PERFORMANCE PREDICTION AND ECONOMIC ANALYSIS OF PERPETUAL AND CONVENTIONAL PAVEMENT DESIGNS USING MECHANISTIC EMPIRICAL MODELS

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ABSTRACT

This paper examines the structural aspects and economics of a perpetual asphalt pavement design verses conventional asphalt pavement designs. The pavement design in this paper was performed using AASHTO-DARWin 3.1 Software. Design inputs for both pavement types were identical as the ESAL, subgrade properties and environmental parameters. The structural analysis was implemented using two multilayer elastic analysis software programs. ELSYM 5 and WESLEA for Windows 3.0 were used to predict the structural performance of both pavement designs.

A performance model was developed with the Mechanistic-Empirical Pavement Design Guide (MEPDG) software version 1.003 for the two pavement designs. The performance model results showed that a perpetual design can overcome several problems that will cause structural distresses in the conventional design such as Bottom-up cracking, fatigue cracking and rutting.

Life Cycle Cost Analysis (LCCA) was performed on both designs. Maintenance and rehabilitation cost was predicted based on the structural performance model results that was determined by MEPDG and the maintenance and rehabilitation programs recommended for similar pavement designs by the Ministry of Transportation of Ontario (MTO). It was also compared with other data available in the literature. The overall Net Present Value of both designs showed that the perpetual pavement is a better economic alternative compared to the conventional pavement design.

RÉSUMÉ

Abstracts provided in English will be translated to French and vice versa.

1.0 INTRODUCTION

This paper presents the structural, technical and economic evaluation of the two pavement designs: conventional and perpetual pavements. In addition, it shows that user delay costs can be reduced by using long life perpetual asphalt pavement designs as they reduce future maintenance and rehabilitation delays.

Structural, technical and economic evaluations of the conventional asphalt pavement and the perpetual asphalt pavement sections were performed by utilizing MEPDG software, ELSYM 5 software, WESLEA for Windows 3.0 and Life Cycle Cost Analysis (LCCA) work sheets. This work represents part of a massive research project aiming to evaluate the perpetual pavement design benefits in comparison to the conventional designs considering several road categories (based on the traffic volume), subgrade quality and various environmental and materials used characteristics. This paper will address the benefits of constructing perpetual pavement design on a moderate traffic highway. The traffic data was determined from the Ministry of Transportation of Ontario (MTO) 2005 Provincial Highways Annual Average Daily Traffic (AADT) [1]. The stresses, strains and pavement deflections were calculated at the layers' interface (top and bottom of each pavement layer) and at the pavement surface of both pavement types using ELSYM 5 and WESLEA for Windows 3.0 programs.

AASHTO 1993 Pavement Design method was used to design and determine the pavement layer thickness for each pavement type. ASHTO-DARWin 3.1 software was implemented in the design process. A thirty year design period was assumed in the design process. This is the typical design period used by the Ministry of Transportation of Ontario in most pavement design operations. The conventional pavement consists of typical asphalt layers on top of granular base and subbase layers on top of the compacted subgrade soils; while, the perpetual pavement consists of all asphalt layers on top of the compacted subgrade soils. All parameters affecting the design of both pavement sections were assumed to be identical in order to ensure consistency in the pavement design stage. The ESAL, design reliability, standard deviation, serviceability index and the subgrade resilient modulus were assumed to be identical in the design of both pavement types.

All physical and mechanical properties of all pavement layers (e.g. modulus of elasticity and Poisson's ratio) were based on a comprehensive literature review of Hot Mixture Asphalt (HMA) dynamic modulus data obtained from the FHWA Design Guide Implementation Team (DGIT), as well as other published resilient and dynamic modulus test data from different sources. All modulus of elasticity values selected for these designs were typical of those obtained by the Ministry of Transportation in Ontario (MTO).

The equivalent single axle loads (ESAL) values were calculated using the traffic data determined from the MTO 2005 Annual Average Daily Traffic report. The subgrade resilient modulus design values were assumed based on the typical values used by MTO for projects on HWY 6 in the Waterloo, Ontario region. The typical elastic modulus values of the MTO were used for the ELSYM 5 to calculate and compare the mechanistic properties (stresses, strains and deflections) of both pavement types.

2.0 BACKGROUND

The primary benefit gained by using the perpetual asphalt pavement designs is that they require only replacement of the top asphalt layers (wearing – or surface - course, or combined top two layers, surface and intermediate course, up to 150 mm) during its in-service life. This structural rehabilitation process is required to maintain a safe and functional performance level and to minimize the top-down cracking potential that may develop on the top pavement layers. The pavement performance models should take into account the role of the lower layers in perpetual pavements which are designed to resist both fatigue cracking and rutting in the long term. Overall, the durable bottom asphalt layers will last throughout the life cycle.

What makes perpetual pavement expected lifetime last for 50 years or even longer is the ability to design each layer to resist a specific mode of distresses. The very lowest base layer is typically produced as a Rich Bottom Mix (RBM) layer i.e. having higher asphalt binder content; usually 0.5 to 0.7% above optimum asphalt content, resulting in reduced tensile strains at the bottom of the asphalt layers. In addition, low level of air-void is essential in this layer ensures high density and maximum fatigue resistance of asphalt layer. Typical air-void levels in the rich bottom mix layer are three to four percent and should not exceed six percent [2]. In addition to all previous design constraints, the total pavement thickness is vital in resisting bottom-up fatigue cracking.

Tensile strains at the bottom of the asphalt layers and vertical compressive strains at the top of the subgrade layer are the two key factors affecting the pavement in-service performance life. If tensile strain value at the bottom of the asphalt pavement is controlled to less than 70 microstrains, this will decrease the ability of bottom-up crack initiation and propagation. Limiting the vertical compressive strain values to 200 microstrain has its significant effect on eliminating the subgrade rutting or structural rutting [3, 4, 5, 6]. The selection of appropriate layer thickness recommended at three to four times nominal maximum aggregate size (NMAZ) and appropriate Performance Grade asphalt binder (PG) grade reduces the need of replacement and reconstruction costs of roadways [7].

