PAVEMENT PERFORMANCE AND LIFE-CYCLE COST EVALUATION OF A POLYMER-MODIFIED ASPHALT CEMENT

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ABSTRACT

A pavement performance and life-cycle cost evaluation of a polymer-modified asphalt cement (Styrelf) has shown technical advantages and cost savings. The evaluation involved seven Ontario asphalt concrete pavements, representing various traffic and climatic conditions, placed between 1987 and 1992. A surface distress survey was completed for representative sections with the polymer-modified asphalt cement and control sections with conventional asphalt cement. Rut depth was determined from transverse profiles. The surface distress information was analyzed using the American Public Works Association PAVER procedures to determine the Pavement Condition Index for each section. This information was used to model the pavement condition through a 30 year analysis period. Life-cycle costing was completed to determine the present worth of the construction, maintenance and rehabilitation costs. The pavement performance modelling indicated the polymer-modified asphalt cement extended the pavement service life by about 4 to 6 years compared with conventional asphalt cement. This service life extension was confirmed by testing representative asphalt concrete cores in the Nottingham Asphalt Tester, which indicated improved rutting resistance and increased fatigue life. The results of the life-cycle cost analysis showed significant life-cycle cost savings for pavements incorporating polymer-modified asphalt cement mixes.

RÉSUMÉ

Une évaluation de la performace routière et du coût d'utilisation sur un cycle de vie d'un bitume polymère (Styrelf) a mis en lumière des avantages techniques et des économies sur les prix de revient. L'évaluation s'est effectuée sur sept chaussées de béton bitumineux posées en Ontario entre 1987 et 1992, représentant diverse conditions climatiques et de circulation. Une étude des dégradations de surface a été réalisée sur des sections representatives avec bitume polymère comme sur des sections de contrôle avec bitume classique. La profondeur de l'orniérage a été déterminée à partir des profils transversaux. Les renseignements sur les dégradations de surface ont été analysés selon les procédures PAVER de l'association des travaux publics américains pour déterminer l'indice de performance du revêtement de chaque section. Ces renseignements ont servi à modéliser la performance du revêtement sur une période d'analyse de 30 ans. Les coûts d'utilisation sur un cycle de vie ont été étudiés afin de définir la valeur actuelle des coûts de construction, d'entretien et de restauration. Le modèle de performance du revêtement indiquait que le bitume polymère prolongeait la vie du revêtement d'environ 4 à 6 ans par rapport au bitume classique. Ce prolongement de la durée de service s'est confirmé par des tests sur l'appareil d'essais pour enrobés Nottingham sur des carottes représentatives prelèvées sur le béton bitumineux. Ces tests ont indiqué une amélioration de la résistance à l'orniérage et une augmentation de l'endurance. Les résultats de l'analyse des coûts d'utilisation sur un cycle de vie ont montré des économies importantes sur ces coûts pour les revêtements incorporant des enrobés avec bitumes polymères.

1. INTRODUCTION

Innovations in asphalt technology and construction practices provide an opportunity to reduce the life-cycle costs of providing smooth and safe pavements. An area of considerable potential is the use of polymer-modified asphalt cements, particularly with the development of performance graded binder technology by the Strategic Highway Research Program [1]. Such research and development activities must be followed by technology implementation and monitoring of asphalt pavements to ensure that the desired life-cycle performance improvements are achieved. Most Canadian asphalt pavements must perform in a rather harsh climate of hot summers and cold winters, with a relatively short construction season. It is necessary for these asphalt pavements to be durable and resistant to permanent deformation (rutting), fatigue cracking and thermal cracking.

A pavement performance and life-cycle cost evaluation has been completed for a specific polymer-modified asphalt cement (Styrelf) that is widely used in Ontario and Quebec [2]. This polymer-modified asphalt cement is a homogeneous, stable binder designed to have increased elasticity and enhanced adhesive and cohesive qualities compared with conventional asphalt cements. The polymer-modified asphalt cement has been engineered to meet the needs of specific paving projects, providing asphalt concrete mixes with improved durability and enhanced resistance to rutting and cracking. Research over the past 15 years, mainly in Europe and the United States, has indicated improved asphalt pavement performance with the polymer-modified asphalt cement. It was considered important to quantify this improvement through an independent engineering evaluation using established pavement condition monitoring techniques and life-cycle costing analysis [3,4]. It should be noted that a recent Ontario Ministry of Transportation comparative evaluation of polymer-modified asphalt cements for major highway asphalt pavement trial sections indicated similar performance improvement and cost effectiveness [5].

2. METHODOLOGY

The field performance evaluation was completed in 1995 for seven Ontario roadway asphalt pavements (conventional, deep strength and composite), placed between 1987 and 1992, covering a range of traffic and climatic conditions, as summarized in Table 1. Representative asphalt pavement sections incorporating the polymer-modified asphalt cement and conventional asphalt cement (control section), one for each roadway where available, were selected for evaluation. Two of the seven roadway asphalt pavements were placed as research sites and include both a polymer-modified asphalt cement section and a conventional asphalt cement (control) section. It was not possible to locate a suitable conventional asphalt cement control section for the Don Valley Parkway site.

2.1 Visual Condition Survey and Transverse Profiles

A detailed visual condition (surface distress) survey of each asphalt pavement section was completed by an experienced pavement engineer. All of the pavement surface distresses were categorized by type, severity and extent (length or area), and the distress details recorded on asphalt pavement condition forms in accordance with the widely used American Public Works Association PAVER system [3]. Rut depths were determined from transverse profiles (100 mm intervals) measured at several cross-sections for each section using a digital incremental profiler (Dipstick^{R}) [6,7].

