CANADIAN TECHNICAL ASPHALT ASSOCIATION PROCEEDINGS

2007

CTAA

PROCEEDINGS

of the

FIFTY-SECOND ANNUAL

CONFERENCE

of the

CANADIAN TECHNICAL ASPHALT ASSOCIATION (CTAA)

Niagara Falls, Ontario

November, 2007

Editor: Stephen Goodman

Editors Emeritus: Leonard Dunn and Elaine Thompson

ISBN 0-921317-67-0

Polyscience Publications Inc.
Laval, Québec, Canada

Eight-Year Performance of a Recycled Freeway Surface in Ontario

Pamela Marks, P.Eng.
Senior Bituminous Engineer
Ministry of Transportation Ontario
Toronto, Ontario

Becca Lane, P.Eng.
Senior Pavement Design Engineer
Ministry of Transportation Ontario
Toronto, Ontario

Thomas Kazmierowski, P.Eng.
Manager, Pavements and Foundations Section
Ministry of Transportation Ontario
Toronto, Ontario

Acknowledgements

The authors would like to acknowledge the Southwest Region staff, for without them the trial sections would never have been constructed and monitoring of the sections would have been impossible. Special acknowledgements go to Kai Tam, Dave Harris, Eric Magni, Neil Zohorsky, Ron Meertens, Michael Plant, John Moffat and Susanne Chan.

ABSTRACT

In 1999, the Ministry of Transportation Ontario (MTO) initiated a demonstration project to evaluate the performance of various pavement rehabilitation strategies used to address premature Dense Friction Course (DFC) ravelling and coarse aggregate loss experienced on Highway 401, east of London. The various pavement rehabilitation strategies utilized on the project included partial depth removal and re-surfacing using DFC, recycled DFC, premium hot in-place surface course using two different equipment technologies (Taisei Rotec and Martec), and microsurfacing.

These recycling technologies support a "zero waste" approach to pavement rehabilitation. Essentially, no resources are wasted and the need for additional pavement materials is minimized. MTO has implemented an innovative pavement recycling program to provide a sustainable rehabilitation option that is safe, efficient, environmentally friendly and cost-effective, that meets the needs of present-day users without compromising those of future generations.

Monitoring in the form of field evaluation and automated pavement testing was conducted to assess the performance of the pavement sections. Evaluation consisted of roughness, rutting and friction measurement, as well as manual distress surveys. Results of the annual pavement testing are provided in this paper, along with details on the project, its construction, and conformance to the end result specification.

RÉSUMÉ

En 1999, le Ministère des Transports de l'Ontario (MTO) a lancé un projet de démonstration pour évaluer la performance de diverses stratégies de réhabilitation des revêtements utilisées pour traiter la détérioration prématurée des couches denses de friction DFC et la perte de gros granulats expérimentées sur l'autoroute 401 à l'est de London. Les diverses stratégies de réhabilitation des revêtements utilisées sur le projet comprenaient l'enlèvement partiel et le resurfaçage avec DFC et DFC recyclé, super couche de surface à chaud en place au moyen de deux techniques d'équipement (Taisei Rotec et Martec) et du microsurfaçage.

Ces techniques de recyclage tolèrent une approche zéro rebut pour la réhabilitation du revêtement. Essentiellement, aucune ressource n'est rejetée et le besoin de matériaux additionnels de revêtements est minimisé. Le MTO a réalisé un programme innovant de recyclage de revêtements pour fournir une option viable de réhabilitation qui est sécuritaire, efficace, favorable à l'environnement et rentable, et qui rencontre les besoins actuels des usagers sans compromettre ceux des générations futures.

On a fait un suivi sous forme d'évaluation en chantier et d'essai automatique du revêtement pour évaluer la performance des sections de revêtement. L'évaluation a consisté en mesure de l'uni, de l'orniérage et de la friction ainsi qu'un relevé manuel des défauts. Les résultats des essais annuels des revêtements sont fournis dans cet exposé avec les détails sur le projet, sa construction et la concordance avec les spécifications du produit fini.

1.0 BACKGROUND

The Ministry of Transportation of Ontario (MTO) has utilized Reclaimed Asphalt Pavement (RAP) in hot mix pavements since the 1970's. It is our belief that natural resources should be conserved and used wisely. Our use of RAP has been restricted from use as a surface course on our heavier trafficked roads in an effort to reduce the risks associated with possible negative effects on pavement life. As the late 1990's approached however, the MTO's experience with the use of Recycled Hot Mix (RHM) had evolved to a point that a demonstration project was proposed for Highway 401, east of London, Ontario.

1.1 Measurable and Significant Benefits

The Kyoto Protocol was adopted in late 1997 to address the problem of global warming by reducing the world's Greenhouse Gas (GHG) emissions. Canada committed to reducing its GHG emissions to six percent below 1990 levels by the time its first commitment period ends in 2012 [1]. It is important for the MTO and the road construction industry to embrace these changes by proactively implementing pavement recycling technologies that will assist in achieving these goals. Pavement recycling technologies such as Hot In-place Recycling (HIR) and central plant recycling are well positioned to assist in achieving these goals.

These recycled pavements meet the criteria of sustainable pavements. A sustainable pavement can be defined as a safe, efficient, environmentally friendly pavement meeting the needs of present-day users without compromising those of future generations. The main criteria established for a sustainable pavement are:

- Optimizing the use of natural resources
- Reducing energy consumption
- Reducing GHG emissions
- Limiting pollution
- Improving health, safety and risk prevention
- Ensuring a high level of user comfort and safety

HIR and central plant recycling address all of these criteria. These technologies support a "zero waste" approach to pavement rehabilitation where the existing road material is reprocessed and reused. Essentially, no resources are wasted and the need for additional pavement materials is minimized.

1.2 Pavement Rehabilitation Strategies

Many of the MTO's Dense Friction Courses (DFC) placed in the early 1990's were experiencing premature ravelling. The ravelling was attributed to the lower asphalt cement content, which led to the loss of the fine aggregate matrix and the eventual plucking of the coarse aggregate. MTO's Southwest Region was particularly interested to find a cost effective rehabilitation strategy to address early deterioration of DFC mixes on MTO highways. It was decided to construct a demonstration project on Highway 401 near London to evaluate different pavement rehabilitation strategies that address ravelling while conserving new aggregates on heavily trafficked highways.

The demonstration project evaluated two different types of HIR trains, central plant RHM with a 30:70 recycled to new aggregate ratio and a control section constructed with new DFC. To promote a fair comparison, MTO evaluated the recycling strategies and control section based on the mix properties, compaction, lift thickness, and smoothness in accordance with its End Result Specifications (ERS). Additionally, two trial sections were constructed on the Eastbound Lanes (EBLs) to evaluate the feasibility of microsurfacing to reduce pavement surface loss due to the ravelling.

1.3 Ontario's Recycled Surface Policy

In the past, MTO limited the use of RAP in surface course to roadways with 2500 or less Average Annual Daily Traffic (AADT) per lane. This restriction was meant to minimize the risks associated with variability of the material and to ensure that the aggregates provided superior pavement friction. This demonstration project was constructed to specifically evaluate the performance of various preservation strategies including HIR recycling, single lift replacement with conventional central plant recycled mix and microsurfacing under heavy traffic as compared to traditional milling and replacement with a single lift of new HMA. In order to compare the recycled and non-recycled portions in a comparable manner, all HMA sections were required to meet the Ministry's Hot Mix Asphalt (HMA) ERS for mix properties, compaction, thickness, smoothness and segregation.

1.4 Location

The demonstration project was located on a section of Highway 401 between the Cities of Toronto and London, Ontario. More specifically, the HIR and RHM sections and the control section were constructed from 1.0 km west of Sweaburg Road outside of the City of Woodstock, westerly to 0.8 km west of Highway 19 on the two outer Westbound Lanes (WBL) over a 11.24 km stretch. The two outer EBLs of Highway 401 from 0.8 km west of Highway 19, to 0.5 km east of Oxford Road 6 (5.01 km) were microsurfaced over a two-year period by two different contractors. Traffic over this section of highway was 57,000 AADT with 30 percent commercial traffic in 2000 (5.8 million Equivalent Single Axle Loads (ESALs)) and has increased to 62,000 AADT with 38.4 percent commercial in 2004 (7.3 million ESALs).

2.0 PRE-CONSTRUCTION CONDITIONS

2.1 Visual Evaluation

This length of Highway 401 was initially constructed in the 1950's, resurfaced, and then widened to 6 lanes in the mid 1990's with a total pavement structure of 200 mm of HMA, including a 40 mm lift of DFC surface course.

Moderate to severe segregation was identified following the completion of the contract. Although the severely segregated areas were repaired, the moderately segregated areas were left in place, only to continue to deteriorate and result in premature ravelling and coarse aggregate loss problems with small potholes forming to the point that the pavement required early rehabilitation.

2.2 Field Test Evaluation

Ride Condition Rating (RCR) for the existing pavement was excellent [2] as determined from measurements obtained using the MTO's Portable Universal Roughness Device (PURD) [3] prior to rehabilitation of the sections. Rutting measurements taken prior to resurfacing, indicated very slight rutting. Friction Numbers measured at 100 km/hr (FN_{100}) were very good in the low forties over the WBL and in the mid-to-high forties over the EBL, as would be expected for a surface course consisting of

premium aggregates. A road radar survey was performed to determine the thickness of the pavement structure. Overall, the results indicated an average of 340 mm of asphaltic concrete and 910 mm of granular material [4].

2.3 Material Properties

The regional office hired a local consultant to carry out field and material testing. Cores were evaluated for surface course lift thickness, compaction, percent air voids, percent asphalt cement content, penetration of the asphalt cement, and aggregate gradation. Material properties were better than expected, with recovered penetration and air voids higher than usual for existing pavement material partially due to the lift only being 4 years old. Since the uniformity of HIR material is dependent on existing material properties, both HIR sections were selected from the two most uniform pavement sections. Material properties are summarized in Table 1 [5].

Table 1. Material Properties Prior to Rehabilitation

Property \ Section	Taisei Rotec HIR	New DFC	Martec HIR	Recycled DFC	Range of WBL Values
Lift Thickness, mm	39	42	46	40	30 – 63
Compaction, %	95.8	96.0	96.8	95.6	94.2 – 97.6
Air Voids, %	4.3	4.0	3.2	4.4	1.8 – 6.2
Asphalt Cement Content, %	5.0	5.2	5.2	5.2	4.6 – 5.7
Passing 4.75 mm Sieve, %	52.2	52.5	54.0	51.4	43.2 – 58.8
Passing 75 μm Sieve, %	3.9	3.6	3.5	3.5	2.9 – 6.0

DFC=Dense Friction Course, HIR=Hot In-place Recycling, WBL=Westbound Lane.

Note that recovered penetration values obtained by the consultant were higher than those obtained by the two laboratories carrying out mix designs for the two HIR sections. Their lower results were noted by the Ministry and verified by test results obtained by MTO's Head Office Laboratory. Recovered penetration values obtained during mix design were more representative at 35 dmm for the Martec HIR section and 30 dmm for the Taisei HIR section.