3.0 STRUCTURAL PAVEMENT DESIGN

3.1 Perpetual Pavements

Over the last few decades, an evolution in pavement materials quality and characterization has taken place due to intensive research work implemented on paving materials. Being able to specify the physical and mechanical features in each pavement layer results in the ability to address specific stresses or deformations that are expected in each of the layers. The perpetual pavement concept was built on designing thick asphalt layers over a strong foundation (subgrade) with at least three Hot Mix Asphalt (HMA) layers.

3.1.1 HMA Base Layers/Lower Binder

Fatigue resistance and bottom-up cracking prevention are the main stresses being addressed by this layer. Increasing the tensile strength of the base layer to overcome the tensile strain generated by the traffic loads can be accomplished by increasing the binder content and decreasing the in-place air void percentage. Thus, creating high density asphalt layer was reported to improve the fatigue cracking resistance and bottom-up cracking [5, 6]. In addition, the total pavement thickness plays a vital role in decreasing the tensile strain generated at the bottom of the asphalt layer by distributing the traffic loads over a larger area. One or more base layers can be used in perpetual pavements based on the total pavement thickness required and the traffic loads.

3.1.2 Intermediate/Upper Binder Layers

This layer should be characterized by the stability and durability in order to achieve the rutting and fatigue potential resistance. The rutting resistance is accomplished by the stone-on-stone contact design, while the fatigue resistance is usually accomplished by the appropriate mixtures design, target proper field compaction levels and selecting appropriate asphalt binder grade. Selecting the appropriate asphalt binder with a suitable high-low-temperature grade is an essential requirement for long-term performance of this layer. This layer is primarily responsible for withstanding the repeated traffic loads expected over the pavement's service life. Similarly, depending on the total pavement thickness one or more intermediate layer can be constructed.

3.1.3 Wearing/Surface Layer

Resisting top-down cracking, surface initiated distresses and rutting of pavement upper layers (100 mm) to prevent permanent deformation in the pavement surface are the main objectives for the surface layer. The most effective material to be used for this layer is the Stone Mastic Asphalt (SMA). High quality Performance Grade (PG) should also be selected to withstand the traffic and weather conditions. In-place air void content is recommended in the range of four to six percent to ensure proper layer stiffness and durability [8].

3.1.4 Subgrade Characteristics and Strength

Subgrade soil properties as characterized by soil resilient modulus, bearing capacity, and shrink-swell as well as frost susceptibility potential are strongly affecting the total perpetual pavement thickness and individual layer properties. The minimum soil resilient modulus recommended for perpetual pavement construction is 25,000 psi [9]. However, most subgarde soils have much lower moduli of that recommended in the literature. Both mechanical and chemical soil stabilization techniques can be utilized to accomplish higher subgrade resilient modulus values. Expansive and frost susceptible soils should be replaced by high quality granular materials and/or mechanically or chemically stabilized using lime, cement and/or fly ash before construction. Soil stabilization depth (150 mm to 600 mm) should be function of both existing soil conditions and expected traffic loadings.

3.2 Conventional Flexible Pavement Design

Conventional asphalt pavement sections constructed on this rural highway consists of Hot Mix Asphalt (HMA) layers on top of granular base and subbase layers. This pavement section is usually constructed on top of naturally compacted subgrade soil unless soil stabilization or reinforcement is needed. The Hot Mix Asphalt (HMA) layers are characterized by their higher stiffness compared to the granular material used in construction of the base and subbase layers. The typical structural design results in a series of layers that gradually decrease in the material quality and stiffness with depth. This fact is reflected by comparing the resilient or dynamic modulus values of the Hot Mix Asphalts (HMA) to that of the granular material or the subgrade resilient modulus. Yet, it is still economically important to incorporate the granular material layers as they contribute to the overall pavement strength, drainage and frost protection, as well as providing protection of the subgrade soils.

The surface course is the layer in contact with traffic loads and normally contains the highest quality materials. It provides characteristics such as friction, smoothness, noise control, rut and shoving resistance and drainage resistance. It also prevents the excessive moisture and free water to penetrate the pavement structure. The top surface "structural" layer is sometimes subdivided into two main layers.

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3.2.1 Wearing/Surface Layer

This layer should be capable of withstanding the traffic loads, rutting, shoving and environmental impacts. It should be frequently rehabilitated and maintained in a proper way to avoid the propagation of top-down cracks and/or distresses to the asphalt layers. A properly designed and funded preservation program is essential to protect this layer. Otherwise, this layer will be subjected to different distresses leading to the removal and replacement of it and perhaps the following asphalt sections before the end of the design life time.

3.2.2 Intermediate/Binder and Base Layers

This layer, in addition to the base layer, provides the bulk of the HMA structure and is designed to distribute traffic loads; while the base course is immediately beneath the intermediate course. It provides additional load distribution and contributes to drainage and frost resistance. Base courses are usually constructed out of durable aggregates that will not be damaged by moisture, repeated traffic loading or frost action.

4.0 ESAL CALCULATIONS FOR THE AASHTO 1993 PAVEMENT DESIGN

Calculation of the Equivalent Single Axle Load (ESAL) was obtained using the procedure highlighted in the AASHTO 1993 Pavement Design Guide software (DARWin 3.1). The target of this project is to evaluate the structural and economical benefits of perpetual pavement designs compared to the conventional flexible pavement designs when addressing medium traffic country roads. As a representative of moderate rural road highway (in this case highway 6), an average traffic volume was chosen from the data published by the Ministry of Transportation of Ontario (MTO) [1]. The provincial Average Annual Daily Traffic (AADT) report published by the Ministry of Transportation of Ontario (MTO) included detailed information about the traffic volumes on different sections of a representative rural highway. An average value that represents most of the sections was chosen for the pavement cross section design in this research project. Some inputs were assumed based on typical values used by MTO in pavement design procedures [10]. The two-way Average Annual Daily Traffic (AADT) is 17,000; the percentage of heavy trucks of the AADT is 20% and number of lanes is two per direction; and the percent of all trucks in design lane is 80% while percent of trucks in the design direction is 50%. The initial truck factor is assumed to 1.2 and the annual truck volume growth rate is 2%. Subgrade resilient modulus value was one of the key assumptions during the design of both pavement sections. It was assumed to be 55,000 Kpa (8000 psi) based on the MTO soil investigation reports for this area.

