a good ride quality, with little or no rutting. This section of Highway 7 had a 1995 average PCR of 62, with an average RCR of 6.8.

## Granular Base Equivalency (GBE)

Field investigation indicated that the existing pavement structure for the westerly portion of the project was 250 mm of HMA, over 160 mm granular base and 450 mm granular subbase. For the easterly portion of the project, the HMA was found to be 325 mm thick.

To calculate the Granular Base Equivalency (GBE) of the existing pavement, a GBE factor of 1.25 was used for the existing HMA (*2*). The existing granular base material was on the fine side of the crushed granular base gradation requirement and a GBE of 0.75 was used for this material. The granular subbase material was sand, very similar to the sandy subgrade material. A GBE of 0.5 was used for this material, which is the recommended factor for old granular subbase.

Based on the procedures outlined in the MTO Pavement Design and Rehabilitation Manual (*2*), the GBE of the existing pavement structure was 620 mm for the western portion and 800 mm for the eastern portion. According to the MTO's routine pavement design procedure, the minimum GBE required for this highway is 750 mm, given the traffic volume and a predominantly non-frost susceptible silty sand subgrade.

## Design Considerations

A number of pavement rehabilitation options were considered, ranging from new construction to salvaging the existing pavement by means of in-situ treatments, such as cold in-place recycling, or partial depth removal (milling) with full depth reclamation (FDR) (*3*). The existence of a large number of entrances, side roads, and intersections precluded the use of excessive grade raises. Recycling was favoured, because the existing HMA pavement was 250-325 mm thick. The extensive, severe, full depth transverse cracking needed to be addressed, as the cracks would most certainly reflect through any thin resurfacing.

The following pavement rehabilitation alternatives were considered:

1. Complete reconstruction by removing the existing pavement, providing new granular base and placing 150 mm HMA. Complete reconstruction would be low risk, but high cost, with a long construction season. Reconstruction would require large quantities of new materials and would not reuse the existing pavement.

2. Milling and in-place full depth reclamation (pulverizing) of the existing pavement with 150 mm HMA. This option would be a low risk treatment with a medium to high cost, a long construction season, and all new HMA required.

3. CIR of the existing pavement with a 50 mm HMA overlay. CIR had the lowest life cycle cost, reused 100 percent the existing HMA material, addressed the reflection cracking, and shortened the construction season.

4. Full depth crack repair, milling and resurfacing. This option was discounted because full depth crack repairs carried out on a project to the east of this location had resulted in poor compaction in the 300 mm wide trenches.

5. Milling, placing a 100 mm granular layer to prevent crack propagation, and overlay with 130 mm HMA. This option was discounted because the 100 mm granular layer would result in a substantial grade raise and significant quantities of new materials.

Life cycle cost analysis over a 30 year period showed that the CIR was the most cost effective solution but CIR was also the best option in terms of salvaging existing materials, minimizing the use of new materials, mitigating reflection cracking, and considerably shortening the construction time when compared to other options.

## Recommended Pavement Strategy

CIR to a depth of 110 mm with a 50 mm HMA overlay was selected as the preferred pavement rehabilitation strategy on this project based on life cycle costing, pavement structure analysis, and constructability. CIR has proven to be an effective rehabilitation treatment for extensively cracked pavements in Ontario as the CIR mix mitigates reflection cracking of the underlying pavement *(1)*.

# <u>CONSTRUCTION</u>

## Change Proposal

Contract 2002-4040 was tendered in early spring 2003. The successful contractor bid the contract as conventional CIR, but submitted a change proposal on April 29, 2003 to substitute 5 km of CIR with CIR with expanded asphalt. In support of the change proposal, the contractor submitted the following benefits for CIR with expanded asphalt:

- Liquid asphalt cement (PGAC 58-28) would be used instead of emulsion.

- CIR with expanded asphalt allows a HMA surface course to be placed after two days of curing, whereas CIR requires a minimum of 14 days curing.

- Wet conditions during the 14-day period can lengthen the curing time of the CIR interfering with other contract items and delaying completion date. CIR with expanded asphalt is not impacted by moisture to the same extent.

- QC testing practices for CIR with expanded asphalt provide the contractor with better quality control.