TABLE 1
PAVEMENT DISTRESS SURVEY SUMMARY

Site	Roadway	Asphalt Cement	Age (Years)	Area (m^2)	Distress Type	Length or Area (m or m^2)	Percent	Deduct Value	PCI
1	Eglinton Avenue (Metro Toronto)	Polymer Modified	4	2290	General Cracking [a] (L)[b] Patching/Utility Cuts (L) Rutting (L) Rutting (M) Edge Cracking (L)	220 21 14.5 3 9	9.61 0.82 0.68 0.13 0.39	12	88
		Conventional 85/100	4	2688	General Cracking (L) Patching/Utility Cuts (L) Rutting (L) Edge Cracking (L) Ravelling (L)	465 16 19.5 6 4	17.30 0.60 0.73 0.22 0.15	14	86
2	Team Canada Drive (City of Brampton)	Polymer Modified	7	2500	General Cracking (L) Alligator Cracking (L) Edge Cracking (L) Slippage Cracking (L)	154 23 9 26	6.16 0.92 0.36 1.04	20	80
	Williams Parkway (City of Brampton)	Conventional 85/100	7	1750	General Cracking (L) General Cracking (M) Alligator Cracking (L) Edge Cracking (L) Rutting (L)	859 105 8 5 50	49.10 6.00 0.46 0.29 2.86	35	65
3	Highway 401 (Near Port Hope)	Polymer Modified	8	938	General Cracking (L) [c]	17	1.81	0	100
		Conventional 85/100	8	938	General Cracking (L) [c]	58	6.18	5	95
4	Coldwater Road (City of Orillia)	Polymer Modified	8	2019	General Cracking (L) General Cracking (M) Ravelling (M)	104 16 0.1	5.15 0.79 0.01	6	94
		Conventional 85/100	8	2019	General Cracking (L) General Cracking (M) Ravelling (L) Ravelling (M) Rutting (L)	94 16 4 0.1 12	4.66 0.79 0.2 0.01 0.59	13	87

PCI = Pavement Condition Index

TABLE 1 (Continued)
PAVEMENT DISTRESS SURVEY SUMMARY

Site	Roadway	Asphalt Cement	Age (Years)	Area (m^2)	Distress Type	Length or Area (m or m^2)	Percent	Deduct Value	PCI
5	Larch Street (Municipality of Sudbury)	Polymer Modified	3	2674	General Cracking (L)	236	8.83	7	93
		Conventional 150/200	3	721	Joint Reflection Cracking (L) General Cracking (L) Patching (L)	217 48 22	30.09 6.66 3.05	18	82
	Elm Street (Municipality of Sudbury)	Polymer Modified	4	900	General Cracking (L)	12	13.33	10	90
6	Regional Road 57 (Municipality of Durham)	Polymer Modified	7	585	No Distress Observed			0	100
		Conventional 85/100	7	585	General Cracking	71	12.14	9	91
7	Don Valley Parkway (Metro Toronto)	Polymer Modified							
		Section 1	6	2650	General Cracking (L)	141	5.32	4	96
		Section 2	5	2625	General Cracking (L)	151	5.75	4	96
		Section 3	4	2725	General Cracking (L)	84	3.08	2	98

PCI Pavement Condition Index
a. General cracking is a composite measure of longitudinal cracks, transverse cracks and meandering cracks.
b. Severity of cracking: L - low severity; M - medium severity; and H - high severity.
c. Some low severity rutting was observed in both the polymer modified asphalt cement and conventional asphalt cement sections. Rutting appeared to be more severe in the conventional asphalt cement section. It was not possible to measure the rutting due to traffic.

The asphalt pavement surface distress information from the condition surveys was analyzed using PAVER procedures to determine the pavement condition index (PCI) for each section [8]. Continuous monitoring of the PCI can be used to establish the rate of pavement deterioration and serve as an objective and rational basis for determining maintenance and rehabilitation needs.

For each distress type at each severity level (medium, low or high) found, the total length or area of distress is divided by the area of the section to determine the distress density as shown in Table 1. This distress type, severity and density is then used to determine a 'deduct' value from standardized asphalt pavement quality deduct curves. The deduct value is the amount that each distress type at each severity level and density detracts from a 'new' asphalt pavement PCI of 100. The adjusted number of deduct values for all distresses is then subtracted from 100 to calculate the section PCI [8].

2.2 Anticipated Pavement Performance and Life-Cycle Costing

The PCIs of the polymer-modified asphalt cement and conventional asphalt cement sections from Table 1 for Highway 401, Coldwater Road, Larch Street and Regional Road 57 were compared with the typical asphalt pavement deterioration curve developed in PAVER to model the anticipated asphalt pavement performance over a 30 year life cycle [8]. Pavement maintenance and rehabilitation schedules, and associated costs, based on practical value engineering experience for Ontario asphalt pavements were assumed for the life-cycle models shown in Figures 1 to 4. Life-cycle costing was then completed to determine the present worth of the construction, maintenance and rehabilitation costs of these asphalt pavement sections [4].

2.3 Testing of Asphalt Concrete Cores

Laboratory comparative characterization testing with the Nottingham Asphalt Tester (NAT) was completed on representative asphalt concrete cores taken from the Eglinton Avenue site. The NAT has been shown to be very useful for determining the basic mechanistic properties of asphalt concrete such as resilient modulus, resistance to fatigue and resistance to permanent deformation (rutting) [9,10].

The repeated load indirect tensile (RLIT) test was used to measure the resilient modulus (Mr) of the asphalt concrete cores at a selected load pulse rise time of 120 ms (equivalent to a sinusoidal loading of 2.5 Hz). The test was performed at a temperature of 20°C. Five load pulses were applied along the vertical diameter of the 150 mm diameter core sample and the resultant peak transient deformation along the horizontal diameter was measured. The resilient modulus, Mr, is a function of load, deformation, sample dimensions and Poisson's ratio (reasonably assumed to be 0.35 at 20°C) [10].

The repeated load indirect tensile fatigue (RLIFAT) test was used to measure the resistance to fatigue of the asphalt concrete cores. The 150 mm diameter core sample was subjected to repeated load pulses until 'failure' occurred. Testing was performed at a temperature of 20°C and a constant initial strain level of 450×10^{-6} for all core samples. This strain level was based on an analysis of the stress distribution within the sample for the indirect tension and resilient modulus measured during the RLIT test [10].