5.0 AASHTO PAVEMENT DESIGN

The same software (DARwin 3.1) was used to perform the structural design of the two pavement types, namely conventional asphalt pavement and perpetual asphalt pavement. The AASHTO 1993 structural design of the two pavement categories result is as presented in figure 1.

The conventional asphalt pavement resulted in the following layers:

- 40 mm (1.5”) hot-mix asphalt surface layer, 80 mm (3.0”) hot-mix asphalt intermediate layer, 100 mm (4.0”) hot-mix asphalt base layer, 100 mm (4.0”) high-quality aggregate base layer and 180 mm (7.0”) high-quality aggregate subbase layer.

While, the perpetual asphalt pavement resulted in the following layers:

- 50 mm (1.6") surface layer of Superpave or SMA 12.5 mm, 90 mm (3.5") intermediate layer of superpave or SMA 19 mm and 120 mm (5.0") of rich bottom mix layer followed by 150 mm (6.0") of open graded drainage layer.

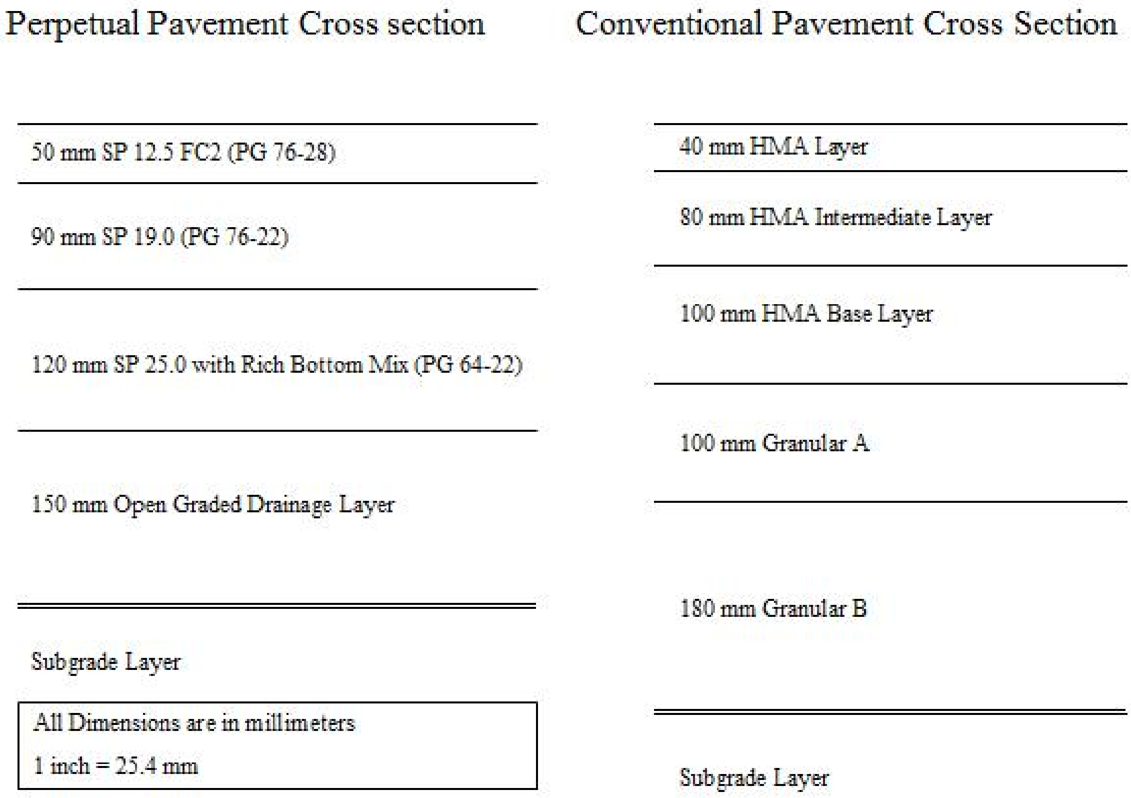

Figure 1 Pavement Cross Section

Figure 1 shows the pavement cross section of the conventional asphalt pavement and the perpetual asphalt pavement, respectively, including proposed asphalt mix types. The elastic modulus of each layer was selected, for subsequent analysis, based on literature search of actual dynamic modulus tests and data performed by the FHWA-DGIT team and other sources. The selected value for each asphalt layer is 750000 psi, 700000 psi and 550000 psi at 20°C for the PG 76-28, PG 76-22 and PG 64-22 respectively. The database of the FHWA-DGIT team shows the dynamic modulus test results at different test temperature and frequencies as specified by the requirements of the dynamic modulus test standards. In addition, the dynamic modulus test results are shown for different mixture types and different asphalt performance grades (PG).

6.0 MECHANISTIC EVALUATION OF CONVENTIONAL AND PERPETUAL PAVEMENTS

Stresses, strains and deflections were calculated for both pavement designs using two mechanistic-empirical multilayer simulation programs. ELSYM 5 and WESLEA for windows version 3.0 are well known software programs to evaluate the pavement sections performance. ELSYM 5 was developed by Gale Ahlborn of the Institute of Transportation and Traffic Engineering (ITTE) at the University of California at Berkeley in 1986 [11]. Over the last two decades, ELSYM 5 was implemented in several pavement research projects and several updates were included to the software to enhance its functionality and accuracy. In addition, WESLEA for Windows software was used to confirm the mechanistic model results. WESLEA software was developed by David H. Timm, Bjorn, Birgisson and Dave Newcomb in 1999 [12]. This software gained sound reputation through several flexible pavement evaluation research projects. Evaluation models were created using the pavement design cross section results obtained by the AASHTO- DARWin 3.1 software and the data provided by the FHWA- DGIT research members. The numerical models developed for both programs were identical to assure the consistency of the evaluation process. A single dual tire loading was assumed and used for the analysis. The evaluation points were selected to be just under the wheel path and in the mid point between the two wheels of the single axle loading conditions.

6.1 MODEL RESULTS

The normal strain results of both mechanistic evaluation softwares are shown for the perpetual asphalt pavement and conventional asphalt pavements, respectively. The deflection results at different layer interfaces for both pavements are also presented.