3.0 CONTRUCTION

3.1 Layout of Trial Sections

The contract consisted of rehabilitating two lanes; the middle lane (L2) and the driving lane (L3). The condition of the passing lane (L1) did not warrant inclusion in the rehabilitation contract. The WBL resurfacing extended over 11.24 km and consisted of:

- HIR premium mix produced using Taisei Rotec equipment (2.85 km, 2 lanes wide)
- Mill 50 mm and resurface with 50 mm new DFC (2.8 km, 2 lanes wide)
- HIR premium mix produced using Martec equipment (2.8 km, 2 lanes wide)
- Mill 50 mm and resurface with RHM premium mix produced at a central plant (2.79 km, 2 lanes wide)

The EBL resurfacing of L2 and L3 consisted of microsurfacing. The rehabilitation of the EBL only extended over the westerly 5.01 km chainage, with L3 being surfaced in 1999 and L2 not till the following year. Both microsurfacing sections used Type 3 aggregate and consisted of both a scratch coat and a surface coat. The layout of the various sections is detailed in Figure 1.

Lane 3	Recycled DFC	Martec HIR	New DFC	Taisei Rotec HIR
Lane 2				
Lane 1		←WBL		
Lane 1		→EBL		
Lane 2	Microsurfacing - 2000			
Lane 3	Microsurfacing - 1999			

DFC=Dense Friction Course, HIR=Hot In-Place Recycling, WBL=West Bound Lane, EBL=East Bound Lane.

Figure 1. Highway 401 Demonstration Project Test Sections

3.2 Observations Made During Construction

In order to diminish the negative effect of the rehabilitation work upon traffic, the work was only carried out at night. Paving of the WBLs took place in June of 1999. Some pick up of the mix was observed on all four WBL sections, particularly before the rollers had warmed up. Working at night may or may not have had an impact on the resulting quality of the completed work, but visual deficiencies were built into some of the test sections due to equipment difficulties. Details provided in the following sections are reported in documentation provided by the consultant [5].

3.2.1 Taisei Rotec HIR

HIR of this section was carried out using Taisei Rotec equipment consisting of three infrared preheaters and a reformer unit that scarifies, mills, rejuvenates, and lays the HIR material [6,7,8,9,10]. The HIR mix design included 0.44 L/m^2 of rejuvenating oil and the equivalent of 15 mm of beneficiating mix using Performance Graded (PG) 58-28 and diabase aggregates designed to supplement the mix reclaimed during scarification (35 mm) to achieve a 50 mm surface lift meeting MTO's ERS requirements. The average actual thickness placed was slightly higher at 57 mm. Work was completed over seven nights with temperatures ranging from a high of 26°C to a low of 18°C. Distresses noted after paving included:

- Moderate midlane segregation throughout.
- Intermittent slight segregation along the longitudinal joint between L2 and L3.
- Mat had a rich appearance.

The segregation may have been attributed to the excessive amount of mix allowed to accumulate in front of the paver screed.

3.2.2 New DFC

This section was completed by the prime contractor. Work included milling an average of 55 mm of the surface and resurfacing with an average of 54 mm of new DFC mix with PG 64-28 and meta-arkose aggregate. The mix was produced at a hot mix plant 55 km from the job site and placed over two nights in September 1999 with temperatures ranging from 20°C to 12°C. Some defects noted after construction included:

- Moderate to severe segregation throughout.
- Coarse aggregate loss.
- Poor longitudinal joint construction.

3.2.3 Martec HIR

This section of HIR was completed by Martec Recycling Corporation of British Columbia using their train consisting of two pre-heaters, a heater milling machine and a heater mixer unit. The pre-heater consisted of a combination hot air and an infrared heating system that heated the existing surface uniformly. The system re-circulates hot air minimizing emissions and energy required when compared to other HIR equipment used in the Province. Work was carried out over five nights with temperatures ranging from a high of 24°C to a low of 13°C.

The HIR mix was designed to contain the equivalent of 10 mm of beneficiating mix made with PG 58-28 and meta-arkose aggregate, as well as 0.43 L/m^2 of rejuvenating oil added to 40 mm of scarified material to bring the final HIR lift to the required 50 mm lift thickness and for the material properties to meet the required ERS requirements. The actual lift thickness was on average 54 mm.

Distresses noted after placement were confined to isolated areas of moderate segregation and slight segregation along the longitudinal joint between L2 and L3.

3.2.4 Recycled DFC

Work in this section consisted of milling an average of 59 mm and replacing with an average of 52 mm of recycled DFC produced using 30:70 ratio of RAP and new meta-arkose aggregate (by total mass of aggregate), with PG 58-28 asphalt cement. The DFC RAP was obtained during milling operations conducted for the installation of the DFC control section. Temperatures during paving ranged from 16°C to 12°C. The following defects were noted after placement:

- Few very slight and intermittent moderate end-load segregation, with early formation of a small pothole.
- L2 and L3 longitudinal joint was poor.
- Transverse joint exhibited moderate segregation.

3.2.5 Microsurfacing

The microsurfacing unit carried the supply of materials required to produce the mix on a continuous flow basis. Only L3 was microsurfaced in 1999. The scratch coat was placed at night under temperatures ranging from 16°C to 12°C. Oversize aggregates created problems with streaks and gouges in the scratch coat, created problems with the screed and conveyor system, and ultimately resulted in equipment failure. The surface course was placed in one night with temperatures falling from 14°C to 10°C, which slowed the curing process. Furthermore, the following morning was rainy and cool, so the lane was not opened to traffic until late that afternoon to ensure adequate curing.

The defects observed in L3 included a few longitudinal gouges from the dragged oversize aggregate and rich transverse joints. The surface texture was coarse, and although ride quality was not affected, a noisier ride resulted.

Based on the slow curing of the microsurfacing placed on L3, microsurfacing of L2 was put off till the following year. Unfortunately, L2 experienced wet, messy workmanship at start-ups, which showed after curing of the transverse joints. Additionally, a 50 mm double groove marked the centre of L2.

3.3 Properties of Material Placed

Both of the HIR and the RHM DFC sections were required to meet the MTO's DFC HMA ERS requirements. This included the physical properties for the aggregates contained in the lifts. All mixes for the WBL met the combined mix property compaction ERS requirements, although penalties were applied to the Martec HIR section mainly as a result of lower compaction. Average values obtained for each of the sections are provided in Table 2. Recovered penetration for the Taisei HIR section was 57 dmm while 63 dmm was measured for the Martec HIR section.

Table 2. Material Properties After Construction

Property \ Section	Taisei Rotec HIR	New DFC	Martec HIR	RHM DFC
Lift Thickness	57	53.8	53.6	51.6
Compaction	94.9	92.8	91.2	91.9
Air Voids, %	3.8	3.7	3.8	3.2
Asphalt Cement Content, %	4.7	5.2	4.8	5.1
Passing 4.75 mm Sieve, %	54.1	51.6	59.8	5.3
Passing 75 μm Sieve, %	4.0	3.5	4.5	4.0

HIR=Hot In-Place Recycling, DFC=Dense Friction Course, RHM=Recycled Hot Mix.

3.4 Surface Smoothness

Smoothness data obtained by profilograph measurements were taken for the WBL after paving was complete, but prior to patching. It showed that the majority of the Taisei HIR section was not smooth, with an average pay factor under one. The majority of the other WBL sections were smooth, with a bonus or full pay generally given. Table 3 provides details on the number of scallops and the pay adjustments made for the WBL sections based on their smoothness.

Table 3. Smoothness Results for Recycled and Control Sections

Demonstration Section	Pay Factor	# of Scallops	Percent of Sublots (%)	
			Bonus and Full Pay	Price Reduced and Rejected
Taisei HIR	0.97	75	29	71
New DFC	1.02	5	95	5
Martec HIR	1.02	25	86	14
RHM DFC	1.02	8	100	0

HIR=Hot In-Place Recycling, DFC=Dense Friction Course, RHM=Recycled Hot Mix.

Repairs were made to the new DFC, Martec HIR and RHM DFC sections to correct for rejectable surface smoothness. No repairs were made to the Taisei HIR section since smoothness was a more general problem occurring randomly throughout.

4.0 PERFORMANCE EVALUATION

The various pavement rehabilitation techniques utilized on the project were monitored for roughness, rutting and pavement friction on a yearly basis using automated equipment. Evaluation of the five sections and the control section also included field evaluation of the pavement condition at two locations for each of the westbound sections and only one for the eastbound sections. One stop was chosen at random, the other located at the designated control section for each particular section on October 12, 2000, June 19, 2002, and June 17, 2004.

4.1 Roughness

The sections were evaluated for roughness utilizing the MTO's PURD equipment until 2000, when the International Roughness Index (IRI) was adopted. Results are provided in Table 4. Roughness measurements reflect the bumps associated with the various repair patches. The Taisei HIR section has no patches over its length and the Martec HIR section very few. This is thought to be why the two HIR sections have a better ride in comparison to the new DFC and RHM DFC sections.

Table 4. Change in Roughness for Trial Sections

Demonstration Section (Note 3)	RCR (Note 1)			IRI (Note 2)			
	Before 1999	After 1999	One Year 2000	Two Years 2001	Three Years 2002	Five Years 2004 (Note 4)	Seven Years (2006) (Note 4)
Taisei Rotec HIR	8.1	8.5	8.8	1.33	1.29	1.38	1.41
New DFC	8.6	8.2	8.2	1.13	1.12	1.08	1.19
Martec HIR	8.3	8.5	8.7	1.02	0.98	1.01	1.11
RHM DFC	8.5	8.0	8.0	0.98	0.98	1.00	1.02
Microsurfacing - 2000	8.4	8.6 (Note 5)	8.2	0.92	0.90	0.89	0.92
Microsurfacing - 1999	8.7	8.0	8.4	0.78	0.78	0.87	0.98

Notes:
1. RCR is Ride Comfort Rating, scale of 0 to 10 with 10 being the smoothest ride from MTO PURD equipment.
2. IRI is International Roughness Index, roughness scale of 0 to 16 with 0 being absolute perfection from ARAN equipment.
3. All Westbound Lane (WBL) testing was carried out in Lane 3.
4. IRI for westbound begins 1km west of Sweaburg Rd and ends 1km east of Culloden Rd. Total length 11.19km
5. Section was not surfaced until 2000, measurement is for roughness before it was microsurfaced.

HIR=Hot In-Place Recycling, DFC=Dense Friction Course, RHM=Recycled Hot Mix, MTO=Ministry of Transportation Ontario, PURD= Portable Universal Roughness Device, ARAN=Automatic Road Analyzer.

4.2 Rutting

Rutting has been very slight in all sections and has not been an issue. Details are provided in Table 5.