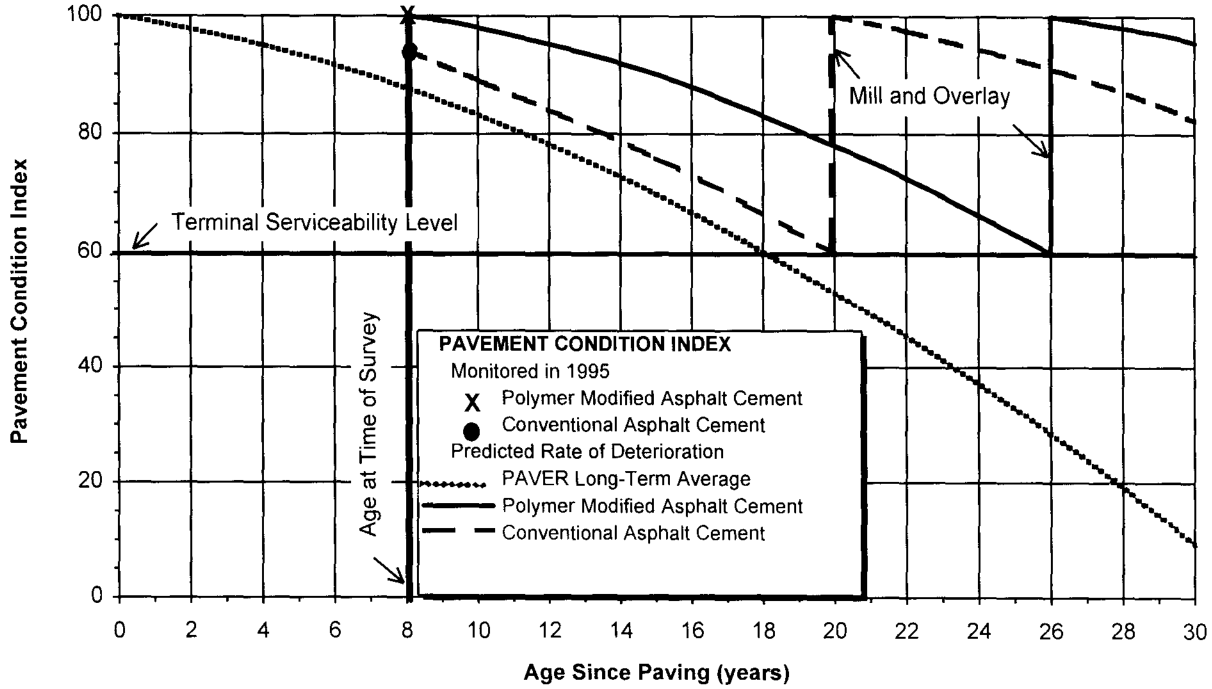


FIGURE 1 Pavement Life-Cycle Modelling. Site 3 - Highway 401.

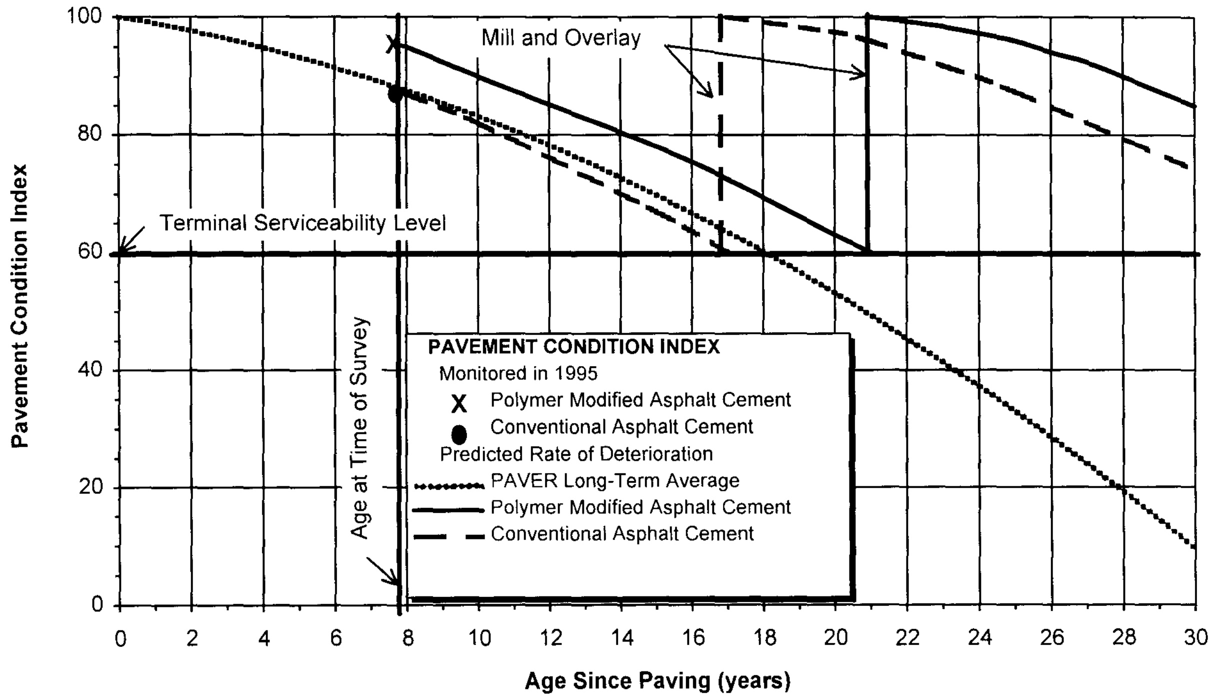


FIGURE 2 Pavement Life-Cycle Modelling. Site 4 - Coldwater Road.