6.1.1 Normal Strain

Figure 2 shows that the normal strains of the perpetual pavement section are in compression for the top layers and as the depth increases the strain values are transferred to tension. In order for the pavement to be considered “perpetual” the strain at the bottom of the asphalt layers i.e. at bottom of the “Rich Bottom Mix” (RBM) layer should not exceed 70 micro strains [13]. As shown in Figure 2, the strain at the bottom of the RBM layer is less than 70 µs. This strain value is believed to limit the initiation and propagation of bottom-up cracks. The normal strain values considered through the pavement analysis was that in the Y-axis direction (perpendicular to road longitudinal axis). The reason for presenting the strain values in this direction is that it was deduced from the results of both software programs and previous research work that the strain value in the Y-axis direction is always greater than that corresponding to the X-axis (road longitudinal axis). Thus, the critical strain values that should cause initiation of cracks are expected to be that in the Y-axis direction. The results of both numerical models in normal strain values were noticed to be almost identical. The similarity in model results of the two softwares confirms the model creation. In addition the results of the two models are accepted when analyzed and compared to other results obtained through previous similar research projects.

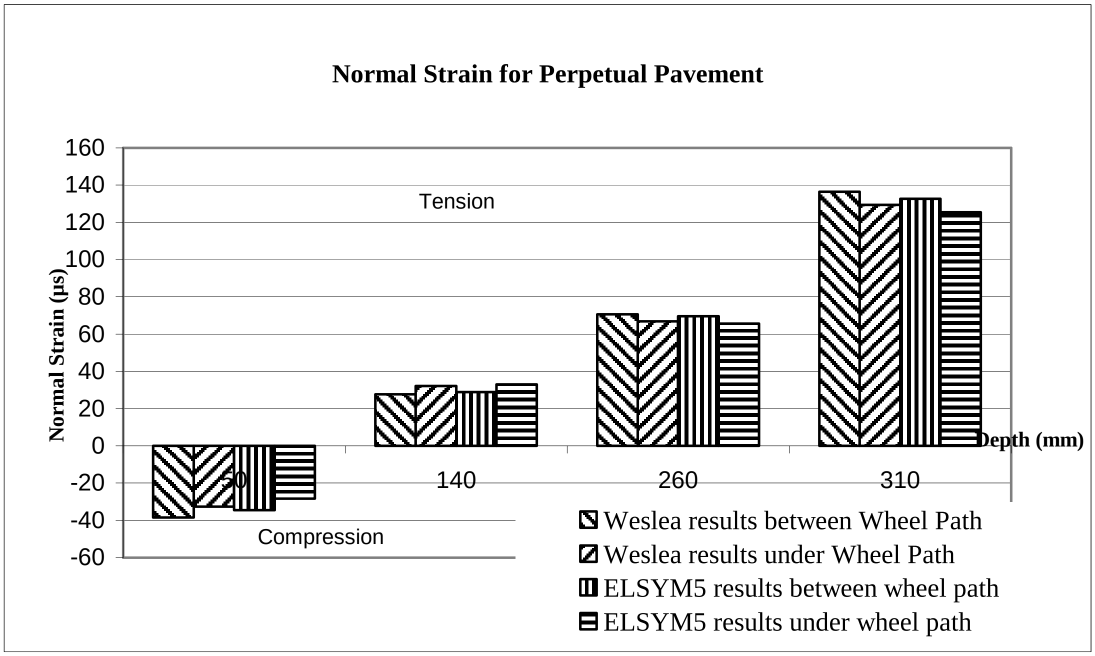

Figure 2 Normal Strain Results for Perpetual Pavement

On the other hand, the normal strain results (Figure 3) for the conventional asphalt pavement shows that the strain values are higher in all layers compared to those of perpetual pavement. The strain value at the bottom of the asphalt layer is exceeding 200 microstrains. This assures the conventional section will be subjected to bottom-up fatigue cracking and will deteriorate at a rapid rate.

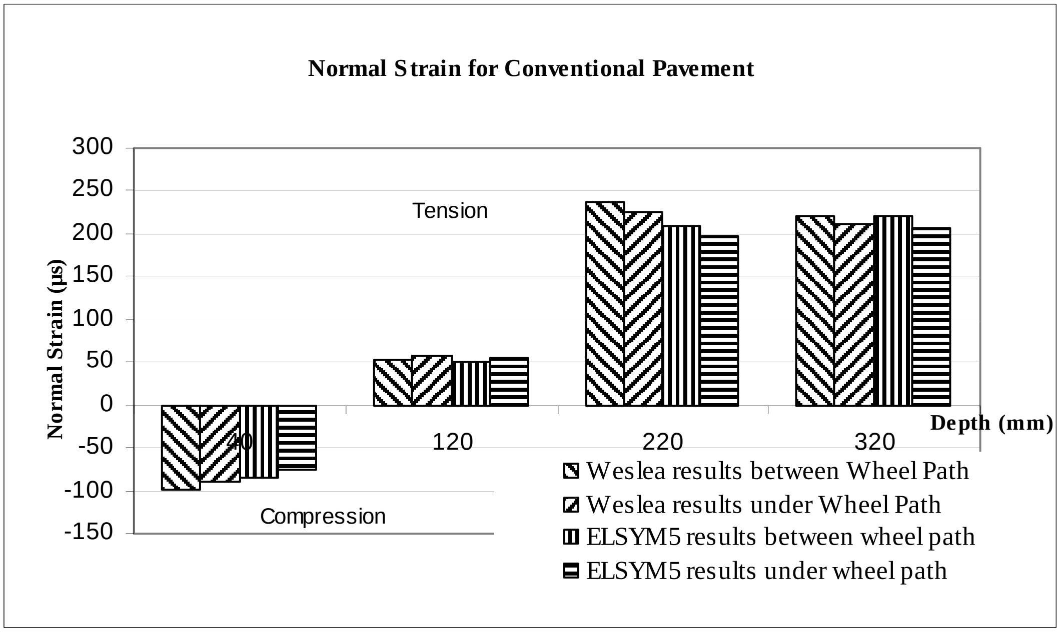

Figure 3 Normal Strain Results for Conventional Pavement

6.1.2 Displacement

Deflections (vertical displacements) values of the two pavement structures are shown in Figure 4 and Figure 5, respectively. The displacement values decrease as the depth increases in the two pavement types. The deflection values show that conventional asphalt pavement will suffer higher deflection values compared to the perpetual asphalt pavement. In addition, there is a significant difference in deflection values under the wheel path and between wheel paths in the conventional design model. This shows that this pavement section may be subjected to more severe rutting due to the difference in deflection values in each layer.