Table 5. Change in Rutting for Recycled and Control Sections

Demonstration Section	Lane	Average Rutting (mm)			
		Previous Conditions	One Year 2000 (Note 1)	Three Years 2002 (Note 2)	Seven Years 2006
Taisei Rotec HIR	WBL	5.7 (L3) 4.0 (L2)	3.1	4.2	4.01
New DFC	WBL		2.8	2.9	3.54
Martec HIR	WBL		2.8	2.3	3.62
RHM DFC	WBL		2.9	2.6	3.96
Microsurfacing - 1999	EBL – L3	4.3	4.0	4.2	4.40
Microsurfacing - 2000	EBL - L2	3.6	(Not surfaced yet)	4.6	3.69

NOTES:
1. Average for L2 and L3 unless specified.
2. Average value for L3 unless specified. Two years for the Microsurfaced EBL L2.
3. Rutting was not evaluated in 2004.
HIR=Hot In-Place Recycling, WBL=West Bound Lane, DFC=Dense Friction Course, RHM=Recycled Hot Mix, EBL=East Bound Lane, L3=Lane 3, L2=Lane 2.

4.3 Pavement Friction

In southern Ontario, highways with high traffic volumes are designated for specific surface courses. In 1999, DFC was the required mix type for this location. MTO requires that DFC consists only of aggregates pre-approved for their high wear and polish resistance [11]. Frictional resistance was measured using MTO's brake force trailer conforming to ASTM E-274 and tested at the posted speed of 100 km/hr. The pavement Friction Numbers (FN_{100}) in Table 6 below are reflective of the good quality dolomitic sandstone that was in the existing DFC surface prior to rehabilitation, in addition to the diabase and meta-arkose added under this contract.

Table 6. Change in Friction Number for Recycled Sections

Demonstration Section	Lane	Friction Number (FN_{100}) at 100 km/hr				
		Before 1999	After 1999	One Year 2000	Three Years 2002	Five Years 2004
Taisei Rotec HIR	WBL – 3	41	43	39	44	43
New DFC	WBL – 3	41	41	41	44	44
Martec HIR	WBL – 3	41	41	43	47	44
RHM DFC	WBL – 3	42	40	40	46	43
Microsurfacing – 2000	EBL – 2	49	Not Paved	44	44	44
Microsurfacing – 1999	EBL – 3	45	42	37	41	41

Note: Friction testing was not carried out in 2006.
DFC=Dense Friction Course, HIR=Hot In-Place Recycling, WBL=West Bound Lane, EBL=East Bound Lane.

4.4 Distresses Observed in 2007

A detailed evaluation was carried out by the Regional Geotechnical Section in 2007 and indicated that for the WBL, the ride is affected by slight distortion throughout, extensive moderate and some severe ravelling at longitudinal paving joints including along the rumble strip. Throughout, there is also slight longitudinal cracking at joints with few multiple and alligator cracking forming between L2 and L3. Flushing is noticeable in the Taisei HIR and RHM DFC sections from secondary compaction in the wheel paths. Frequent slight Edge-of-Pavement (E/P) cracking and few slight transverse cracks were also noted. Detailed observations are provided in Table 7.

Table 7. 2006 Visual Observations

Section	PCR	RCR	Distresses
Taisei Rotec HIR	57	6.0	Moderate distortion throughout. Some moderate rutting in wheel track. Few potholes at E/P and at centre line. Extensive moderate ravelling. Extensive slight longitudinal cracking. Frequent slight transverse cracks. Few areas of slight flushing occurring in the dense mat in wheel track.
New DFC	71	7.0	Slight distortion throughout. Moderate centreline crack. Frequent slight transverse cracking. Intermittent slight midlane cracking. Segregation repair patches have rough surface. Frequent moderate ravelling in end-load segregation areas with potholes forming. Few potholes along outside E/P and intermittent potholes in wheel track.
Martec HIR	74	7.6	Throughout slight to moderate longitudinal joint cracking and slight transverse cracking. Frequent moderate ravelling with multiple to alligatored slight longitudinal cracks resulting in a sharp drop in the pavement quality. Outside E/P ravelling with a few potholes appearing. Segregation repair patches have rough surface. Small potholes developing.
RHM DFC	77	7.4	Slight centreline cracking throughout. Extensive slight E/P cracking. Intermittent slight longitudinal wheel path cracking. Slight transverse cracking throughout. Frequent moderate ravelling from end-load segregation and in the wheel tracks. Few small potholes. Segregation repair patches have rough surface resulting low ride index.

HIR=Hot In-Place Recycling, PCR=Pavement Condition Rating, RCR=Ride Condition Rating, DFC=Dense Friction Course, RHM=Recycled Hot Mix, E/P=Edge of Pavement.

5.0 FINDINGS

5.1 Taisei Rotec Section

This section exhibited more distresses than the other westbound sections, with segregation and a rich appearing mat immediately evident and progressing to extensive slight and frequent moderate ravelling, a few areas of moderate flushing, and localized rutting after one year in service.

By the third year the surface looked better than expected. Although still segregated, traffic had kneaded the mat and tightened up the surface texture resulting in no additional ravelling, although one 150 mm pothole had appeared. Review in successive years showed no change until 2006, with severity and extent of the distress increasing and the flushed surface reappearing. Cracking was limited over the section with the extent of the slight transverse and longitudinal cracks that appeared in the third year changing from few to extensive for the longitudinal cracks and frequent for the transverse cracks in 2007. Figure 2 provides a visual indication of the condition of this section in 2007.

Figure 2. Distresses in Taisei HIR Section in 2007 after Eight Years in Service

5.2 New DFC Section

This section represented the normal procedure and therefore, was used as the control section from which to evaluate all the other demonstration sections. Surprisingly, the control section did not perform as well as some of the other sections, with distresses evident mainly due to poor workmanship. Distresses identified at the initial stages included ravelling that was a direct result of segregation of the mix during construction. End-load segregation occurred throughout, with 24 areas exhibiting moderate segregation milled and replaced. Review after one year showed very slight ravelling at midlane and centreline throughout the section.

By year three the mat was of a fairly uniform texture and end-load segregation had lessened due to traffic kneading as noticed in the Taisei Rotec section. In general, the ravelling had not changed but very slight longitudinal cracking was evident frequently along the joints and one 150 mm pothole had appeared. No changes were noted until after the fifth year (2005), when frequent moderate ravelling of the end-load segregated areas that were not repaired was observed and a few potholes had appeared. The frequent transverse cracking was observed in early 2007 as slight, the longitudinal joint cracking moderate and intermittent slight midlane cracking had developed. Overall, the section performed satisfactorily as illustrated in Figure 3, although not as well as expected due to equipment and workmanship issues.

Figure 3. Condition of New DFC Section in 2007 after Eight Years in Service

5.3 Martec HIR Section

Three patch repairs were made to this section although they were limited to repair for roller pick-up and not for segregation. The section was the smoothest and after one year only exhibited a few areas of very slight ravelling. It was in excellent condition with both the longitudinal joints and mat texture performing very well and no real change in performance noted until year six.

By year six the ravelling was moderate and occurring frequently with some potholes starting. In addition, slight to moderate longitudinal joint cracking and slight transverse cracking was observed throughout with a few multiple to alligatored longitudinal cracks of slight severity accounting for a sharp drop in the pavement quality. The centreline joint exhibited no distresses, although a few potholes had appeared along the ravelled outside E/P. Overall this section displayed excellent performance as illustrated in Figure 4.

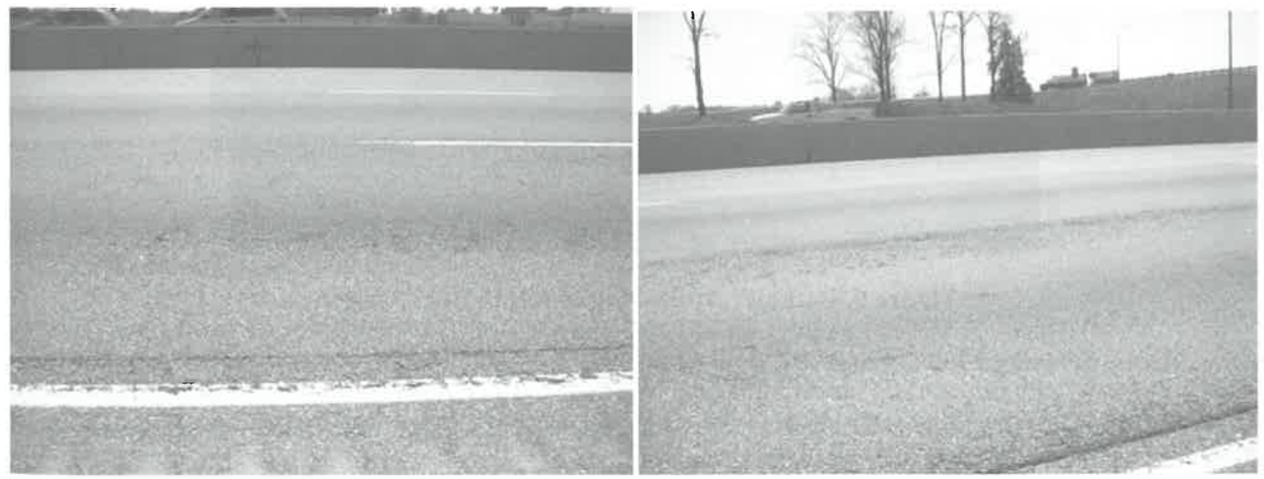


Figure 4. Performance of Martec HIR Section

5.4 RHM DFC Section

This section was of considerable interest as the Ministry wanted to evaluate what effect (if any), that recycled material might have on the performance of a premium surface course on a busy highway. Conditions were considered ideal as the RAP used in the RHM DFC was only 4 years old. Care was taken to ensure that the RAP would only contain aggregates of premium quality. As with the new DFC section, repairs were carried out for segregated mix (26 patches in total for this section).

After the third year, the mat remained in very good condition. The surface was wearing uniformly throughout with frequent very slight longitudinal cracking and a few areas of slight midlane ravelling. By year five, the mat was still in good uniform condition throughout, although the surface was not as tight as the Martec HIR section.

By 2005, the centreline longitudinal joint crack was slight throughout, the E/P was exhibiting frequent slight cracking and by 2007 it had progressed throughout the entire section, although it was not ravelling like the Martec HIR section. Other distresses had also appeared in 2007 including frequent moderate ravelling in the wheel paths and within the areas of end-load segregation, a few small potholes, intermittent slight wheel path cracking, and slight transverse cracking had appeared. Figure 5 shows the condition of one of the potholes within the RHM DFC section.

Figure 5. Potholes Appearing in RHM DFC Section

5.5 Micorsurfacing 1999 Section

After one year, this section (L3) showed no distresses. Slight ravelling throughout with few small diameter patched holes were observed during the third year review. By the fifth year, the microsurfacing showed a few areas of very severe ravelling in addition to potholes as shown in Figure 6. The potholes could have resulted from reflected end-load segregation in the underlying DFC. The section was resurfaced later that year (2004).