- After compaction, the CIR with expanded asphalt can be opened immediately to traffic without restriction. The entire operation occupies 500 m length of roadway, enabling traffic flow to be easily maintained.

- CIR with expanded asphalt will reduce overall construction time.

- The work would be carried out at no additional cost (costs of bringing in a second recycler, reduced quantities of CIR, mobilization, mix design, and testing to be borne by the contractor).

MTO accepted the change proposal with a four-year warranty on the CIR with expanded asphalt.

## Warranty Requirements

The four-year warranty applies to field performance of the HMA surface course and the CIR with expanded asphalt. The warranty began on August 29, 2003, the date of completion of the HMA paving.

The warranty requires that MTO complete a distress survey for the entire length of the contract in accordance with the MTO Manual for Condition Rating of Flexible Pavements (SP-024) (*4*) between May 1st and July 31st of 2007. The contractor will have until the end of the warranty period to repair deficiencies identified in the distress survey.

The distress survey will compare performance of the CIR and CIR with expanded asphalt and establish any significant variation in defects. In the event of a significant deficiency, repairs to the CIR with expanded asphalt will be undertaken. All repairs, except for routing and sealing, shall be a minimum of one-lane width and shall cover the extent of the distress for a minimum length of 3 m. If the distress survey results indicate a pervasive and repetitive distress or substandard materials rather than an isolated occurrence, then the repairs will apply to the entire length of the contract.

## CIR with Expanded Asphalt Mix Design

The contractor obtained seven cores of the existing HMA pavement for mix design purposes. The gradation of the reclaimed material (after extraction) met the requirements of the expanded asphalt specification. The average asphalt cement content of the existing HMA was found to be 5.3 percent.

When foamed, the PGAC 58-28 used in the mix design had a half-life of 21 seconds, with an expansion ratio of 17, at a water content of 2.75 percent. The mix design was completed at asphalt cement increments of 0.5 percent, with values ranging from 0.5 percent to 2.5 percent asphalt cement. Based on the results of the mix design, the recommended expanded asphalt content was 1.0 percent. The recommended moisture content was 4 percent. Mix design properties for an expanded asphalt content of 1 percent are presented in Table 1.

## CIR Mix Design

Samples obtained for the CIR mix design found the average asphalt cement content of the reclaimed asphalt pavement to be 5.1 percent. The recovered penetration was 38.

Two CIR mix designs were used on the contract. The CIR specification requires a minimum of 1.2 percent emulsified asphalt and submission of a new mix design if the percent emulsion is adjusted by 0.2 percent or more from the mix design. The original mix design called for 1.5 percent emulsion and a moisture content of 3.0 percent (Table 1). This mix design appeared to be too rich in the field. A new mix design was used which required 1.2 percent emulsion and a moisture content of 3.5 percent. The mix designs used a HF 150MP emulsion.

**Table 1. Mix Design Properties of CIR and CIR with Expanded Asphalt**

| | | |
|---|---|---|
| **CIR with expanded asphalt** | **Property** | **Added Asphalt Cement = 1%** |
| | Bulk Relative Density | 2,227 kg/m3 |
| | Dry Tensile Strength | 485 kPa |
| | Wet Tensile Strength | 488 kPa |
| | Tensile Strength Ratio | 100% |
| **CIR** | **Property** | **Added Emulsion = 1.5%** |
| | Stability (N @ 22°C) Unsoaked | 25,855 |
| | Flow (0.25 mm ) Unsoaked | 14.7 |
| | Stability (N @ 22°C) Soaked | 20,142 |
| | Flow (0.25 mm ) Soaked | 15.8 |
| | Retained Stability | 77.9% |
| | Bulk Relative Density | 2,284 kg/m3 |
| | Maximum Relative Density | 2,438 kg/m3 |
| | Air Voids | 8.2 % |

## Placement

Construction of the CIR and CIR with expanded asphalt began in early July, 2003. Both were placed with a CIR train consisting of a milling machine and mobile screening/crushing deck. The conventional CIR train then fed the processed RAP into a Midland mix paver, which added the emulsion and placed the material. The CIR with expanded asphalt train fed the processed RAP into an on-board twin-shaft pugmill where the expanded asphalt was added and mixed. The material was then conveyed into a heavy-duty paver with dual tamping bars in the screed. Eight km of CIR was placed over a nine-day period from July 2 to July 15, 2003. The average production rate for the CIR was 6,622 $m^2$/day for a single lane (10,500 $m^2$ best production rate). Production of the CIR was slowed by the need to change the mix design to adjust to field conditions encountered.