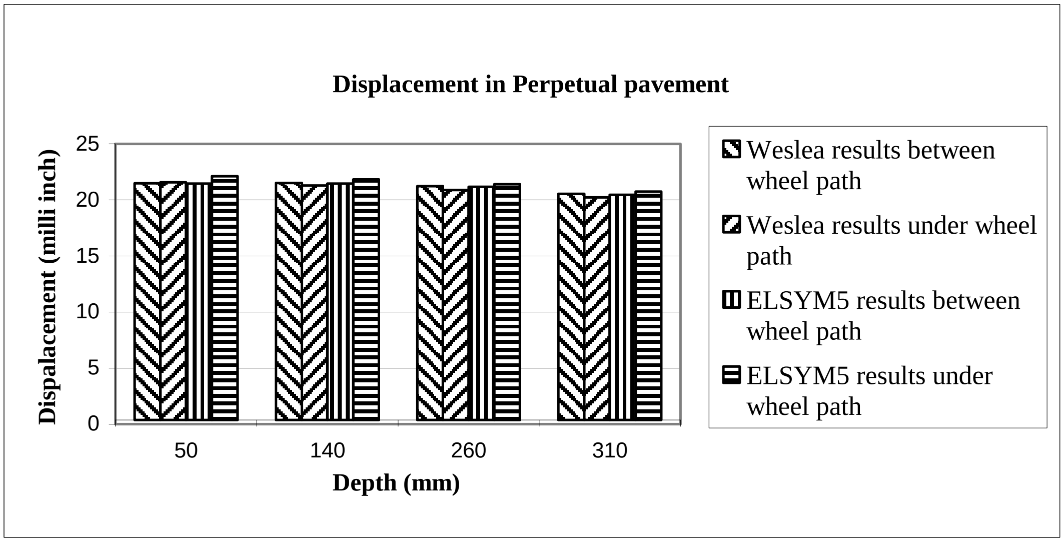

Figure 4 Displacements in Perpetual Pavement

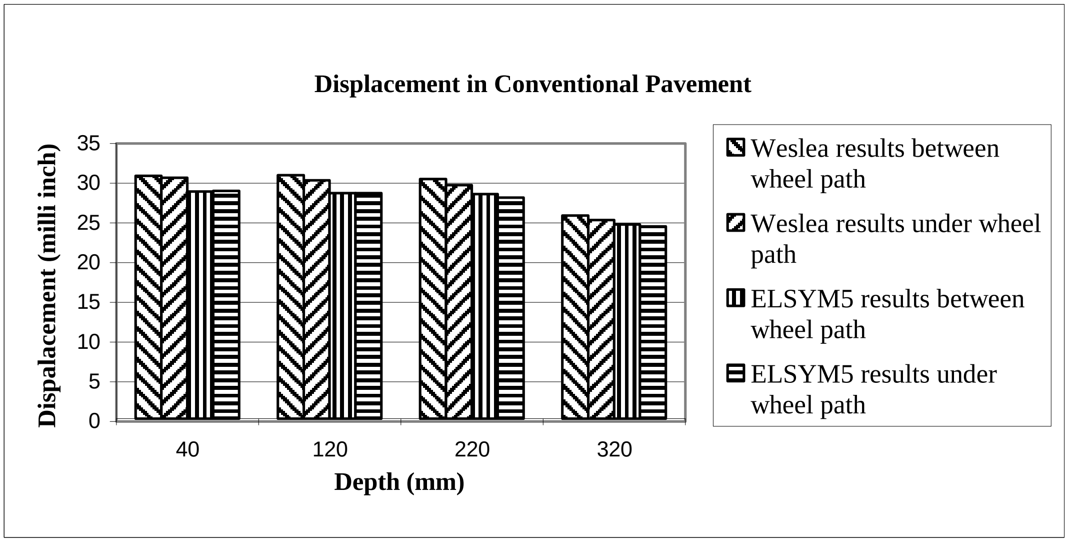

Figure 5 Displacements in Conventional Pavement

7.0 MEPDG MODEL

From Mechanistic Empirical Pavement Design Guide (MEPDG) software model was used to evaluate both of the pavement designs. MEPDG software is characterized by its ability to predict the pavement performance in terms of distress types. The MEPDG software outputs include: top-down cracking, bottom up cracking, thermal cracking, rutting and IRI values expected through the analysis time. The evaluation of both pavement structures assumed an analysis period of 50 years. A summary of the MEPDG inputs for the perpetual and conventional pavement are presented in tables 1 and 2 respectively.

As built volumetric properties such as voids in mineral aggregate (VMA), percentage of air voids, percentage of volumetric binder content and total unit weight were assumed in this model based on intensive literature review of typical values used by typical mixes produced by the Ministry of Transportation of Ontario (MTO) [14, 15].

Table 1 MEPDG Input Data for the Perpetual Pavement Design

Layer 1		**Layer 3**	
Thickness (mm)	50	Thickness (mm)	120
PG	PG 76-28	PG	PG 64-22
Volumetric Properties as Built		Volumetric Properties as Built	
Mixture VMA (%)	18	Mixture VMA (%)	18
Air Voids (%)	5	Air voids (%)	3
Volumetric Binder Content (%)	13	Volumetric Binder Content (%)	14
Total Unit Weight (pcf)	153	Total Unit Weight (pcf)	152
Layer 2		**Layer 4**	
Thickness (mm)	90	Thickness (mm)	150
PG	PG 76-22	Open Graded Drainage Layer	
Volumetric Properties as Built		Volumetric Properties as Built	
Mixture VMA (%)	17	Total Unit Weight (pcf)	150
Air voids (%)	5	Poisson’s ratio	0.35
Volumetric Binder Content (%)	12	Elastic/Resilient Modulus (psi)	200000
Total Unit Weight (pcf)	151	Thermal Conductivity (BTU/hr-ft-F°)	1.25

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Table 2 MEPDG Input Data for Conventional Pavement Design