Figure 6. Severe Ravelling and Potholes in Lane 3 Microsurfacing

5.6 Microsurfacing 2000 Section

Lane 2 was placed in 2000 and showed immediate evidence of poor workmanship at the start up locations. In 2002, the surface was rough and in a few locations the microsurfacing was delaminating. Delaminated areas varied in size from small spots to up to 140 m^2. The conditions continued to deteriorate to frequent very severe delaminating of the microsurfacing. In 2004, sections of the microsurfacing were peeling off throughout, as shown in Figure 7. The delamination could have resulted from reflected load end segregation in the underlying DFC. Tack coat was not specified on this contract and the very severe delamination could have been directly linked to its' absence.

Figure 7. Delamination of Lane 2 Microsurfacing in 2004 after 4 Years in Service

5.7 Life Cycle of Sections

The expected life for microsurfacing on a high volume roadway is five to seven years, less than the 12 years expected for a lift of DFC hot mix. The two microsurfacing sections were removed and resurfaced in 2004 and the other four WBL sections have reached (or are soon to reach) the end of their service. Estimated service life for the WBL sections are:

- Taisei Rotec HIR – 7 to 8 years,
- New DFC – 8 to 9 years,
- Martec HIR – 9 to 10 years, and
- RHM DFC – 9 to 10 years.

None of the WBL sections will meet or exceed their expected service life. Two of the three sections containing recycled material performed the best.

6.0 SUMMARY

Both microsurfacing sections did not meet their five to seven year life expectancy. Having potholed and delaminated, they were both removed and resurfaced in 2004 with Stone Mastic Asphalt (SMA), which was the current Ministry surface course requirement for the traffic volumes on that stretch on roadway. Based on the experience gained on this project, the Ministry now routinely applies tack coats to HMA surfaces prior to microsurfacing. Additionally, it is the opinion of the Ministry that microsurfacing cannot be expected to hold a surface that is dry and ravelling for more than a few years.

The WBL sections were to be evaluated in relation to the control section, which consisted of milling the existing surface and repaving with new DFC that normally has a life expectancy of 12 years for heavily trafficked highways. Due to construction defects built into the new DFC control section, it did not perform as well as two of the recycled sections. Performance of the four WBL sections is summarized as follows:

- The Martec HIR section provided the best initial performance, although recently ravelling and cracking severity and frequency have increased. It has an anticipated life expectancy of 9 to 10 years.
- Followed closely in general performance was the RHM DFC section. This section has a similar life expectancy to the Martec HIR section of 9 to 10 years.
- The new DFC section exhibited end-load segregation throughout and many repairs were carried out immediately after construction. However, not all the segregation was removed and the repair patches resulted in a rougher ride. This has effectively shortened the life expectancy from 12 years to 8 to 9 years. This pavement section has reached the end of its life and will be scheduled for rehabilitation.
- The Taisei Rotec HIR section exhibited material segregation related defects and had numerous scallops. Since the defects were scattered throughout, no repairs were made and they can be directly attributed to the shortened life of 7 to 8 years for this section from the expected 9 to 12 years typical for HIR. This section has reached the end of its life and will be scheduled for rehabilitation.
- Longitudinal joints in both of the HIR sections are performing better than the longitudinal joints in the new and recycled DFC sections.
- Both conventional and in-place recycled HMA, if properly designed and constructed, can meet the same specification requirements.

Although none of the recycled sections have met the 12 year life expected for a new DFC overlay, their relative performance on this heavily trafficked highway indicates that when properly constructed, these recycled mixes can perform to the same level as an equivalent mix containing no RAP. Recycled mixes can and should be required to meet the same material requirements as their conventional non recycled counter parts as was required for this project.

7.0 CONCLUSIONS

The Ministry of Transportation's Environmental Bill of Rights has a mission statement to support its mandate of being a provincial leader in cost effective transportation, supporting the province's broader economic, social, and environmental objectives:

> "We will facilitate the mobility of people and goods, and promote the development of industries that provide transportation systems, services, and products, in ways that reflect the needs of Ontario's diverse population and support the broader economic, social and environmental objectives of the province."

One of the main environmental commitments of the Ministry is to protect air, water and land resources for future generations and the long-term survival of plants, animals and aquatic life. As part of putting this environmental commitment into action, the MTO is reducing construction-related GHG by promoting, monitoring and encouraging innovative pavement recycling techniques such as HIR and central plant recycling.

This commitment to recycling is helping address the Kyoto Protocol commitments and refining highway rehabilitation to achieve a zero waste, environmentally conscious, rehabilitation contract. To date, HIR and central plant recycling are cost effective and environmental friendly pavement rehabilitation options in terms of reducing costs, re-using existing non-renewable resources, minimizing use of new material, reducing transportation of construction materials and lowering GHG emissions.

The Ministry of Transportation has contributed and continues to contribute to the protection and enhancement of the environment though implementation and promotion of innovative pavement recycling techniques such as HIR and central plant recycling.

REFERENCES

[1] Environment Canada. Canada's Fourth National Report on Climate Change: Actions to Meet Commitments Under the United Nations Framework Convention on Climate Change. Government of Canada, 2006.

[2] Chong GJ, Phang WA. "Manual for Condition Rating of Flexible Pavements - Distress Manifestations", Report SP-024, Ministry of Transportation Ontario, Downsview, Ontario (1989).

[3] Ministry of Transportation Ontario. Pavement Design and Rehabilitation Manual, SDO-90-01, Downsview, Ontario (1990).

[4] Geophysics GPR International Incorporated. "Automated Pavement Data Collection Investigation Along a portion of Highway 401, Woodstock, Ontario", Ontario (1999).

[5] AGRA Earth & Environmental Limited. "Demonstration Project LDC 30-99-32 Highway 401 WBL from 1.0 km West of Sweaburg Road Westerly to 0.8 km West of Highway 19 Highway 401 EBL From 0.8 km West of Highway 19 to 0.5 km East of Oxford Road 6", AGRA Report, Ontario (1999).

[6] Kazmierowski TJ, Marks P, Lee S. "Ten Year Performance Review of In-Situ Hot Mix Recycling in Ontario", Transportation Research Record No. 1684, Issues in the Design of New and Rehabilitated Pavements, Transportation Research Board, National Research Council, National Academies, Washington, D.C., 194-202 (1999).

[7] Bradbury A, Marks P, Kazmierowski TJ. "Performance of In-Situ Hot Mix Recycling as a Maintenance Technique in Canada", Proceedings, 13th World Meeting of the International Road Federation, Toronto, Ontario, (1997).

[8] Kazmierowski TJ, Bradbury A. "The Evolution of Hot In-Place Recycling in Ontario", Pre-Print CD-ROM, 74th Annual Meeting of the Transportation Research Board, National Research Council, National Academies, Washington, D.C. (1995).

[9] Kazmierowski TJ, Bradbury A, Marks, P. "Seven Years of Experience with Hot In-Place Recycling in Ontario", Proceedings, Canadian Technical Asphalt Association, 39, 156-172 (1994).

[10] Marks P, Kazmierowski T, Bradbury A. "Performance of In-Situ Hot Mix Recycling as a Maintenance Technique in Ontario", Proceedings, 5th Paving in Cold Areas Workshop, Kananaskis, Alberta (1993).

[11] Roger C, Gorman B, Lane B. "Skid Resistant Aggregates in Ontario", Proceedings, Canadian Technical Asphalt Association, 46, 51-76 (2001).

REFERENCES

[1] Tighe SL, Capuruço R, Jeffray A. "Evaluation of Semi Automated/Automated Pavement Condition Surveys: An Ontario Field Study", Report, Ministry of Transportation of Ontario Highway Infrastructure Innovation Funding Program, Toronto, Ontario (2006).

[2] Luhr DR. "A Proposed Methodology to Quantify and Verify Automated Crack Survey Measurements", Pre-Print CD-ROM, 78th Annual Meeting of the Transportation Research Board, National Research Council, National Academies, Washington, D.C. (1999).

[3] Wang KCP, Elliot RP. "Investigation of Image Archiving for Pavement Surface Distress Survey, A Final Report", Mack–Blackwell Transportation Center, Department of Civil Engineering, University of Arkansas, Fayetteville (1999).

[4] Highway Research Board. "Standard Nomenclature and Definitions for Pavement Components and Deficiencies", Special Report No. 113, Highway Research Board, National Academy of Sciences, Washington, D.C. (1970).

[5] Sokolic I, Gunaratne M, Mraz A, Nazef A. "Evaluation of Pavement Distress Imaging Systems", Pre-print CD-ROM, 83rd Annual Meeting of the Transportation Research Board, National Research Council, National Academies, Washington, D.C. (2004).

[6] Roadw [illegible] Information", http://www.roadware.com, (Octo [illegible]

[7] ASTM [illegible] ndard Practice for Computing International Roug [illegible] e Measurements", Annual Book of ASTM Stand [illegible] ment Systems, 04.03, West Conshohocken, Penn [illegible]

Ten-Year Performance of a SMA Freeway Pavement in Ontario

Becca Lane, P.Eng.
Head, Pavements and Foundations Section
Ministry of Transportation Ontario
Downsview, Ontario

Gerhard Kennepohl, P.Eng., Ph.D.
Adjunct Professor
University of Waterloo
Waterloo, Ontario

Tom Kazmierowski, P.Eng.
Manager, Materials Engineering and Research Office
Ministry of Transportation Ontario
Downsview, Ontario

Chris Raymond, P.Eng., Ph.D.
Senior Pavement Design Engineer
Ministry of Transportation Ontario
Downsview, Ontario

Kai Tam, P.Eng., Ph.D.
Manager, Bituminous Section
Ministry of Transportation Ontario
Downsview, Ontario

Acknowledgements

Thank you to Andrew Alkins, Frank Marciello, Jason Wade, Sam Cui and Rob Kohlberger.

ABSTRACT

The first major high-volume freeway trial of Stone Mastic Asphalt (SMA) in Canada was constructed on Highway 401 west of Toronto in 1996. SMA is a heavy duty, gap-graded hot mix asphalt, composed of 100 percent crushed coarse aggregate and mastic stabilized asphalt cement. The performance to date has shown that the SMA aggregate skeleton with stone-on-stone contact will withstand rutting due to heavy truckloads. Additional asphalt cement binder provides increased durability, and resistance to aging and cracking of the mix. Stabilization of the additional asphalt cement and prevention of binder run-off during construction are achieved through an increase in fines and filler, the addition of fibres, and polymer-modification.

This paper describes the 10-year performance of the Ministry's first full-scale SMA trial. SMA was constructed on Highway 401 adjacent to a Dense Friction Course (DFC) for the purpose of comparing field performance. Since construction in 1996, the Ministry has been monitoring the performance of both the SMA and DFC mixes. Performance evaluation has included annual roughness and rutting measurement, frictional properties, and manual distress surveys. The results from ten years of performance evaluation are presented in detail, with the results indicating that both the SMA and DFC are performing well.