Five km of CIR with expanded asphalt was placed over a three-day period from July 7 to July 9, 2003. The average production rate for CIR with expanded asphalt was 12,500 $m^2$/day for a single lane (16,387 $m^2$ best production rate). Figures 2 and 3 show the CIR and CIR with expanded asphalt trains. Figures 4 and 5 show the compacted mat for the CIR and CIR with expanded asphalt.


**Figure 2. Cold-In-Place Recycling Train.**

**Figure 3. Cold-In-Place Recycling with Expanded Asphalt Train.**

**Figure 4. Completed Surface of Cold-In-Place Recycled mix.**

**Figure 5. Completed Surface of Cold-In-Place Recycled with Expanded Asphalt mix.**

## QUALITY CONTROL / QUALITY ASSURANCE TESTING

### Indirect Tensile Strength Testing of CIR with Expanded Asphalt

For testing purposes, a lot consisted of a single day's production of CIR with expanded asphalt. Each lot was divided into a minimum of three equal sub-lots, each 5,000 $m^2$ or smaller.

Prior to compaction, the Contractor obtained one random 15 kg sample of the CIR with expanded asphalt from each sub-lot, to test for dry tensile strength, wet tensile strength, and tensile strength ratio. Acceptance criteria for indirect tensile strength was based on the lot mean computed from quality assurance test results for each sub-lot.

Samples of CIR with expanded asphalt were tested for dry tensile strength, wet tensile strength, and tensile strength ratio in accordance with American Society for Testing and Materials (ASTM) D4867/D4867M (*5*). Prior to manufacture of the briquettes, samples of CIR with expanded asphalt were moisture conditioned to the field moisture content. Laboratory prepared samples were cured at 60 ± 2°C after fabrication for a period of 72 ± 4 hours before determining the strength properties.

The minimum requirements were: 350 kPa dry tensile strength,175 kPa wet tensile strength and a tensile strength ratio of 50. Tensile strength test results are summarized in Table 2.

**Table 2. Construction QA/QC Indirect Tensile Strength Testing – CIR with Expanded Asphalt**

| | Quality Assurance Results | | | Quality Control Results | | |
|---|---|---|---|---|---|---|
| **Lot / Sub-lot** | **Dry Tensile Strength (kPa)** | **Wet Tensile Strength (kPa)** | **Tensile Strength Ratio** | **Dry Tensile Strength (kPa)** | **Wet Tensile Strength (kPa)** | **Tensile Strength Ratio** |
| 1 / 1 | 340 | 214 | 63% | 425 | 300 | 71% |
| 1 / 2 | 275 | 236 | 86% | 333 | 242 | 73% |
| 1 / 3 | 362 | 232 | 64% | 475 | 317 | 67% |
| 1 / 4 | 271 | 198 | 73% | 555 | 333 | 60% |
| 2 / 1 | 269 | 209 | 78% | 413 | 343 | 83% |
| 2 / 2 | 344 | 206 | 60% | 620 | 382 | 63% |
| 2 / 3 | 250 | 187 | 75% | 573 | 348 | 61% |
| 3 / 1 | 221 | 179 | 81% | 560 | 417 | 75% |
| 3 / 2 | 212 | 188 | 89% | 552 | 355 | 64% |
| 3 / 3 | 259 | 177 | 68% | --- | --- | --- |
| Mean | 280 | 203 | 74% | 501 | 337 | 70% |
| Stdev | 51.7 | 20.7 | 0.10 | 94.1 | 49.6 | 0.08 |

An examination of the test data showed that the QC test results met the specification while QA test results did not. Discrepancies between QC and QA testing may be attributable to the lack of a clearly defined test procedure. The specification for CIR with expanded asphalt states that ASTM D4867/D4867M (*5*) must be modified by moisture conditioning the samples prior to manufacture of the briquettes. While the QC laboratory was able to carry out testing immediately upon receipt of the samples, the QA testing was delayed. Moisture loss occurred due to water condensing on the inside of the plastic sample bags. The test method requires compaction of the lab sample (briquette) at the field moisture content. If the optimum moisture is not achieved, the result is a decrease in density and a lower indirect tensile strength.