Layer 1		**Layer 3**	
Thickness (mm)	40	Thickness (mm)	100
PG	PG 76-22	PG	PG 64-22
Volumetric Properties as Built		Volumetric Properties as Built	
Mixture VMA (%)	18	Mixture VMA (%)	18
Air Voids (%):	5	Air Voids (%):	3
Volumetric Binder Content (%):	13	Volumetric Binder Content (%):	14
Total Unit Weight (pcf):	153	Total Unit Weight (pcf):	152
Layer 2		**Layer 4**	
Thickness (mm)	80	Thickness (mm)	100
PG	PG 76-22	Aggregate Base Layer	
Volumetric Properties as Built		Maximum Dry Unit Weight (pcf)	127.7
Mixture VMA (%)	17	Specific Gravity of Solids, Gs	2.7
Air Voids (%):	5	Saturated Hydraulic Conductivity (ft/hr)	0.05054
Volumetric Binder Content (%):	12	Optimum Gravimetric Water Content (%)	7.4
Total Unit Weight (pcf):	151	Calculated Degree of Saturation (%)	62.2

Layer 5	
Thickness (mm)	180
Aggregate Subbase Layer	
Maximum Dry Unit Weight (pcf)	127.7
Specific Gravity of Solids, Gs	2.7
Saturated Hydraulic Conductivity (ft/hr)	0.05054
Optimum Gravimetric Water Content (%)	7.4
Calculated Degree of Saturation (%)	62.2

7.1 MEPDG Pavement Performance Prediction Results

In general, all the MEPDG results show a superior performance prediction for the perpetual pavement structure over the more traditional conventional pavement structure.

The MEPDG analysis predicted that top down cracking for the perpetual pavement design will be minimal to that of the conventional design. This shows that the actual top/down crack propagation is less likely to occur in the perpetual pavement structure compared to conventional asphalt pavement structure. It is important to reiterate that both pavements were designed for a 30 year design period and to emphasize that the top asphalt layers are typically replaced every 10 to 20 years. The results of the surface/down cracking model are not accurate for either the conventional or perpetual pavement. The MEPDG runs were repeated with slightly different inputs for several times and the data inputs were double checked but the results were almost identical. This may be due to some form of error in the MEPDG surface/down software model. Overall, this result reflects only the performance trend of the two pavement designs.

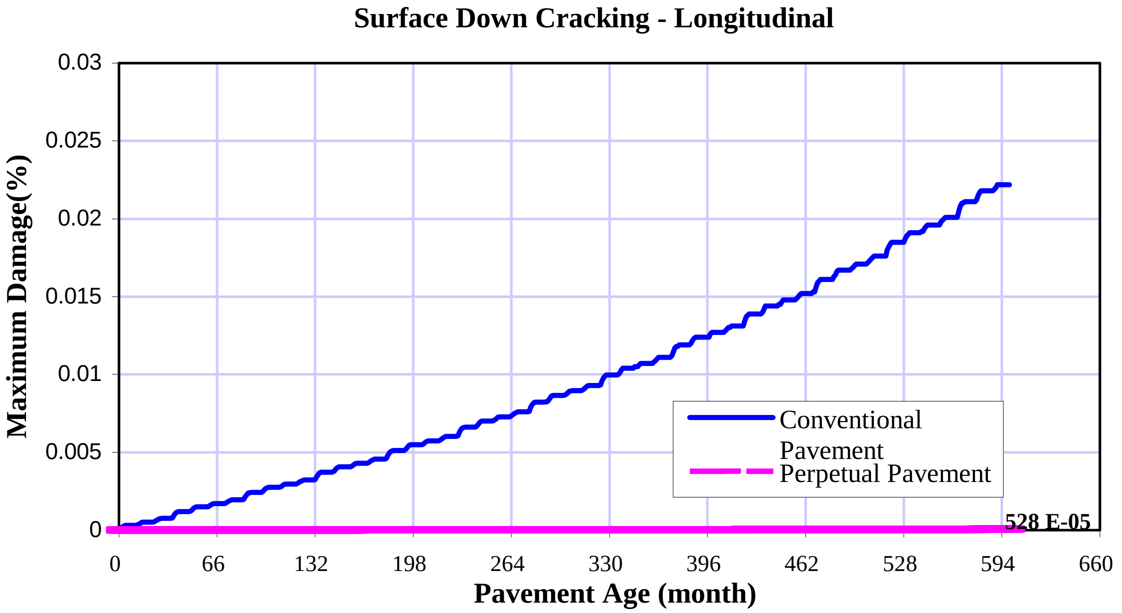

Figure 6 Surface Down Cracking Damage Percentage

The main benefit of the perpetual pavement design is that bottom-up fatigue cracking is reduced. This goal is achieved through using a Rich Bottom Mix (RBM) asphalt layer at the bottom of the asphalt layers. Figure 7 presents the expected performance of both pavement designs and it can be deduced that the perpetual pavement is capable of resisting the bottom-up fatigue cracking phenomenon for even longer than the 50 year analysis period. On the other hand, conventional pavement design shows a more rapid deterioration and bottom-up crack propagation in comparison to the perpetual pavement design would result in rehabilitation of the asphalt layers every 30 years approximately.

Permanent deformation prediction for both pavement designs is presented in Figure 8. The conventional pavement design is showing severe total rutting which includes rutting in both the asphalt and base/subbase layers. While the rutting value at the bottom of the asphalt layers in both pavement designs is relatively close, there is a great difference between the total rutting values in the two pavement designs. This shows the effect of constructing relatively thick asphalt layer with Rich Bottom Mix (RBM) over a soil subgrade. It is believed that this construction methodology is leading to a better rutting resistant pavement section compared to the conventional construction methodology which is placing the asphalt layers over a granular base and subbase layers. It is important to emphasize that upper pavement layers are usually replaced in 10-20 years cycles. This maintenance activity is capable of treating the surface rutting in both pavement designs.

Figure 9 presents the IRI expected value over the 50 year analysis period of the MEPDG model. IRI values for perpetual pavement design is slightly better than that of the conventional design. The two pavements are expected to exceed the maximum design limit for IRI, before the end of the analysis period. It is important to mention that usually pavement surfaces are usually replaced in 10 to 20 year cycles. This process improves the IRI values and restores the functional performance of the pavement structure.