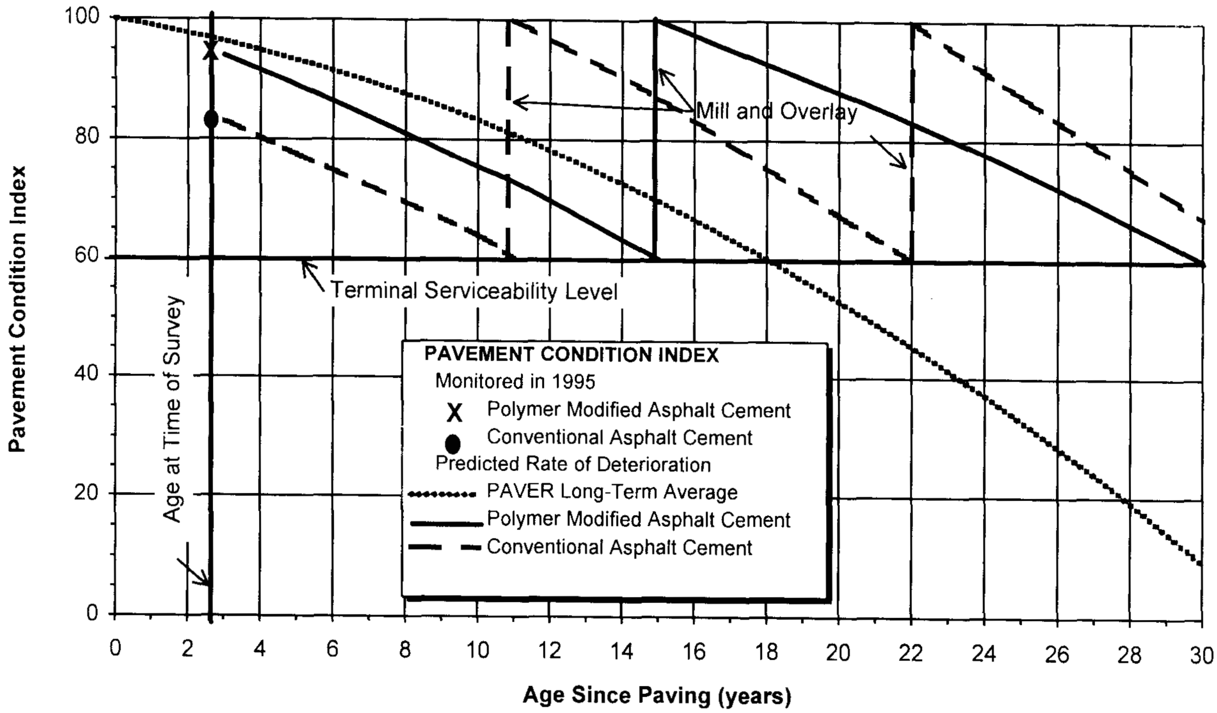


FIGURE 3 Pavement Life-Cycle Modelling. Site 5 - Larch Street.

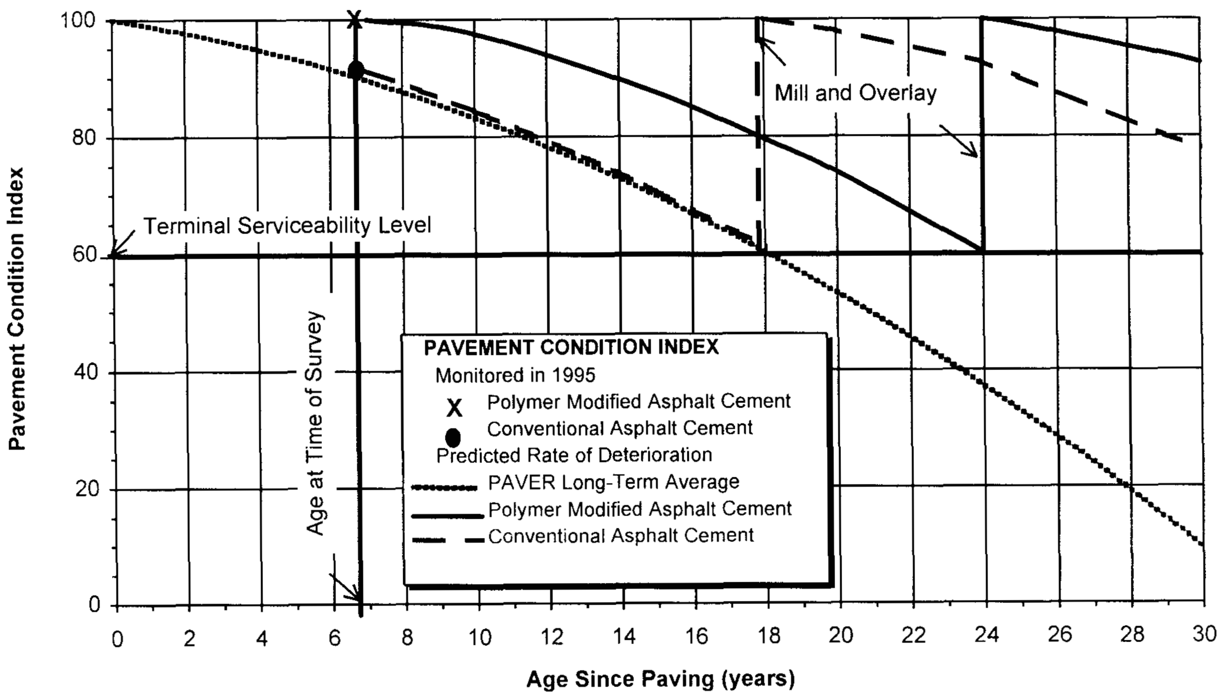


FIGURE 4 Pavement Life-Cycle Modelling. Site 6 - Regional Road 57.

The repeated load axial (RLA) test was used to measure the resistance to permanent deformation (rutting) of the asphalt concrete cores (Figure 5). This is a basic type of dynamic creep test which provides a relationship between axial strain and the number of load pulses [9]. The asphalt concrete core is subjected to repeated load pulses in the axial mode of loading. Test conditions adopted for the RLA test were: temperature 40°C; conditioning stress 10 kPa; conditioning period 10 minutes; test stress 100 kPa; load cycle stress duration 1s and rest period 1s; test duration 3600 load cycles [10].

3. CONDITION OF THE ASPHALT CONCRETE PAVEMENTS

The general surface condition of the asphalt pavement sections surveyed ranged from fair to excellent. A summary of the information from the visual condition (surface distress) surveys is given in Table 1. The pavement condition index (PCI) of the asphalt pavement sections incorporating the polymer-modified asphalt cement ranged from 80 to 100, compared with a PCI range of 65 to 95 for sections incorporating conventional asphalt cement.