The contract stated that acceptance of the CIR with expanded asphalt was based on QA test results for the indirect tensile strength testing. Although there were discrepancies between the dry and wet tensile strength data, the tensile strength ratios obtained by the QC and QA laboratories were similar, as shown in Table 2. The contractor had confidence in the QC results, while the QA testing was carried out by a less experienced lab. Considering the problems with the QA testing, the acceptable results achieved by the QC lab, MTO's lack of experience with this new product, and the four-year warranty on the CIR with expanded asphalt, MTO chose to accept the CIR with expanded asphalt without a price reduction. A new test method LS-297 (*6*) has since been written to provide a well defined testing procedure and reduce testing variability.

## Compaction of CIR and CIR with Expanded Asphalt

For both processes, compaction in the field was achieved using a pneumatic tired breakdown roller and a conventional steel drum finishing roller. At the start of production, and whenever the existing pavement significantly changed in composition, the target density of the CIR with expanded asphalt and the CIR was to be determined by the Contractor according to LS-300 (*7*) with material reclaimed from the roadway. The specification required that each lot be compacted to a minimum of 96.0 percent of the target density established for the mix in the laboratory, with no result falling below 95.0 percent.

Prior to HMA overlay, the Contractor randomly obtained one slab sample from each sub-lot to test for compaction. The slab samples were dry cut 150 x 150 mm and removed intact from the roadway. Compaction of the slab samples was determined in the laboratory according to LS-306 (*8*). Compaction results met the contract requirements for both the CIR and CIR with expanded asphalt.

## Profile Correction

Contract documents required the CIR / CIR with expanded asphalt to be placed at a cross-section slope of 2.0 percent. Since the CIR / CIR with expanded asphalt process cannot significantly alter an existing roadway profile, the 2.0 percent cross-fall can only be achieved if the existing surface is close to the surface profile expected. The 110 mm CIR / CIR with expanded asphalt process lacks in-place material required to correct long sections of pavement with cross-slope greater than 2.0 percent, and where the cross-slope is less than 2.0 percent, a surplus of material results. A roadway cross-fall survey carried out in December, 1999 found the average cross-fall on the existing roadway to be 2.0 percent, with measurements ranging from 0.2-5.4 percent.

The CIR contractor did make a significant effort to meet the profile requirements, relocating excess material to super-elevated areas. Micro-milling equipment was also brought in to correct the CIR profile and improve the ride prior to HMA overlay.

## Moisture

The contract required that the mean moisture content for each lot of CIR be less than 2.0 percent with no sub-lot moisture content exceeding 3.0 percent. The moisture content of the CIR was determined according to LS-291 (*9*) from slab samples taken from the roadway.

Although the CIR placement occurred in early to mid July, by August 13, the 2 percent moisture criteria had not been met, possibly due to wet weather conditions. The contractor asked permission to overlay, claiming that at this time of year it was possible that moisture conditions would not be met before the winter. With several weeks of summer ahead, the Ministry preferred to wait for the moisture requirements to be met. HMA overlay of the CIR mix, placed July 2-15, was carried out August 18-22.

According to the contract, the CIR with expanded asphalt was only required to cure for a minimum of two calendar days prior to overlay. However, hot mix paving could not practically begin until the CIR material was ready for over-lay. HMA overlay of the CIR with expanded asphalt was carried out July 31, August 6 and 8 for the CIR with expanded asphalt, which was placed July 7-9.

## POST-CONSTRUCTION TESTING AND EVALUATION

### Indirect Tensile Strength Testing

The CIR with expanded asphalt trial on Highway 7 was the MTO's first use of this new technology. To evaluate the material outside of the contract environment, both the CIR and CIR with expanded asphalt material were sampled and tested in-house to allow a comparison of the materials. During construction, three 15 kg samples of the CIR and three 15 kg samples of the CIR with expanded asphalt were randomly obtained from the beginning, middle, and end of the work and shipped to MTO's Central Laboratory for testing. Following a six-month delay, briquettes were made for dry tensile strength (DTS), wet tensile strength (WTS), and tensile strength ratio (TSR) according to LS-297 (*6*). Results of this testing are presented in Table 3.