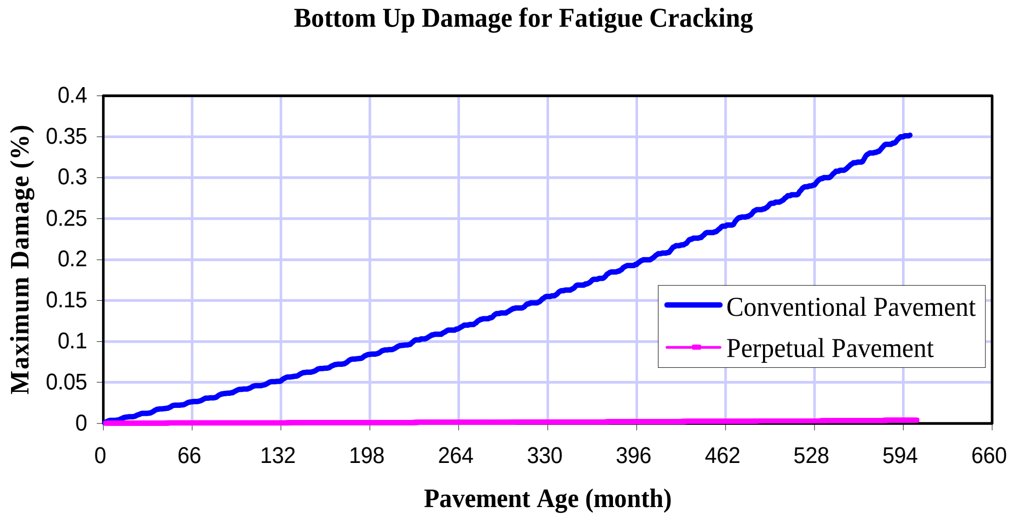

Figure 7 Bottom Up Damage for Fatigue Cracking

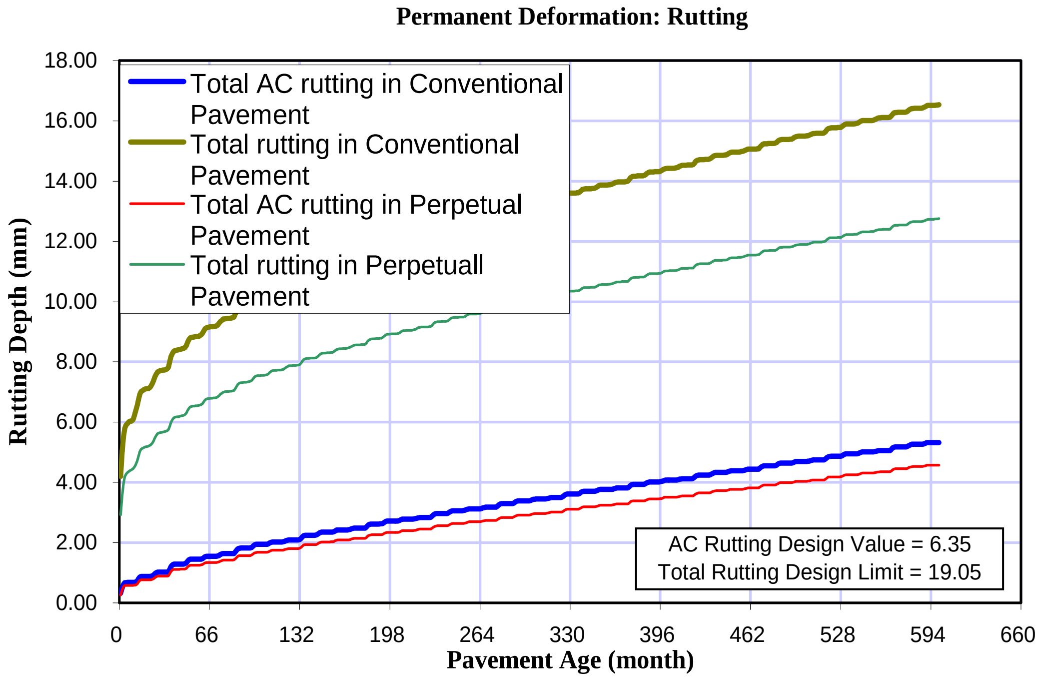

Figure 8 Total and AC Rutting

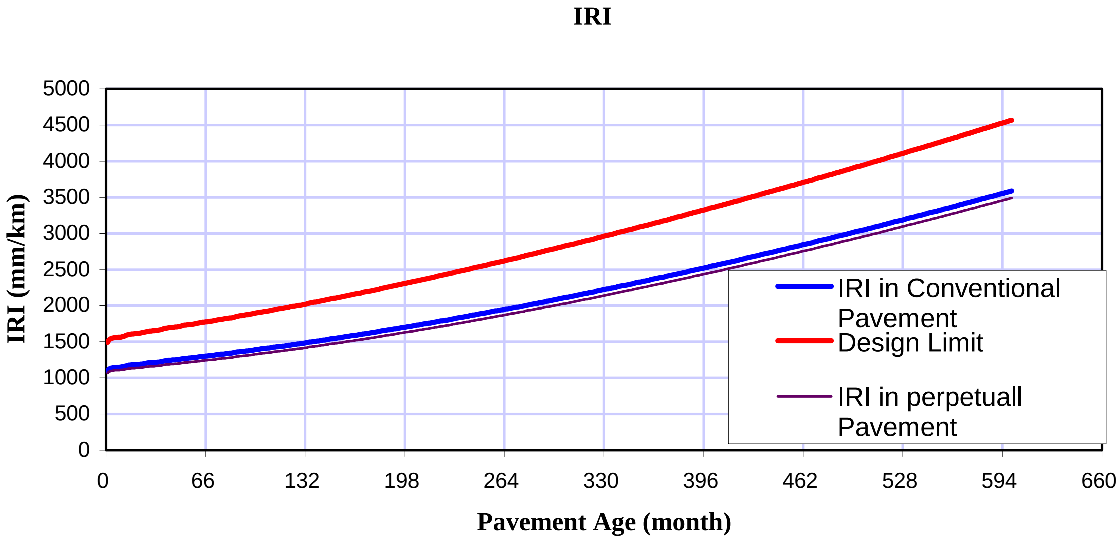

Figure 9 IRI Values

In Summary, all the MEPDG performance prediction results show that the perpetual pavement is structurally performing in much a much better way than the conventional pavement. In addition, based on the MEPDG performance prediction results, the in-service life of the perpetual pavement is expected to meet and exceed the 50 year analysis period.