3.1 Eglinton Avenue (Metro Toronto)

The overall condition of the Eglinton Avenue asphalt pavement (Site 1) was considered to be good four years after resurfacing in 1991. Both sections exhibited low severity longitudinal, transverse and meandering cracking, with the density of this general cracking for the conventional asphalt cement section approximately twice that of the polymer-modified asphalt cement section (Table 1). Low severity edge cracking and patching/utility cut distresses were found in both sections. There was some low severity rutting in both sections and localized medium severity rutting at a bus stop area of the polymer-modified asphalt cement section. The severity of rutting was generally determined with the digital incremental profiler (Dipstick^{R}), as shown for typical Eglinton Avenue transverse profiles in Figure 6. The average depth of rutting was 13 mm greater for the conventional asphalt cement section compared with the polymer-modified asphalt cement section.

The PCIs of the polymer-modified asphalt and conventional asphalt cement sections were 88 and 86 respectively. While both of the sections have the same composite pavement structure (asphalt concrete-surface over portland cement concrete base), the traffic on the polymer-modified asphalt cement section is higher than on the conventional asphalt cement section with considerable traffic leaving between the sections to access an adjacent major freeway. For this reason, these sections were not included in the life-cycle cost analyses.

3.2 Team Canada Drive/Williams Parkway (City of Brampton)

The Team Canada Drive (Site 1) section was resurfaced in 1988 using hot-mix asphalt concrete incorporating the polymer-modified asphalt cement. As an adjacent control section was not paved, a section of Williams Parkway that was constructed the same year using similar hot-mix asphalt concrete incorporating conventional asphalt cement was selected as a control section. The PCIs of the Team Canada Drive and Williams Parkway asphalt pavement sections were determined to be 80 and 65 respectively, after seven years (Table 1). However, Williams Parkway receives more traffic than Team Canada Drive, but a more suitable control section was not available in the City of Brampton. For this reason, these sections were not included in the life-cycle cost analyses.

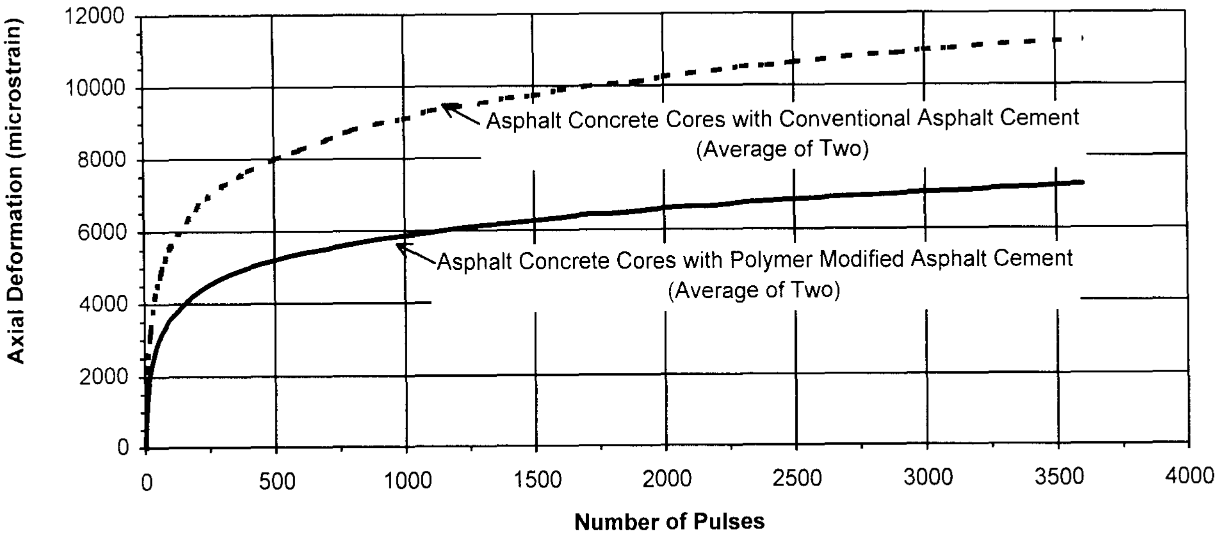
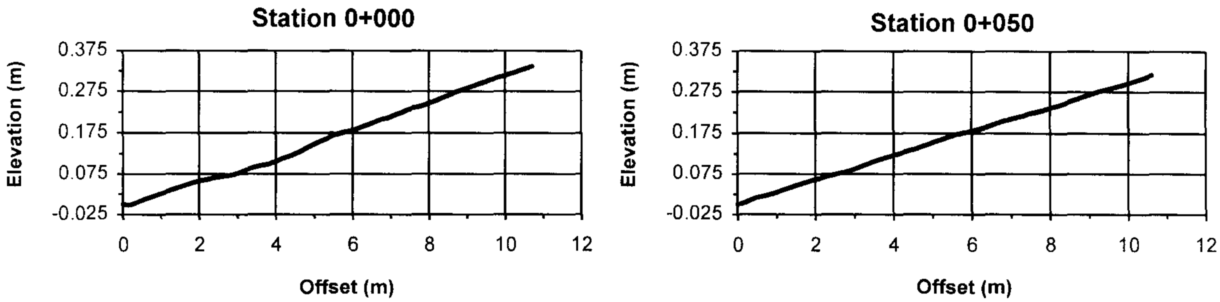
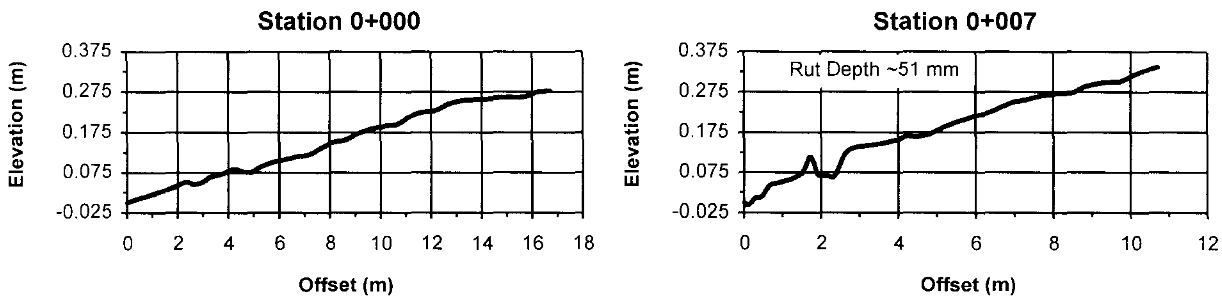


FIGURE 5 Permanent Deformation (Creep) of Asphalt Pavement Core Samples in Repeated Load Axial Test. (Axial Strain Measured in Nottingham Asphalt Tester.)