RÉSUMÉ

Le premier essai important d'enrobé à matrice de pierre SMA sur une autoroute à trafic élevé au Canada a été construit sur l'autoroute 401 à l'ouest de Toronto en 1996. Le SMA est un enrobé bitumineux à chaud discontinu résistant composé de 100 pour cent de gros granulats concassés et d'une matrice de bitume stabilisé. La performance à ce jour a montré que le squelette de granulats du SMA avec le contact pierre sur pierre va résister à l'orniérage par les poids lourds. Le bitume additionnel procure à l'enrobé une durabilité, une résistance au vieillissement et à la fissuration accrues. La stabilisation du bitume additionnel et la prévention du ruissellement du liant durant la construction sont accomplies par une augmentation des fines et du filler, l'ajout de fibres et la modification au polymère.

Cet exposé décrit les 10 années de performance du premier essai à pleine échelle du Ministère. Le SMA a été construit sur l'autoroute 401 accolé à une couche de friction dense DFC dans le but de comparer la performance en chantier. Depuis la construction en 1996, le Ministère a fait le suivi de la performance des deux enrobés SMA et DFC. L'évaluation de la performance comprenait les mesures annuelles de l'uni et de l'orniérage, des propriétés de frottement et l'étude manuelle des détériorations. On présente en détail les résultats de 10 années de performance qui montrent que le SMA et le DFC ont une bonne performance.

1.0 INTRODUCTION

1.1 SMA Overview

Stone Mastic Asphalt (SMA) is a gap-graded, impermeable surface course asphalt mix, generally composed of 75 percent crushed premium coarse aggregate, 20 percent crushed premium fine aggregate, and a rich asphalt cement / mineral filler matrix, with about 3 percent air voids. Because of the high asphalt cement content (6 percent minimum) and the gap-graded aggregate, fibres are used as a stabilizer in the mix to prevent drain-down of the asphalt cement during mixing, hauling, placing and compaction. Cellulose fibres are added typically at 0.3 percent by weight of mix. The asphalt cement is often polymer modified to increase the viscosity, also to prevent drain-down.

SMA offers the potential of a more durable, longer lasting surface course. Stone-on-stone coarse aggregate contact results in a high-stability mix with significant internal friction; resistant to rutting and abrasion. The increased asphalt cement content is less susceptible to low temperature cracking, provides crack healing properties, fatigue resistance, good aging properties, and improved durability.

SMA was developed about 40 years ago in Germany. European experience with SMA has been good, with SMA observed to outlast and outperform conventional mixtures [1]. SMA provides excellent durability, and increased resistance to rutting and fatigue cracking. The macrotexture of the SMA mixtures has been found to increase friction during wet weather and to provide improved surface drainage in comparison with dense-graded mixtures. SMA mixes have low air voids that can protect the underlying mixtures from water infiltration. SMA mixtures are less susceptible to cracking, due to the rich mastic providing self-healing qualities.

SMA does have its disadvantages. Polymer-modified asphalt cements and the addition of cellulose fibres mean increased costs over conventional mixes, although the additional costs may be justified with improved performance. SMA is also a more complicated mix to produce, sensitive to excess asphalt cement content and variable aggregate proportions, which may cause flushing. These construction challenges will most likely be overcome as contractors gain more experience.

1.2 Ontario's First Freeway Trial of Stone Mastic Asphalt

SMA use in North America was first introduced in Ontario as a Contractor's trial in 1990, on Miller Avenue in the Toronto area. The Ontario Ministry of Transportation (MTO) carried out its first full freeway trial of SMA in 1996. This 11 km trial, constructed on Highway 401 between Trafalgar Road and Highway 25 near Milton, was intended to compare the performance of an SMA surface course in the three eastbound lanes to Dense Friction Course (DFC) placed in the westbound lanes. This paper presents a 10-year performance review of this SMA freeway trial.

2.0 PAVEMENT HISTORY

2.1 Background

This section of Highway 401 is classified as a Divided Rural Freeway, designated as Class I (Freeway), with a design speed of 120 km/hr and a posted speed of 100 km/hr. The cross-section consists of 3 lanes in each direction with a concrete median barrier, and fully paved median and outside shoulders. In 1995, traffic volumes were 80,000 Annual Average Daily Traffic (AADT) with 20 percent commercial vehicles.

In 2006, traffic volumes were 120,362 AADT, with 17 percent commercial traffic resulting in an Equivalent Single Axle Load (ESAL) count of 7,106,752 per year.

2.2 Construction History

Highway 401 within the project limits was originally constructed in the 1950's with 225 mm of Portland cement concrete pavement over 300 mm of granular base.

Two resurfacing contracts were carried out in 1970 and 1974. Under Contract 70-30, the eastbound lanes were resurfaced with 32 mm of HL-1 surface course, over 38 mm of HL-6 binder course and 76 mm of HL-6 modified levelling course over the existing concrete pavement. The westbound lanes were resurfaced under Contract 74-165 with 38 mm of HL-1 surface course, over a 38 mm HL-6 binder course, HL-6 padding course and 50 mm of HL-6 modified lower binder course over the existing concrete pavement.

In 1981, this section of Highway 401 was widened to its current 6 lane cross-section under Contract 81-67, with 38 mm of DFC, over 38 mm of HL-8 upper binder course, 38 mm of HL-8 middle binder course, 2 x 76 mm of HL-8 lower binder course, over 450 mm of granular material. The upper two lifts extended full width across the 6 lanes. Fully paved shoulders consisted of 38 mm of HL-3 over 115 mm of HL-8. The DFC surface contained 100 percent steel slag aggregates, which resulted in accelerated pavement deterioration including extensive raveling and map cracking.

2.3 Pavement Condition Prior to Resurfacing

In 1995, the existing pavement was in fair to poor condition with a Pavement Condition Rating (PCR) of 66 (eastbound) and 64 (westbound) on a scale of 0 to 100. Pavement distresses included:

- extensive, moderate raveling;
- intermittent, moderate longitudinal wheel track cracking;
- frequent, severe centreline cracking;
- frequent, moderate transverse cracking;
- frequent, moderate midlane cracking; and
- extensive, moderate map cracking.

Rehabilitation recommendations were to mill 40 mm to remove the DFC with steel slag aggregate, and place 40 mm of DFC surface course over 40 mm of Heavy Duty Binder Course (HDBC). It was decided that this contract would be the Ministry's first full-fledged freeway trial to compare SMA to DFC.

3.0 CONSTRUCTION OF SMA TRIAL

3.1 Contract Requirements

Contract 96-50 called for two lift resurfacing of a milled surface on Highway 401 from 1.4 km east of Trafalgar Road westerly to 1.0 km west of Highway 25 (Figure 1). The work consisted of milling 40 mm (actual depth was 55 mm) and replacing with 40 mm of SMA over 40 mm of HDBC for the eastbound lanes and 40 mm of DFC over 40 mm of HDBC of the westbound lanes. Contract quantities were 243,767 m^2 of DFC, 255,892 m^2 of SMA and 281,773 m^2 of HDBC.

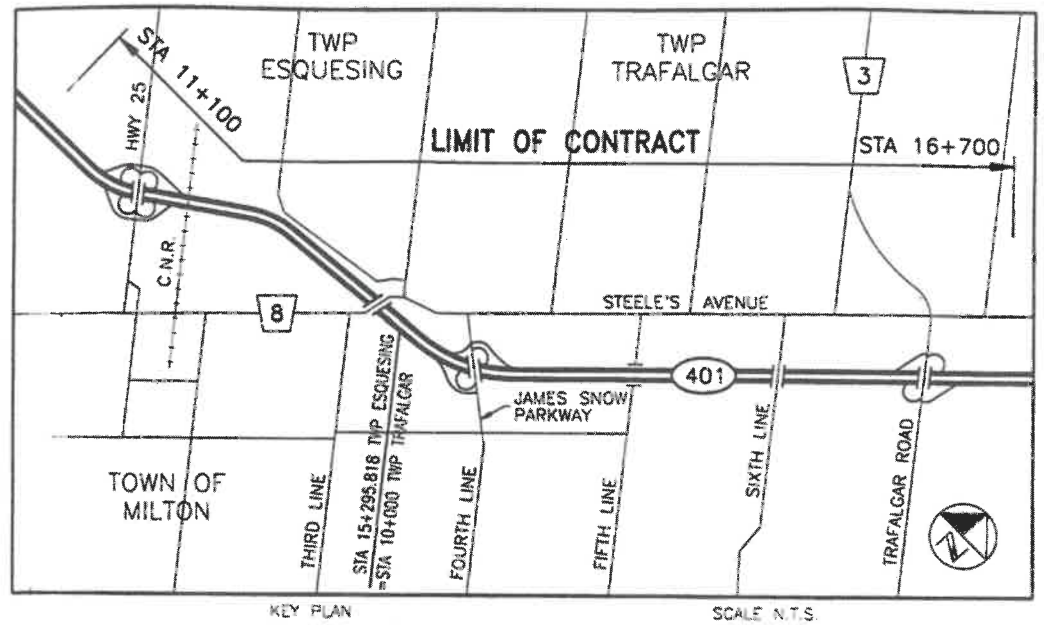


Figure 1. Location of Highway 401 Stone Mastic Asphalt (SMA) Trial near Milton, Ontario

In addition to the mix design requirements and Quality Control/Quality Assurance (QC/QA) testing requirements in place for traditional Ministry contracts, this contract incorporated a 3-year warranty based on pavement condition. The warranty requirements outlined repairs for excessive coarse aggregate loss, raveling and segregation, flushing, rippling and shoving, wheel track rutting, and cracking of all types.

After partial depth pavement removal, the Contractor was required to conduct a crack survey of all existing pavement surfaces to be resurfaced to estimate the total length of existing cracks expected to reflect through the new pavement surface prior to the end of the warranty period.

The 40 mm layer of HDBC was placed in the eastbound lanes between September 3-18, 1996 and in the westbound lanes between September 20 to October 9, 1996. The SMA was placed in the eastbound lanes between September 19 to October 23, 1996. Construction issues resulted in carry-over work, with the DFC placed during May and June 2007. The completion date of the contract was June 13, 1997.

3.2 SMA Mix Properties

SMA is a heavy-duty gap graded hot mix asphalt with a relatively large proportion of stones and an additional amount of mastic-stabilized asphalt cement. The SMA mixture has an aggregate skeleton with coarse aggregate stone-on-stone contact to withstand damage due to heavy truck loads.

The SMA mix design requirements followed the Federal Highway Administration's "Model Guidelines, Stone Mastic Asphalt (SMA) Surface Course" [2]. The Marshall mix design method [3] was used, with 50 blows per face and a target of 3 to 4 percent air voids. Present day SMA design would require 75 blows per face, or a 100-gyration Superpave design.

Proper materials selection and mix design are key factors in hot mix performance. The SMA consisted of 75 percent traprock coarse aggregate, 20 percent traprock screenings, 5 percent flyash, 0.3 percent cellulose fibre, and 6 percent asphalt cement. As-built SMA mix properties are compared to the contract specification and the submitted mix design in Table 1.