**Table 3. MTO Laboratory Testing Indirect Tensile Strength Test Results**

| | CIR with expanded asphalt | | | CIR | | |
|---|---|---|---|---|---|---|
| | **Dry Tensile Strength (kPa)** | **Wet Tensile Strength (kPa)** | **Tensile Strength Ratio** | **Dry Tensile Strength (kPa)** | **Wet Tensile Strength (kPa)** | **Tensile Strength Ratio** |
| Random samples obtained during production | 707 | 567 | 80% | 193 | 52 | 27% |
| | 784 | 595 | 76% | 175 | 60 | 34% |
| | 693 | 511 | 74% | 191 | 62 | 33% |
| | 269 | 144 | 53% | 136 | 126 | 92% |
| | 298 | 131 | 44% | 143 | 109 | 76% |
| | 278 | 150 | 54% | 157 | 99 | 63% |
| | 421 | 254 | 60% | 262 | 113 | 43% |
| | 375 | 255 | 68% | 255 | 123 | 48% |
| | 424 | 266 | 63% | 269 | 135 | 50% |
| Mean | 472 | 319 | 64% | 198 | 98 | 52% |
| Stdev | 201 | 187 | 0.12 | 51.9 | 31.6 | 0.22 |

At first glance it would appear that the CIR with expanded asphalt results, although quite variable, are significantly better than the CIR results. A more detailed review of the test data show that the wet and dry tensile strength of both materials is directly related to the bulk relative density of the briquette. Briquettes for the testing were compacted in accordance with the test method however, the CIR with expanded asphalt material was more readily compacted, and the denser briquettes gave higher indirect tensile strengths, as indicated in Figure 6.

These results seem to indicate that the tensile strength of both materials is dependent on density. It was decided to look at the in-place density of the CIR and CIR with expanded asphalt pavements. Cores obtained eight months after construction were tested to determine if there were compaction differences in the field. Eight cores of CIR and ten cores of CIR with expanded asphalt were obtained and the density of each core was measured. Results indicated that the mean density of the two materials was similar. Analysis of Variance (ANOVA) carried out on the two data sets confirmed that the density of the materials was statistically the same.

The field density of the CIR and CIR with expanded asphalt (2.233-2.249 $t/m^3$) corresponds to the bulk relative density of the CIR with expanded asphalt briquettes with the highest dry and wet tensile strengths, as indicated in Figure 6. It is likely that, had the testing been carried out on fresh material shortly after sampling, the briquettes would have been more readily compacted to the required density. Since testing was delayed for several months, the material had cured and was difficult to compact, resulting in low and variable densities, and in turn low and variable tensile strengths.