5A Eglinton Avenue - Polymer Modified Asphalt Cement.



5B Eglinton Avenue - Conventional Asphalt Cement.

FIGURE 6 Typical Transverse Profiles Measured Using Digital Incremental Profiler.

3.3 Highway 401 (Near Port Hope)

A modified hot-mix asphalt concrete test site was placed on Highway 401 by the Ontario Ministry of Transportation in June 1987 (Site 3) [5]. This test site involves various hot-mix asphalt concretes including a section incorporating the polymer-modified asphalt cement and a conventional asphalt cement control section. These test sections are considered to be most appropriate for modified asphalt pavements performance monitoring, comparison (Figure 1) and life-cycle cost analyses. After eight years of heavy traffic service, there were only 17 m of low severity transverse cracking in the polymer-modified asphalt cement section compared with 58 m in the conventional asphalt cement control section. There was low severity rutting for both sections with this rutting appearing to be more severe in the control section. It was not possible to complete transverse profile measurements to quantify the rutting severity and extent due to high traffic on the freeway. Transverse profiles should be measured with the incremental digital profiler and the distress survey updated annually to monitor the rate of deterioration for these sections. The PCIs of the polymer-modified asphalt cement and conventional asphalt cement control sections were determined to be 100 and 95 respectively (Table 1). These asphalt pavement performance observations for the Highway 401 site are similar to those of the Ontario Ministry of Transportation [5].

3.4 Coldwater Road (City of Orillia)

Coldwater Road (Site 4) was resurfaced in 1987 using hot-mix asphalt concrete with a section incorporating the polymer-modified asphalt cement and a conventional asphalt cement control section. Both sections exhibited low and medium severity longitudinal, transverse and meandering cracking (general cracking) and medium severity ravelling after eight years. There was also low severity ravelling and rutting in the control section. The PCIs of the polymer-modified asphalt cement and conventional asphalt cement control sections were determined to be 94 and 87 respectively (Table 1). Given their similar paving and traffic conditions, these sections are considered appropriate for asphalt pavement performance comparison (Figure 2) and life-cycle cost analyses.

3.5 Larch Street and Elm Street (Regional Municipality of Sudbury)

A composite pavement reconstruction project on Larch Street (Site 5) in 1992 included a section of asphalt concrete surface course incorporating the polymer-modified asphalt cement and a conventional asphalt cement control section. The density of low severity joint reflection (composite pavement action) and transverse cracking was 37 percent for the control section, as compared with only 9 percent low severity transverse cracking for the polymer-modified asphalt cement section after three years. The PCIs of the polymer-modified asphalt cement and conventional asphalt cement control sections were determined to be 93 and 82 respectively (Table 1). Given their similar paving and traffic conditions, these sections are considered appropriate for asphalt pavement performance comparison (Figure 3) and life-cycle cost analyses.

A section of composite pavement on Elm Street was resurfaced in 1991 with hot-mix asphalt concrete incorporating the polymer-modified asphalt cement. This section had 13 percent low severity transverse cracking after four years (Table 1). Elm Street receives significantly more traffic than Larch Street. There was no control section available for Elm Street.

3.6 Regional Road 57 (Regional Municipality of Durham)

These asphalt pavement sections were placed on Regional Road 57 (Site 6) in 1988 as part of a Canadian Strategic Highway Research Program (C-SHRP) Long Term Pavement Performance (LTPP) study. After seven years of service, there was no distress for the polymer-modified asphalt cement section (PCI of 100) and 71 m of low severity longitudinal cracking and transverse cracking (Table 1) for the conventional asphalt cement control section (PCI of 91). Given their similar paving and traffic conditions, these sections are considered appropriate for asphalt pavement performance comparison (Figure 4) and life-cycle cost analyses. These sections were resurfaced with one lift of hot-mix asphalt concrete. An adjacent section resurfaced at the same time with two lifts of hot-mix asphalt concrete incorporating conventional asphalt cement had only 9 m of low severity transverse cracking, indicating the importance of existing cracking and overlay thickness to asphalt pavement performance.

3.7 Don Valley Parkway (Metro Toronto)

Three sections of the Don Valley Parkway deep-strength asphalt pavement (Site 7), ranging in heavy traffic service from four to six years, have been resurfaced with hot-mix asphalt concrete incorporating the polymer-modified asphalt cement. There was a relatively small amount of low severity longitudinal and transverse cracking in each of these sections, with PCIs determined to be in the 96 to 98 range (Table 1). Unfortunately, a suitable control section could not be identified on the Don Valley Parkway as Metro Transportation has used only modified asphalt cements for all of the recent resurfacing of this major arterial route.

4. LABORATORY CHARACTERIZATION TESTING

The results of the Nottingham Tester (NAT) repeated load indirect tensile (TLIT) resilient modulus (Mr), repeated load indirect fatigue (RLIFAT) and repeated load axial (RLA) permanent deformation testing of asphalt concrete core samples from Eglinton Avenue (Site 1) are summarized in Table 2. The permanent deformations (creep) of the asphalt core samples in the RLA test, a measure of resistance to rutting, are shown in Figure 5. The average Mr of the asphalt concrete incorporating the polymer-modified asphalt cement was 2309 MPa, compared with 3046 MPa for the asphalt concrete with conventional asphalt cement. This indicates that both asphalt concretes have similar properties in terms of ability to spread vehicle loads (proportional to cube root) to the pavement structure.