Table 1. Stone Mastic Asphalt (SMA) Mix Properties

Mix Properties	Specification	Mix Design	Field Testing
Asphalt Cement Content, %	6.0 minimum	6.0	5.9
Voids, %	3 to 4%	3.4	4.4
Voids in the Mineral Aggregate, %	17.0 minimum		
Fibre, %	0.30	0.3	0.31
Marshall Stability, N	6200 minimum	7820	7052
Marshall Flow, 0.25 mm	8.0-16.0		
Retained Marshall Stability, %	70 minimum		
Drain down at Production Temperature	0.30 % maximum		
Marshall Compaction, Blows per Face	50	50	
Aggregate Gradation			
Sieve Size	**Percent Passing by weight**		
16.0 mm	100	100	100
13.2 mm	---	99.8	99.5
12.5 mm	85-95	---	---
9.5 mm	75 maximum	74.1	70.2
4.75 mm	20-28	25.9	24.2
2.36 mm	16-24	19.2	17.3
1.18 mm	---	16.2	14.5
600 μm	12-16	14.3	12.9
300 μm	12-15	12.5	11.7
150 μm		10.7	10.4
75 μm	8-10	8.9	8.5

The asphalt cement used was a Petro-Canada 85-100 penetration grade, rather than a polymer-modified or Performance Graded Asphalt Cement (PGAC). SMA constructed today would require PGAC with a two grade bump-up on the high temperature grade (PG 70-28 in the Toronto area).

The coarse aggregate was traprock from Marmora Quarry, which is a premium coarse aggregate on the Ministry's approved aggregate sources list for DFC. Fine Aggregate #1 was rescreened scalpings from Marmora Quarry. The mineral filler, Fine Aggregate #2 was Lakeview Type F flyash. Fibre used was Interfibe Roadcel, modified cellulose fibre, which was added at 0.3 percent by weight to the mix.

3.3 DFC Mix Properties

DFC is the premium surface course with high frictional resistance used on high volume roads. The DFC mix design requirements are outlined in Table 2. The DFC mix was constructed with the same Petro-Canada 85-100 penetration grade asphalt cement, as well as Marmora traprock coarse and fine premium quarried aggregate. Fine Aggregate #2 was a blend sand from IKO.

Table 2. Dense Friction Course (DFC) Mix Requirements

Properties	MTO DFC Requirements	Submitted DFC Mix Design
Asphalt Cement Content, %	4.5 min	4.7
Air Voids, %	2.5 to 3.5	3.0
Voids in the Mineral Aggregate, %	-	12.5
Marshall Stability, N	8900 min.	16000
Marshall Flow, 0.25 mm	8.0 min.	14.6
Marshall Retained Stability, %	70 min.	91
Marshall Compaction, Blows per Face	75	75
Aggregate Gradation		
Sieve Size	**Percent Passing by weight**	
16.0 mm	100	100.0
13.2 mm	98-100	99.8
9.5 mm	75-90	81.6
4.75 mm	45 to 50% by volume	49.7
2.36 mm	30-50	35.9
1.18 mm	22-40	28.4
600 μm	16-35	22.7
300 μm	7-26	11.7
150 μm	3-10	8.5
75 μm	3-6	6.0

3.4 HDBC Mix Properties

HDBC is a high stability mix designed to resist rutting. The HDBC mix design incorporates a traditional Marshall mix design procedure based the Asphalt Institute MS-2 Mix Design Procedure [3] and a nominal maximum aggregate size of 19 mm. The mix design was constructed with 85-100 penetration grade asphalt cement and local quarried limestone aggregate.

3.5 SMA Construction Issues

As with any new technology, a steep learning curve was encountered when placing the SMA mix. The three most prevalent problems during construction were variable asphalt cement content, inconsistent filler and fibre addition, and a stop-and-go operation.

Control charts indicated that the production process was out of control over the first several days of paving (Figure 2). High variability in asphalt cement content produced flushing in about one-third of the eastbound Lane 3 (outside lane) starting at Highway 25, much of which was removed and replaced. This was attributed to plant problems. There were also problems related to the addition and dispersion of the cellulose fibre. The contractor used a drum mix plant with automated filler and fibre addition, but it still resulted in inconsistent addition of each component. Construction records also show that the contractor was not achieving the targeted 94 percent compaction (typically achieving 90 to 92 percent).

The Project Construction Report had the following comments: "SMA proved to be difficult to produce, since the volume of fibres was clogging the plant. It worked fine, so long as the operation was continuous, but when work had to stop for any length of time, there was a delay in re-start due to the mix."

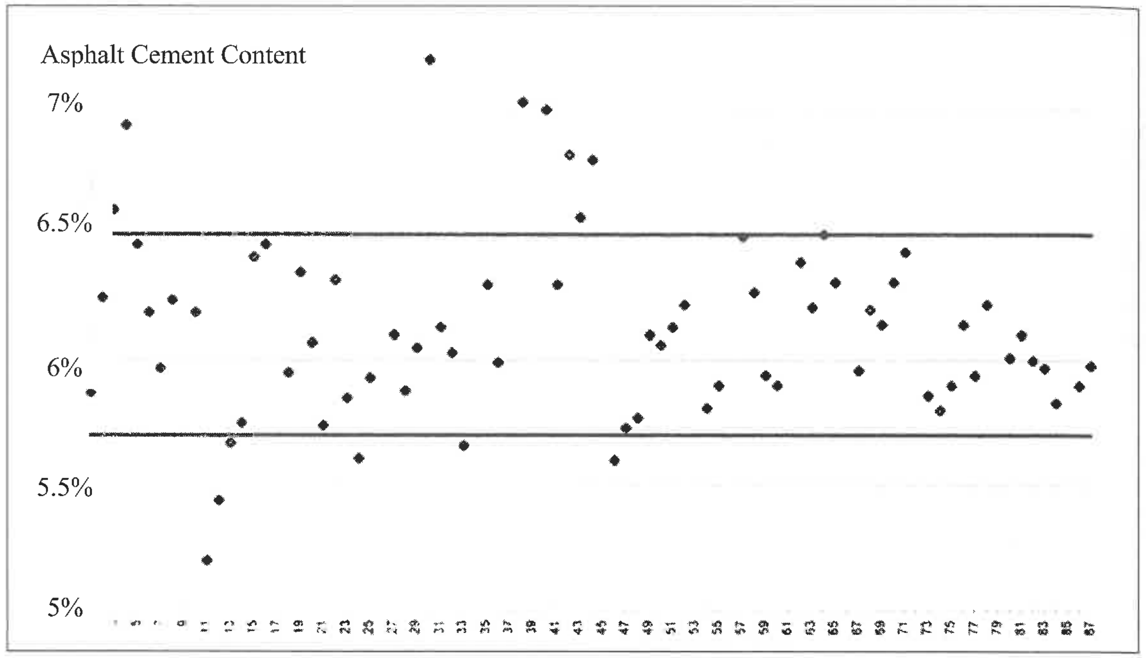


Figure 2. Quality Control Chart of Asphalt Cement Content on SMA Trial

4.0 PAVEMENT PERFORMANCE

4.1 Performance Monitoring

The SMA trial project has been monitored annually with MTO's Automated Road Analyser (ARAN), which measures rutting in mm and roughness in terms of International Roughness Index (IRI) in m/km. Periodic friction measurements were also made with an ASTM E-274 brake-force trailer.

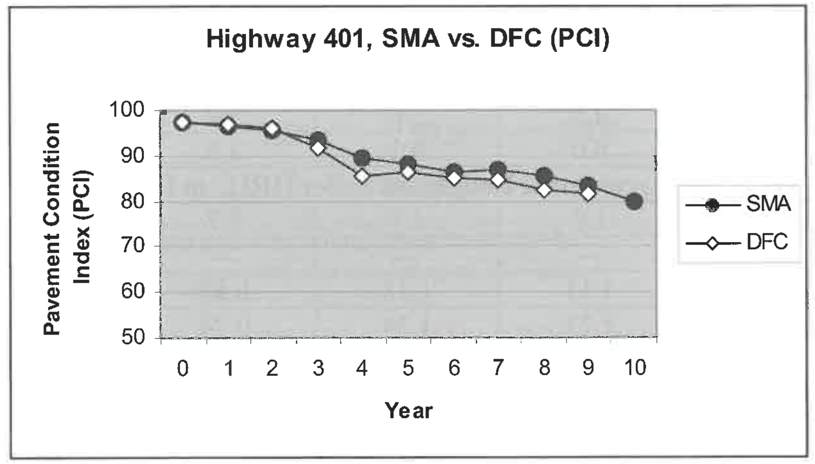
The Ministry's main pavement performance indicators are the Pavement Condition Index (PCI), which is a measure of pavement serviceability [4], the IRI and the Distress Manifestation Index (DMI). These indicators are measured annually and stored in the Ministry's Pavement Management System (PMS2) for network and project level evaluation [5]. The PCI, IRI and DMI for the ten-year performance period of 1996 –2006 of the Highway 401 SMA and DFC trial are presented in Table 3. Figures 3 and 4 are graphical plots of the two main performance indicators: PCI and IRI.

PCI values for the SMA and DFC indicate that both pavement types are performing very well after 10 years in service on a high volume freeway. IRI values indicate that the DFC was constructed considerably smoother than the SMA surface. The initial IRI values of 0.71 for DFC and 0.97 for SMA, show the impact of construction practices and workmanship on smoothness values over the lifetime of the pavement. Construction issues arising from the new SMA technology, including numerous starts and stops, resulted in a much rougher ride. The DFC trial was constructed smoother and remained smoother over the monitoring period. However both sections experienced identical rates of ride deterioration, i.e. +0.03 m/km per year.

Table 3. Pavement Performance Indicators for SMA and DFC on Highway 401

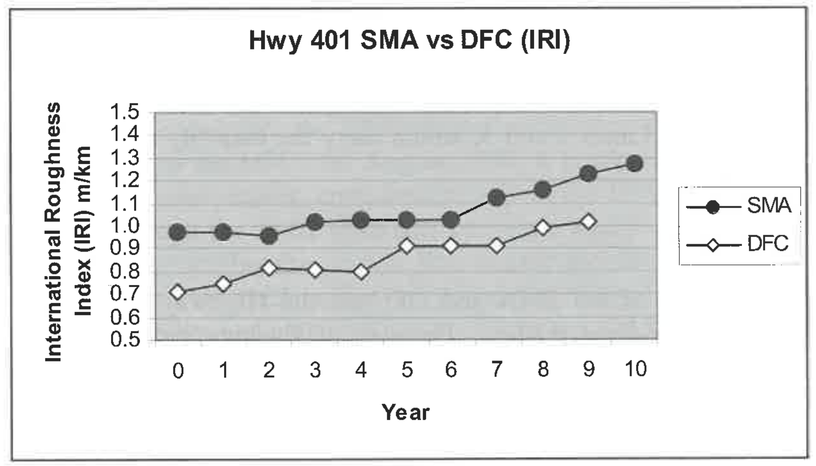
MIX	INDEX	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
SMA	PCI	68.4	96.4	95.5	93.3	89.5	88.2	86.4	86.8	85.6	83.3	79.7
	IRI		0.97	0.96	1.02	1.03	1.03	1.03	1.12	1.16	1.23	1.27
	DMI	7.69	9.89	9.86	9.65	9.28	9.16	8.93	9.05	8.95	8.74	8.38
DFC	PCI	65.2	97.4	96.7	96.1	91.8	85.5	86.2	85.2	84.5	82.6	81.58
	IRI		0.71	0.75	0.82	0.81	0.8	0.91	0.91	0.91	0.99	1.02
	DMI	7.44	10	10	9.93	9.48	8.83	8.81	9.16	8.62	8.47	8.37

Note: SMA is Stone Mastic Asphalt, DFC is Dense Friction Course, PCI is Pavement Condition Index, IRI is International Roughness Index, DMI is Distress Manifestation Index.