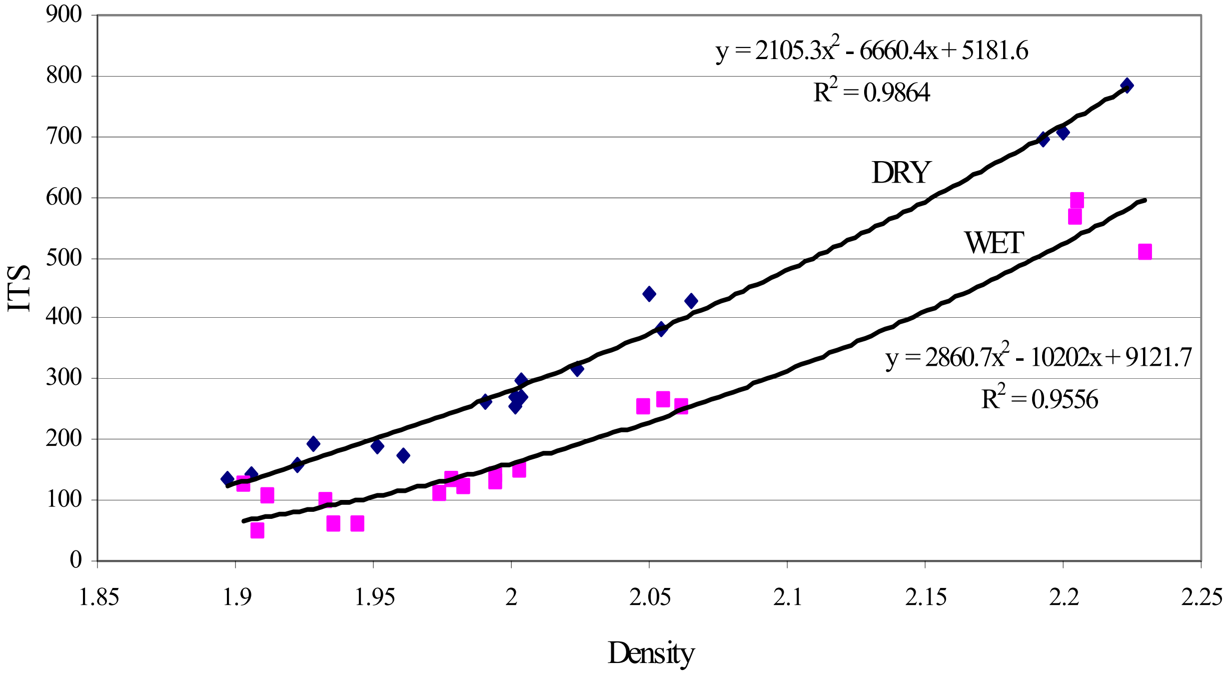


**Figure 6. Indirect tensile strength versus briquette density for samples of CIR and CIR with expanded asphalt.**

## Resilient Modulus Testing

Resilient modulus testing was carried out on core samples of the CIR and CIR with expanded asphalt obtained eight months after construction, according to ASTM D4123-82, Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. In Table 4, resilient modulus is reported as the mean result of tests carried out on 5 cores of each material. Resilient modulus was determined at two different testing frequencies (1 and 0.5 Hz) and three different horizontal displacements (0.015, 0.025, 0.035 mm). Resilient modulus results for the CIR ranged from 1141 to 1629 MPa. Resilient modulus results for the CIR with expanded asphalt ranged from 1194 to 1704 MPa. ANOVA analysis found the resilient modulus results for CIR and CIR with expanded asphalt to be statistically the same.

**Table 4. Resilient Modulus Test Results for the CIR and CIR with Expanded Asphalt**

| Material | Resilient Modulus @ f =1Hz | Resilient Modulus @ f =0.5 Hz | Resilient Modulus @ d = 0.015 mm | Resilient Modulus @ d = 0.025 mm | Resilient Modulus @ d = 0.035 mm |
|---|---|---|---|---|---|
| CIR | 1510 MPa | 1214 MPa | 1629 MPa | 1314 MPa | 1141 MPa |
| CIR with expanded asphalt | 1643 MPa | 1431 MPa | 1704 MPa | 1375 MPa | 1194 MPa |

## Falling Weight Deflectometer Testing

Falling Weight Deflectometer (FWD) testing was carried out on Highway 7 prior to and immediately following construction, and one-year after construction, providing an opportunity to compare the CIR and CIR with expanded asphalt, and to determine the change in the overall strength of the pavement structure. FWD results are presented in Table 5.

FWD equipment applies a dynamic load at different levels varying from 20 kN to 70 kN to determine the deflection response of the pavement. The measured dynamic deflections are normalized to represent a deflection load of 40 kN at a temperature of 21°C. The deflection data can also be used to back calculate the material properties of individual layers of known thickness. FWD tests were carried out in the inner wheel path of the driving lane, in both directions.

### *Pre-Construction Falling Weight Deflectometer Testing*

FWD testing was first carried out on the project in June 2003, prior to construction. A total of 68 FWD tests were carried out. The normalized dynamic deflection ranged from 0.18 to 0.42 mm with a mean of 0.31 mm. In addition to the deflection analysis, the pavement layer moduli were back calculated using ELMOD 5. The average back-calculated resilient modulus for each layer was as follows: 1,683 MPa for the HMA; 260 MPa for the granular base; 180 MPa (assumed) for the granular subbase; and 81 MPa for the subgrade.