The asphalt concrete incorporating the polymer-modified asphalt cement exhibited significantly better fatigue endurance and improved rutting resistance compared with the asphalt concrete incorporating conventional asphalt cement. The RLIFAT and RLA testing indicates a fatigue life about 8 times longer and a rutting resistance about 1.6 times greater for the asphalt concrete incorporating the polymer-modified asphalt cement. These general testing trends appear to be in accordance with the distress survey observations and transverse profile monitoring at the seven roadway sites. Similar improvements in fatigue endurance and rutting resistance have also been found during NAT characterization of Metro Transportation stone mastic asphalt (SMA) and high stability surface course (HL 1) mixes incorporating the polymer-modified asphalt cement [10]. It is clear that the polymer-modified asphalt cement is reducing the temperature susceptibility and improving the fatigue endurance of the asphalt concretes.

TABLE 2
Summary of Asphalt Concrete Core Sample Testing in Nottingham Asphalt Tester

Sample	Asphalt Cement	Resilient Modulus (MPa @ 20°C)	Fatigue Life (Number of Cycles)	Axial Deformation (microstrain) (3600 pulses of 100 kPa)
1-1	Polymer-Modified	2497		7161
1-2		2268	2009	
1-3		2432		6641
1-4		2040	2733	
	Average	2309	2371	6901
2-1	Conventional	3045		11268
2-2		2777	282	
2-3		3092		11108
2-4		3268	296	
	Average	3046	289	11188

5. LIFE-CYCLE COST ANALYSIS

Agency rational pavement investment decisions require consideration of the total cost of each alternative over its design life. The asphalt pavement alternative with the lowest initial cost may not be the most cost-effective once factors such as maintenance, rehabilitation, inflation and interest costs over its design life are taken into account. Pavement life-cycle costing can be defined as the economic assessment of competing construction, maintenance and reconstruction alternatives (designs, materials and methods), considering all significant costs and benefits (savings) over the design life (analysis period), expressed in terms of equivalent dollars [4].

5.1 Life-Cycle Costing

The present-worth method of life-cycle cost analysis is generally used for pavement investment decisions (Ontario Ministry of Transportation and Asphalt Institute for instance). All initial (construction) and future costs over the design life are converted (discounted) to one single present cost (worth). The pavement alternative that meets the design requirements (life, traffic volume and loadings) for a desired level of functional service, at the lowest cost over time (present-worth cost) represents the optimum pavement investment. There are five major cost components that must be considered during the life-cycle costing: initial costs (construction costs); maintenance costs (crack sealing for instance); rehabilitation costs (resurfacing for instance); residual value at end of the analysis period; and user costs, which are difficult to quantify.

The most 'controversial' aspect of any pavement life-cycle costing is the selection of an appropriate discount rate (true interest rate) in terms of: inflation rate (annual compound rate of increase in cost of pavement construction, maintenance and reconstruction); and interest rate associated with agency borrowing money (market interest rate which includes both inflation and return representing the real cost of capital) [11]. The offsetting effects of interest and inflation are characterized by the discount rate:

$$\text{discount rate (\%)} = \frac{\text{interest rate (\%) - inflation rate (\%)}}{1 + \text{inflation rate (\%)}/100} \qquad \text{Equation 1}$$

$$\text{present worth} = \frac{\text{future cost at year n}}{(1 + \text{discount rate})^n} \qquad \text{Equation 2}$$

It is important that an appropriate discount rate is selected. Selection of a high discount rate (higher than appropriate interest rate and/or lower than appropriate inflation rate) favours an alternative with lower initial costs and higher future costs over an extended period of time. The reverse is true with a discount rate (real interest rate) that is too low. While there may be large differences between interest and inflation rates from time-to-time (about 11 percent in 1986 for instance), interest and inflation rates tend to interact and influence each other so that they move together within a relatively narrow range over an extended period of time [11]. Historically, the nominal discount rate (interest rate minus inflation rate) over an extended period of time has been about 3 to 4 percent (U.S. Federal Highway Administration for instance) [11].

The analysis period is the length of time selected for consideration of the life-cycle costs. It is not necessarily the service life of the pavement. Agencies typically adopt 20, 30 or 40 years in their life-cycle cost analyses.

5.2 Values and Models Assumed for Life-Cycle Cost Evaluation

A 30 year analysis period was adopted for the life-cycle cost analyses of the Highway 401, Coldwater Road, Larch Street and Regional Road 57 polymer-modified asphalt cement and conventional asphalt cement control sections considered (Sites 3, 4, 5 and 6). The interest and inflation rates were taken as 7.5 and 4.0 percent respectively from representative Royal Bank of Canada rate trend publications [12].

The expected service life of the pavement, and maintenance and rehabilitation requirements during this period, must be considered for equivalent life-cycle cost comparisons. Road-user costs such as traffic delays during asphalt pavement construction and rehabilitation were not considered as they are difficult to quantify and any impact cost savings do not flow back to the agency. However, these road-user costs represent a significant nuisance and cost burden that should be reduced through innovative contracting practices such as cost-plus-time and lane rental bidding, particularly in congested urban areas [5,13].

In order to determine the expected service life of the asphalt pavement sections for the four sites analyzed, the 1995 PCIs determined from the distress surveys were plotted in Figures 1 to 4 against the typical asphalt pavement deterioration curve (long-term average) developed in PAVER [3]. The actual long-term rate of deterioration of the asphalt pavement sections is not known as only the 1995 PCIs are available. The pavement condition data for the sections (Table 1) strongly supports using a reduced rate of deterioration for the polymer-modified asphalt cement sections compared with the conventional asphalt cement control sections and PAVER long-term average. However, to be conservative in the analysis, the rate of deterioration for all of the asphalt pavement sections was modelled to follow the PAVER long-term average.