Note: SMA is Stone Mastic Asphalt, DFC is Dense Friction Course.

Figure 3. Pavement Condition Index (PCI) for SMA and DFC



Note: SMA is Stone Mastic Asphalt, DFC is Dense Friction Course.

Figure 4. International Roughness Index (IRI) for SMA and DFC

4.2 Rutting and Roughness

All three lanes of the SMA and DFC have been monitored periodically with MTO's ARAN, which measures rutting in mm and IRI in m/km. A lane-by-lane analysis is presented in Table 4.

Table 4. Detailed Rutting and Roughness Data obtained by ARAN

ARAN DATA	Stone Mastic Asphalt (SMA) Eastbound			Dense Friction Course (DFC) Westbound		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
Rutting, mm						
1999	4.3	4.4	5.5	3.3	3.5	3.8
2000	---	4.6	5.3	---	---	---
2001	3.4	4.8	4.8	2.4	3.1	3.2
2004	---	---	---	---	---	---
2005	3.4	5.0	5.3	3.8	3.6	3.8
2006	3.1	4.9	5.6	3.4	3.7	3.6
2007	4.3	6.0	6.1	3.8	4.3	4.0
International Roughness Index (IRI), m/km						
2001	0.9	1.0	1.1	0.7	0.8	0.8
2003	---	---	---	---	1.08	1.10
2004	0.94	1.14	1.18	0.69	0.88	0.92
2005	0.99	1.23	1.34	0.74	0.95	1.01
2006	1.09	1.38	1.49	0.88	1.13	1.15
2007	0.99	1.27	1.25	0.77	1.06	1.07

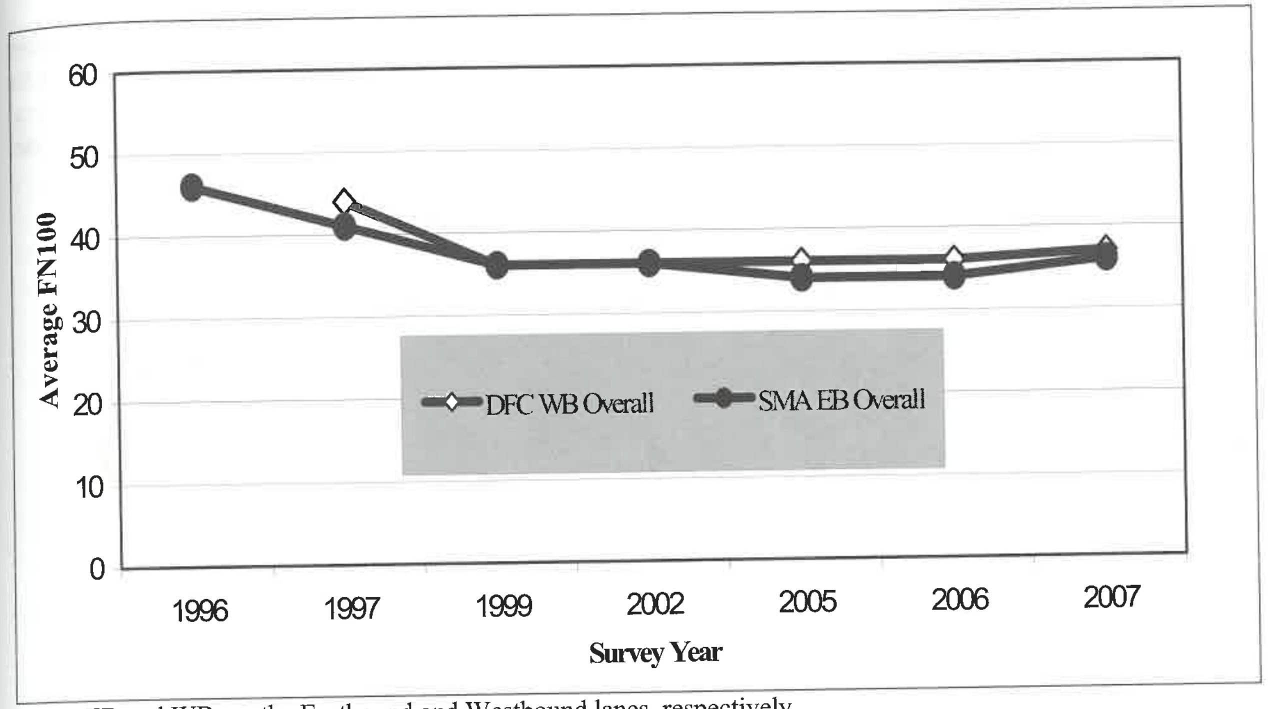
Note: ARAN is Automated Road Analyzer.

Both the SMA and DFC are performing very well with no significant rutting. The DFC has slightly less rutting (4 mm) than the SMA (6 mm). A statistical ANOVA analysis of the data showed this slight difference to be statistically significant. The slightly higher amount of rutting in the SMA may be attributable to the asphalt cement variability and flushing issues that occurred in Lane 3 during construction, resulting in initial wheel path consolidation under traffic.

The data indicates that Lane 1 (median lane) is performing the best for both the DFC and SMA, with a smoother ride and less rutting. Lanes 2 and 3, which carry the majority of the truck traffic are showing similar good performance.

4.3 Friction

Periodic friction measurements of the SMA and DFC on the Highway 401 trial were made with the Ministry's ASTM E-274 brake-force trailer. Because of flushing issues on the first several days' production of SMA, friction measurements were taken on both the SMA and DFC in the first year after construction. The friction testing was continued as part of the long-term monitoring program for this trial project. The friction testing was carried out at a test speed of 100 km/hr. Considering that both the DFC and SMA mixes used the same Marmora traprock coarse and fine aggregate, the friction results are very similar. The friction testing results are graphically presented in Figure 5. These results are in the acceptable range, comparable to other premium surface mixes with similar aggregates types.



Note: EB and WB are the Eastbound and Westbound lanes, respectively.
FN100 is the Friction Number recorded at a test speed of 100 km/h.

Figure 5. Friction Test Results for Stone Mastic Asphalt (SMA) and Dense Friction Course (DFC)

4.4 Visual Distress Survey (1999)

Visual distress surveys of the SMA and DFC were first made in 1999; 3 years after placement of the SMA and 2 years after placement of the DFC. At that time, the SMA and DFC on the Highway 401 trial section appeared to have similar performance, with no significant pavement distress. One exception was the transverse cracking. Since the SMA and DFC were placed as part of an overlay over concrete pavement, it was expected that there would be reflection cracking from the underlying PCC pavement joints and cracks. A detailed crack mapping survey was carried out prior to resurfacing, to exempt these reflection cracks from the warranty.

In the early years following construction, the SMA showed a significant improvement in the resistance to reflection cracking compared to the DFC. In August 1999, a crack survey showed only 44 transverse reflection cracks in the SMA trial section, compared to 155 in the DFC control section. The reflection cracks that did propagate through the SMA were still very tight and had not degraded significantly with time. This was thought to be attributable to the rich mastic providing self-healing qualities. It was expected that this early evidence of crack mitigation properties of the SMA when compared to the DFC would result in increased durability and extended service life of the SMA.

4.5 Visual Distress Survey (2007)

A visual distress survey was carried out in May 2007 to assess the ten-year performance of the SMA and DFC on Highway 401. A crack count carried out at highway speed yielded 626 transverse cracks in the eastbound SMA section and 290 transverse cracks in the westbound DFC.

The field review of the DFC pavement was carried out in two 250 m locations. Transverse cracks were occurring every 30 m and appeared to be located above existing concrete joints. Some transverse cracks were sealed, however slight alligator and multiple cracking, raveling and some potholing were present at the transverse reflection cracks (Figure 6). Transverse crack widths varied from 25 to 75 mm. Otherwise, the DFC mix was performing well, with very few locations of raveling observed.

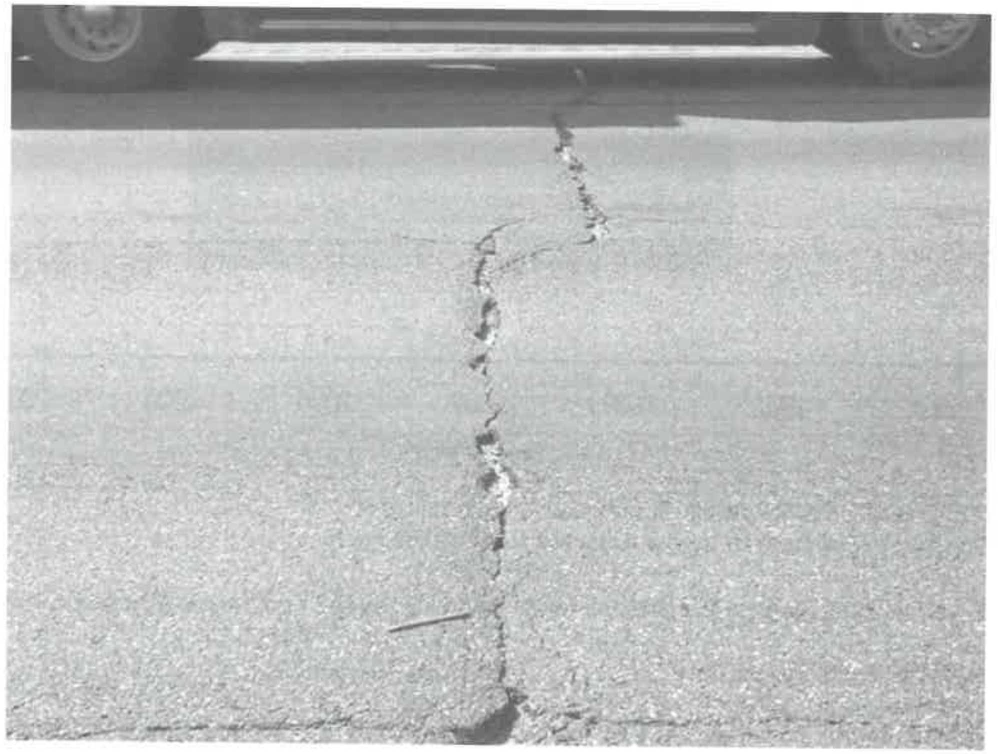


Figure 6. Typical Raveling of Transverse Cracks in Dense Friction Course (DFC) Pavement

The field review of the SMA pavement was also carried out in two 250 m locations. The most westerly section of the SMA, which was the first constructed, was exhibiting significantly more distresses than the rest of the SMA. Initial construction issues were the likely cause of these distresses. Transverse cracks occurred randomly and varied in separation from 5 to 25 m. All transverse cracks were rout and sealed and in good condition (Figure 7). Very few transverse cracks had multiple cracks propagating from them. The longitudinal joint between Lanes 1 and 2 was raveling and potholing throughout, most likely the result of poor compaction at the joint, and workmanship issues with the new SMA mix (Figure 8).