### *Post-Construction Falling Weight Deflectometer Testing*

In September 2003, following construction, FWD testing was carried out to determine the post-construction strength of the pavement structure. A total of 34 FWD tests were carried out on both the CIR and CIR with expanded asphalt. The normalized dynamic deflection of the CIR with expanded asphalt ranged from 0.21 to 0.36 mm with a mean of 0.27 mm. The normalized dynamic deflection of the CIR ranged from 0.23 to 0.34 mm with a mean of 0.29 mm. ANOVA analysis carried out to compare the post-construction FWD test results for the CIR and CIR with expanded asphalt found that the results were statistically different, indicating that the CIR with expanded asphalt pavement structure was slightly stronger than the CIR pavement structure ($F = 5.28 > F_{crit} = 3.98$).

The mean deflection of the pre-construction FWD data was 0.31 mm, compared to mean deflections post-construction of 0.29 mm (CIR) and 0.27 mm (CIR with expanded asphalt). ANOVA analysis also shows that the pre-construction and post-construction data are statistically different for both the CIR ($F = 7.8 > F_{crit} = 3.94$) and CIR with expanded asphalt ($F = 20.91 > F_{crit} = 3.94$). These results show an increase in strength of the pavement structure.

In addition to the deflection analysis, the pavement layer moduli were back calculated. The average back-calculated resilient modulus for each layer was as follows: 3200 MPa for the HMA; 1173 MPa for the CIR with expanded asphalt; 1059 MPa for the CIR; 220 MPa for the granular base and subbase combined; and 81 MPa for the subgrade.

Based on the back calculated resilient moduli, it was unlikely that either the CIR with expanded asphalt or the CIR layer had achieved final strength levels. Emulsion stabilization of 100 percent RAP typically yields resilient moduli, when fully cured, in the neighbourhood of 1,400 MPa to 1,700 MPa. This implies that only 60 percent to 70 percent of the final strength has been achieved. It was proposed to revisit the trial sections on an annual basis to evaluate the in-situ resilient moduli of the CIR and CIR with expanded asphalt.

### *Falling Weight Deflectometer Testing at One-Year After Construction*

In September 2004, one-year after construction, FWD testing was carried out on the CIR with expanded asphalt and CIR trial sections. A total of 30 FWD tests were carried out on both the CIR and CIR with expanded asphalt. The normalized dynamic deflection of the CIR with expanded asphalt ranged from 0.14 to 0.21 mm with a mean of 0.17 mm. The normalized dynamic deflection of the CIR ranged from 0.11 to 0.21 mm with a mean of 0.17 mm. ANOVA analysis carried out to compare the FWD test results for the CIR and CIR with expanded asphalt found that the results were statistically the same. Test results at one year indicated that both materials had undergone a strength gain over the year, CIR from 0.29 mm to 0.17 mm mean deflection and CIR with expanded asphalt from 0.27 to 0.17 mm mean deflection.

FWD testing will be carried out on an annual basis in the future as a means of monitoring the long-term pavement performance of the CIR with expanded asphalt.

**Table 5. Falling Weight Deflectometer Test Results for the CIR and CIR with Expanded Asphalt**

| Test Date | Pavement Structure | No. of Tests | Normalized Dynamic Deflection | |
|---|---|---|---|---|
| | | | Mean (mm) | Range (mm) |
| **June 2003** | **Old HMA** | 68 | 0.31 | 0.18-0.42 |
| **Sept. 2003** | **CIR** | 34 | 0.29 | 0.23-0.34 |
| | **CIR with Expanded Asphalt** | 34 | 0.27 | 0.21-0.36 |
| **Sept. 2004** | **CIR** | 30 | 0.17 | 0.14-0.21 |
| | **CIR with Expanded Asphalt** | 30 | 0.17 | 0.11-0.21 |

## Roughness and Rutting

Shortly after placing the HMA surface course, MTO carried out a survey of roughness and rutting using the Automated Road Analyser (ARAN). An ARAN survey was also carried out in the year after construction. The average International Roughness Index (IRI) immediately after construction was found to be 1.16 for the CIR with expanded asphalt and 1.00 for the CIR, indicative of a fairly smooth pavement.