When the asphalt pavement condition (PCI) deteriorates to a terminal serviceability level of 60, it is assumed that a pavement rehabilitation strategy of milling and hot-mix asphalt overlay will be adopted to restore the pavement condition. The hot-mix asphalt concrete type for overlaying each section is assumed to be the same as for the initial paving. This overall modelling of the asphalt pavement performance with time for the sections at the four sites analyzed is given in Figures 1 to 4. Regular maintenance activities such as crack sealing and patching have also been included in the analyses based on practical experience with asphalt pavement maintenance. The estimated construction, maintenance and rehabilitation unit costs for asphalt pavements were taken from recent Ontario Ministry of Transportation life-cycle cost analyses [14].

A residual value calculation is necessary to account for the intrinsic value of the asphalt pavement after the design life (analysis period of 30 years) has been achieved. This residual value represents the available asphalt pavement service life, beyond the analysis period of 30 years, until it again reaches the terminal serviceability level of 60. Only the asphalt pavement (surfacing) was used in the life-cycle cost analyses as the remainder of the pavement structure is the same for each section at a site and will have no influence on the analysis.

5.3 Life-Cycle Cost Analysis of Sections

A summary of the assumptions made for the life-cycle cost analyses of the asphalt pavement sections modelled in Figures 1 to 4 is given in Table 3. An example of the detailed asphalt pavement alternative life-cycle cost analysis for the Highway 401 (Site 3) polymer-modified asphalt cement and conventional asphalt cement control sections is given in Table 4. These life-cycle cost analyses were completed for each of the four sites as summarized in Table 5.

The results of the overall life-cycle cost evaluation (Table 5) indicate that the 'average' present worth of the polymer-modified asphalt cement sections is about $ 3800. per lane kilometre less ('cheaper') than the conventional asphalt cement control sections. This reflects the distress surveys that indicate a comparative increased service life of between 4 to 6 years can be expected when using hot-mix asphalt concretes incorporating the polymer-modified asphalt cement. Other important, but less tangible, benefits include reduced road-user delay costs with less rehabilitation closures and improved average ride quality with the longer service life of the polymer-modified asphalt cement sections. These findings are similar to a recent Ontario Ministry of Transportation comparative evaluation of polymer-modified asphalt cements [5]. Based on this type of positive experience, the Ministry will switch existing Ontario asphalt cement requirements to performance graded asphalt binder specifications (SHRP), of which the polymer-modified asphalt cement is a major source, in January 1997 [15].

TABLE 3
Life-Cycle Cost Assumptions.

Pavement Structure Costs ($/lane-km)	
Polymer-Modified Asphalt Cement	$19,800.
Conventional Asphalt Cement	$17,100.
Pavement Rehabilitation Costs ($/lane-km)	
Mill 50 mm and Resurface 50 mm	
Polymer-Modified Asphalt Cement	$26,500.
Conventional Asphalt Cement	$23,750.
Pavement Maintenance Costs ($/lane-km)	
First Maintenance	
Rout and Seal 125 m of Transverse Cracks	
Rout and Seal 125 m of Centreline Cracks	$375.
Second Maintenance	
Rout and Seal 250 m of Transverse Cracks	
Rout and Seal 125 m of Centreline Cracks	$562.50
Third Maintenance	
Mill 40 mm and Patch 40 mm (5% of Area)	$1,312.50
Analysis Period	30 years
Interest Rate	7.5%
Inflation Rate	4.0%

6. CONCLUSIONS

The results of the asphalt pavement monitoring and laboratory testing program strongly suggest that the performance of hot-mix asphalt concrete incorporating the polymer-modified asphalt cement is superior to conventional hot-mix asphalt concrete. While the polymer-modified asphalt cement pavement sections had a higher initial cost than conventional asphalt cement sections, they do have a lower life-cycle cost present-worth value of some $ 3800. per lane kilometre. This lower life-cycle cost more than justifies a higher initial cost polymer-modified asphalt cement pavement investment for long-term benefits such as 4 to 6 years increased service life and reduced road-user impacts.

TABLE 4
Pavement Alternative Life-Cycle Cost Analysis
Site 3 - Highway 401.

4A Polymer-Modified Asphalt Cement

Year	Activity	Initial Cost	Inflation Multiplier (4%)	Inflated Cost	Interest Multiplier (7.5%)	Present Worth of Cost
0	Construction	$19,800	1.000	$19,800.	1.000	$19,800.
10	Rout and Seal	$375	1.480	$555.	0.485	$269.
15	Rout and Seal	$563.	1.801	$1,013.	0.338	$342.
21	Mill and Patch	$1,313.	2.279	$2,991.	0.219	$655.
26	Mill and Overlay	$26,500.	2.772	$73,458.	0.153	$11,202
30	Residual Value	($22,423)	3.243	($72,718)	0.114	($8,304)
					Total Present Worth of Costs	**$23,965.**

4B Conventional Asphalt Cement

Year	Activity	Initial Cost	Inflation Multiplier (4%)	Inflated Cost	Interest Multiplier (7.5%)	Present Worth of Cost
0	Construction	$17,100.	1.000	$17,100.	1.000	$17,100.
5	Rout and Seal	$375.	1.217	$456.	0.697	$318.
9	Rout and Seal	$563.	1.423	$800.	0.522	$418.
15	Mill and Patch	$1,313.	1.801	$2,364.	0.338	$799.
20	Mill and Overlay	$23,750.	2.191	$52,036.	0.235	$12,249
25	Rout and Seal	$365.	2.666	$1,000.	0.164	$164.
30	Residual Value	($11,875.)	3.243	($38,511.)	0.114	($4,398.)
					Total Present Worth of Costs	**$26,650.**

TABLE 5
Life-Cycle Cost Analysis Summary
Total Present Worth of Costs ($/lane-km) - Thirty Year Analysis Period

Site	Roadway	Polymer-Modified Asphalt Cement	Conventional Asphalt Cement	Savings $/lane-km
3	Highway 401	23,965	26,650	2,685.
4	Coldwater Road	28,991	30,603	1,612.
5	Larch Street	38,574	46,138	7,564.
6	Regional Road 57	25,680	29,196	3,516.
			Average	3,844.

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