Several locations of moderate raveling were observed (Figure 9). This raveling was also evident in areas of pavement edge rumble strips, which had severely deteriorated. Raveling may be the result of drain-down occurring during placement, since asphalt plant problems at the start of construction resulted in variable asphalt cement content and fibre addition.

Overall, the one-year older SMA appears to be performing at a slightly lower serviceability level than the DFC. However the DFC is showing signs of multiple and alligator cracking, raveling and potholing at the transverse cracks, while the SMA cracks are sealed and tight, with very few slight cracks propagating from them. This may be an indication that the DFC will begin to deteriorate more rapidly than the SMA.

**Figure 7.
Sealed Transverse Crack in Stone Mastic Asphalt (SMA) Surface**

**Figure 8.
Sealed Longitudinal Joint, Exhibiting Multiple Cracks, Raveling, and Potholing in Stone Mastic Asphalt (SMA) Surface**

**Figure 9.
Raveling in Stone Mastic Asphalt (SMA) Surface**

5.0 DISCUSSION

Since construction of the test sections discussed in this paper, MTO has implemented changes in the hot mix types. The SMA now used by the Ministry is an SMA 12.5 meeting the American Association of State Highway Officials (AASHTO) specification requirements. DFC hot mix has been replaced with Superpave 12.5 FC2 mix, which is based on AASHTO Superpave 12.5 requirements with the additional requirement for 45 to 55 percent aggregate passing the 4.75 mm sieve. Both SMA and Superpave 12.5 FC2 continue to use premium coarse and fine aggregate. HDBC has been replaced with Superpave 19.0 meeting AASHTO requirements. Since the late 1990's, Ontario has also implemented PGAC. Where a 85/100 penetration grade asphalt cement was used on this project, a PG 70-28 asphalt cement would now be called for in the upper 100 mm of HMA at high traffic locations such as this project.

Distresses occurring in the SMA pavement are most likely the result of difficulties encountered at the asphalt plant and during placement of the new SMA mix. Poor longitudinal joints are likely the result of workmanship and compaction issues. Raveling may be the result of drain-down occurring during mixing, hauling, placing and compaction. The asphalt plant was experiencing problems adding the cellulose fibres used as a stabilizer in the mix to prevent drain-down of the asphalt cement. The asphalt cement content was highly variable, and penetration grade asphalt cement was used. Polymer-modified asphalt cements used in SMA today are more viscous, which also prevents drain-down.

6.0 LIFE CYCLE COSTING OF SMA

MTO has been conducting Life Cycle Cost (LCC) analysis of pavement designs since the early 1970's. In 1997, MTO retained an independent consultant team to carry out a comprehensive review of the Ministry's LCC process for the selection of freeway pavement designs. The two-year study, completed in December 1998, recommended changes to MTO's LCC procedures [6]. Based on feedback from the asphalt and concrete industries, follow-up studies in 2000 [7] and 2007 [8] were carried out to incorporate the benefits of new technologies such as SMA and assess their impact on LCC. These studies looked at the effect that SMA mixtures have on the performance of premium HMA pavements and their impact on LCC models for freeway pavements.

The SMA pavement design for high volume freeways used in MTO's LCC model is:

40 mm SMA surface course (PG 70-28)
60 mm Superpave 19 mm (PG 64-28)
220 mm Superpave 25 mm (PG 58-28)
100 mm Open Graded Drainage Layer
100 mm Granular A base
450 mm Granular B subbase

Anticipated LCC benefits of SMA include improved performance and durability, resulting in longer service lives and reduced maintenance costs. Rich SMA mixes reduce oxidation and moisture infiltration, reducing the potential for raveling and other surface defects, and protecting the underlying layers throughout the service life of the pavement. In addition, the use of SMA should reduce the potential for fatigue cracks initiating at or near the surface of the pavement, which will also help protect the underlying pavement from moisture infiltration. With this protection throughout the life of the pavement, it can be expected that the underlying pavement layers may not degrade at the same rate as pavements with conventional surface mixtures.

Actual performance data was gathered from pavements in Ontario and regions with similar environmental and loading conditions, to determine the average increase in life associated with using SMA over conventional surface course mixes. The life-cycle model was then revised to account for the anticipated improvement in long-term performance with the use of SMA mixes, including revisions to the timing of maintenance and rehabilitation treatments.

It is anticipated that there will be reductions in the amount of maintenance treatments required with the use of SMA. These reductions are estimated based upon the benefits that are anticipated primarily from the reduced quantities and severities of transverse cracking and raveling.

The LCC model also gives additional life to SMA overlays, due to improved durability. The life of the first overlay is assumed to be 13 years, compared to 12 years for DFC (or Superpave 12.5 FC2). This was based on decreased durability related distresses and improved resistance to top-down fatigue cracking.

The revised life-cycle model for SMA pavement [8] is given below:

Year 3:	Rout-and-seal
Year 9:	Selective patching; Rout-and-seal
Year 15:	Selective patching; Rout-and-seal
Year 19:	Selective patching; Rout-and-seal
Year 21:	Mill 50 mm & 50 mm SMA overlay
Year 24:	Rout-and-seal
Year 28:	Selective patching; Rout-and-seal
Year 32:	Rout-and-seal
Year 34:	Mill 50 mm & 50 mm SMA overlay
Year 37:	Rout-and-seal
Year 41:	Selective patching; Rout-and-seal
Year 44:	Rout-and-seal
Year 46:	Mill 50 mm & 50 mm SMA overlay
Year 50:	Salvage value (7 year overlay)

Based on the performance data gathered in the 1997/98 LCCA study [6], durability is one of the more frequent failure modes identified for high-volume pavements with a DFC surface. Initial life for SMA is 21 years, compared to an initial life of 19 years for DFC (or Superpave 12.5 FC2) for comparable freeway pavement structures [8,9].

Although the anticipated benefits of SMA have been discussed at length, there is still concern that the higher construction costs for SMA outweigh the LCC benefits. MTO experience has shown that SMA has a 30 to 50 percent higher cost than Superpave 12.5 FC2. This is partly due to higher asphalt cement content, which can be up to 2 percent higher than standard gap-graded Superpave mixtures. SMA also requires the use of polymer-modified asphalts, fillers and fibres, which have increased costs. As Contractors gain experience with SMA mixes, it is expected that the price gap between SMA and Superpave 12.5 FC2 will begin to narrow.

7.0 CONCLUSIONS

Performance monitoring, including roughness, rutting and friction measurement, as well as detailed pavement surface distresses surveys, indicate that the SMA trial section is performing similarly to the DFC control section after 10 years of service on a high volume freeway.

PCI values for the SMA (PCI=80) and DFC (PCI=81) indicate that both pavement types are performing very well. Initial IRI values indicate that the DFC (IRI=0.71 m/km) was constructed considerably more smooth than the SMA surface (IRI=0.97 m/km), with construction issues arising from the new SMA technology, including numerous starts and stops, resulted in a much rougher ride. The DFC trial was constructed smoother and remained smoother over the monitoring period.

After 10 years, both the SMA and DFC display no significant rutting, with the DFC having slightly less rutting (4 mm) than the SMA (6 mm).

In the early life of the SMA overlay, reflection cracking was minimal, suggesting that the SMA mix was more resistant to cracking than the DFC. The SMA overlay has performed well, but it did not prevent reflection cracking from the underlying concrete pavement. However, the occurrence of the reflection cracking in the SMA appeared later and occurred at a slower rate than in the DFC overlay. This observed behaviour is attributed to the thermoplastic properties of the asphalt cement/filler mastic-rich mixture, and the kneading action of the traffic.

Transverse cracks in the DFC surface are starting to deteriorate, which may be an indication that the DFC will begin to deteriorate faster than the SMA.

As with any new technology, a steep learning curve was encountered when placing the SMA mix. The three most prevalent problems during construction were variable asphalt cement content, inconsistent filler and fibre addition, and a stop-and-go operation. Distresses occurring in the SMA pavement are most likely the result of difficulties encountered at the asphalt plant and during placement of the new SMA mix. Poor longitudinal joints are likely the result of workmanship and compaction issues. Raveling may be the result of drain-down occurring during mixing, hauling, placing and compaction. The asphalt plant was experiencing problems adding the cellulose fibres used as a stabilizer in the mix to prevent drain-down of the asphalt cement. Variable asphalt cement contents resulted in flushed areas that were removed and replaced.

Overall, the SMA performance has shown good rutting resistance, fatigue endurance, and improved durability. MTO will continue to monitor the long-term performance of its first freeway SMA trial.

REFERENCES

[1] Kennepohl G, Aurilio V, Uzarowski L, Emery JJ, Lum P. "Ontario's Experience with SMA and Performance To Date", Proceedings, Canadian Technical Asphalt Association, 44, 495-516 (1999).

[2] Federal Highway Administration, "Model Guidelines, Stone Mastic Asphalt (SMA) Surface Course", Washington, 1994.

[3] Asphalt Institute, Mix Design Method for Asphalt Concrete and Other Hot Mix Types, Manual Series No. 2 (MS-2), Sixth Edition, Asphalt Institute, Lexington, Kentucky (1995).

[4] Ontario Ministry of Transportation (MTO). Pavement Design and Rehabilitation Manual, MTO SDO-90-01, Downsview, Ontario (1990).

[5] Ningyuan L, Kazmierowski T, Lane B. "Modelling Long-Term Flexible Pavement Performance of Ontario Highways", Proceedings, 10th International Conference on Asphalt Pavements, International Society for Asphalt Pavements (ISAP), Quebec City, Quebec (2006).

[6] Smith KL, Gharaibeh NG, Darter MI, Von Quintus H, Killingsworth B, Barton R, Kobia K. "Review of Life-Cycle Cost Analysis Procedures", Final Report, Ministry of Transportation of Ontario, Downsview, Ontario (1998).

[7] Hein DK, Hajek JJ, Smith KL, Darter MI, Rao S, Killingsworth B, Von Quintas H. "Benefits of New Technologies and their Impact on Life Cycle Models", Final Report, Ministry of Transportation of Ontario, Downsview, Ontario (2000).

[8] Hein DK et al. "Life Cycle Cost 2006 Update", Final Report, Ministry of Transportation of Ontario, Downsview, Ontario (2007).

[9] Lane B, Kazmierowski, T. "Guidelines for the Use of LCCA on MTO freeway Projects", MTO Materials Engineering and Research Office (MERO) Report No. 018, Ministry of Transportation of Ontario (MTO), Downsview, Ontario (2005).