ARAN measurements taken in the year after construction indicate that both sections are exhibiting good ride characteristics. The average IRI was found to be 1.03 for the CIR with expanded asphalt and 0.95 for the CIR. CIR has a lower IRI value than CIR with expanded asphalt, indicating that the CIR section continues to have a smoother ride. Note that the CIR was micro-milled during construction to correct profile prior to surface course overlay, which likely improved smoothness of the pavement.

The average rut depth immediately after construction was found to be 2.6 mm for the CIR with expanded asphalt and 2.9 mm for the CIR, both very slight in severity. The CIR with expanded asphalt had slightly less rutting overall but was more variable than the CIR. One-year after construction, the average rut depth was found to be 4.3 mm for the CIR with expanded asphalt and 4.2 mm for the CIR, indicating that both pavements are experiencing similar rutting performance.

## Field Review

In September of 2004, a one-year field review of the pavement was carried out. Both the CIR and CIR with expanded asphalt pavements are performing well. The ride comfort rating was good (RCR = 9.0) and the overall pavement condition was very good (PCI = 93). Subjectively, the CIR pavement ride was slightly better than the CIR with expanded asphalt ride. No distinguishable rutting, distortion or cracking was observed in either section.

## CONCLUSIONS

CIR has been found to mitigate reflective cracking, extending pavement life. By reusing 100 percent of the existing aggregates and asphalt cement, the authors believe that CIR is both environmentally sustainable and cost-effective. MTO has successfully carried out over 50 CIR contracts since the late 1980's. CIR with expanded asphalt is a new development in CIR technology that appears to be a promising alternative to the conventional method.

CIR with expanded asphalt placement resulted in a fairly smooth, hard, uniform surface suitable for temporary traffic, and provided an excellent platform for HMA paving operations. The CIR with expanded asphalt placement progressed in a continuous and efficient manner, placing 5 km over a three day period.

Short-term results indicate that the CIR with expanded asphalt with a 50 mm HMA overlay provided an equivalently performing pavement structure compared to conventional CIR with a 50 mm HMA overlay at a similar cost.

Resilient modulus, FWD and ARAN results indicate that the CIR and CIR with expanded asphalt pavements are performing similarly. A field review in the year following construction showed no discernable distortion, rutting, or cracking. Ongoing performance monitoring and field testing will assess the long-term performance of CIR with expanded asphalt at this location.

Based on short-term results, CIR with expanded asphalt appears to provide an acceptable in-place recycling/rehabilitation strategy that conserves resources and provides an economic alternative to conventional CIR. Benefits of CIR with expanded asphalt include a reduction in curing time and an extension to the construction season.

## REFERENCES


1. Kazmierowski, TJ, Marks, P and Lee, S. "Ten Year Performance Review of In-situ Hot Mix Recycling in Ontario", 78th Annual Meeting of the Transportation Research Board, Washington, DC, TRR#1684, Jan. (1999).

2. Ministry of Transportation Ontario. SDO-90-01, Pavement Design and Rehabilitation Manual, Queen's Printer for Ontario (1990).

3. Ministry of Transportation Ontario. "Pavement Design Report, Highway 7", WP 51-98-00, Strata Engineering Corporation, June (2000).

4. Ministry of Transportation Ontario. SP-024, Manual for Condition Rating of Flexible Pavements, Queen's Printer for Ontario (1989).

5. American Society for Testing and Materials (ASTM) D4867/D4867M-96. "Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures", Annual Book of ASTM Standards, Vol. 0403, 485-489 (1996).

6. Ministry of Transportation Ontario. "Determination of Indirect Tensile Strength of Expanded Asphalt Mixes", Laboratory Testing Manual, LS-297, Ronen Publishing House, Toronto (2004).

7. Ministry of Transportation Ontario. "Preparation of Marshall Specimens for Cold In-Place Recycled Mixtures", Laboratory Testing Manual, LS-300, Ronen Publishing House, Toronto (1996).

8. Ministry of Transportation Ontario. "Bulk Relative Density of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens", Laboratory Testing Manual, LS-306, Ronen Publishing House, Toronto (1996).

9. Ministry of Transportation Ontario. "Moisture Content of Cold In-place Recycled Mixes", Laboratory Testing Manual, LS-291, Ronen Publishing House, Toronto (1999).