8.0 LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis (LCCA) was also performed to evaluate the two design methods. Superior pavement performance predictions supported by reasonable economic analysis is essential to justify any capital investment.

It is important to highlight that the life cycle cost analysis (LCCA) procedure will be performed under the following assumptions:

1. Best possible unit cost estimates for pavement material, maintenance and rehabilitation, and labor in Ontario are obtained through the Ministry of Transportation of Ontario (MTO). The final life cycle cost analysis reports submitted to MTO in 1998 and 2006 were used for estimating the material, maintenance and rehabilitation costs [16, 17]. However if necessary, some unit costs were assumed based on national averages.

2. The LCCA evaluation period is proposed to be 70 years for the two pavement design alternatives.

3. Preventative maintenance, scheduled maintenance, and/or rehabilitation treatments were assumed based on the recommendations of the MTO reports.

4. Inflation costs per treatment and/or maintenance activities are not used and are assumed constant between different rehabilitation options. This is a common practice that is mostly used in LCCA.

5. LCCA was conducted at several discount rates; LCCA are conducted at 3%, 4% and 5%.

6. Initial construction costs will include labor and materials’ costs associated with the constructions of the pavement structure.

7. User delay costs during different maintenance and rehabilitation activities were not taken into account in this LCCA due to the lack of sufficient data and to simplify the LCCA calculation.

It is also important to emphasize the following additional LCCA assumptions:

1. The cost of construction at year zero was based on the unit cost item per ton. The material weight was determined by assuming a unit length of 1 km and road width of 15.0m (2 lanes per direction, each of 3.75m width), the thickness of each layer was previously presented in Figure 1. Multiplying every layer’s volume in cubic meters by the material’s density in ton/m3, we can determine the weight needed to pave 1 km of the road.

2. Material costs assumed based on the 1998 LCCA Ontario report, were modified as a result of the inflation rate and price changes: equation 1 was used to modify the material costs: inflation rate was assumed to be 3%.

$$\Pr esent \quad \cos t = Cost \quad at \quad 1998 \times \left(1 + r\right)^n \qquad \text{(Eq. 1)}$$

Where

r = Inflation rate (3%)

n = Number of years between the year at which data was collected and the present (10 years)

3. Longitudinal cracks were assumed to have developed along the joints and/or at both lane edges. While; transverse cracks were assumed to have developed at each 90 m edge to edge.

4. The cost of mill and overlay was based on the unit cost per square meter and the area expected to be overlaid.

5. The salvage value was assumed to be 20% of the total pavement cost for conventional asphalt concrete and for the full depth perpetual pavement.

The construction costs of a conventional asphalt pavement and a perpetual asphalt pavement are presented in tables 3 and 4 respectively.

Table 3 Construction Cost Calculation of Conventional Asphalt Pavement

Length (m)	(40 mm) Dense Friction Course Density = 2.7 t/m^3	(80mm) Heavy Duty Binder Course Density = 2.45 t/m^3	(100 mm) HMA Base HL-8 Density = 2.45 t/m^3	(100 mm) Granular A Density = 3.12 t/m^3	(180 mm) Granular B Density = 2.05 t/m^3	SUM
1,000	**\$113,400**	**\$152,880**	**\$176,400**	**\$79,560**	**\$55,350**	**\$577,590**
1,000	**\$113,400**	**\$152,880**	**\$176,400**	**\$79,560**	**\$55,350**	**\$577,590**
					Avg	**\$577,590**
					SUM	**\$1,155,180**

Table 4 Construction Cost Calculation of Perpetual Asphalt Pavement

Length (m)	(50 mm) Superpave 12.5 FC 2 Density = 2.56 t/m^3	(90 mm) Superpave 19 Density = 2.41 t/m^3	(120 mm) Superpave 25 Density = 2.34 t/m^3	(180 mm) Open Graded Drainage Layer	SUM
1,000	**\$203,520**	**\$253,773**	**\$248,508**	**\$84,964**	**\$790,765**
1,000	**\$203,520**	**\$253,773**	**\$248,508**	**\$84,964**	**\$790,765**
				Avg	**\$790,765**
				Sum	**\$1,581,530**

The Life Cycle Cost Analysis (LCCA) model was performed using the Stantec LCCA program. Tables 5 and 6 presents the maintenance and rehabilitation schedule for both conventional asphalt and perpetual pavements, respectively.

TABLE 5 Maintenance Schedule of a Conventional Pavement

Maintenance Activity	Year
Rout and Crack Sealing (352 m/km)	4
Rout and Crack Sealing (352 m/km)	7
Rout and Crack Sealing (352 m/km)	10
5% Mill and Patch 50 mm	10
Rout and Crack Sealing (704 m/km)	14
20% Mill and Patch 50 mm	18
Rout and Crack Sealing (704 m/km)	21
Tack Coat	25
Mill 50 mm Asphalt Pavement	26
Superpave 12.5 FC2 - 50 mm	26
Rout and Crack Sealing (352 m/km)	29
Rout and Crack Sealing (352 m/km)	33
Rout and Crack Sealing (352 m/km)	35
20% Mill and Patch 50 mm	37
Partial Reconstruction of Pavement	40
Rout and Crack Sealing (352 m/km)	44
Rout and Crack Sealing (352 m/km)	47
Rout and Crack Sealing (352 m/km)	50
5% Mill and Patch 50 mm	50
Rout and Crack Sealing (704 m/km)	54
20% Mill and Patch 50 mm	58
Rout and Crack Sealing (704 m/km)	61
Tack Coat	65
Mill 50 mm Asphalt Pavement	66
Superpave 12.5 FC2 - 50 mm	66
Rout and Crack Sealing (352 m/km)	69

TABLE 6 Maintenance Schedule of a Perpetual Pavement

Maintenance Activity	Year
Rout and Crack Sealing (280m/km)	5
Rout and Crack Sealing (280m/km)	10
3% Mill and Patch 40 mm	14
Rout and Crack Sealing (560m/km)	18
15% Mill and Patch 40 mm	22
Mill 50mm Asphalt pavement	27
SMA- 50 mm	27
Tack Coat	27
Rout and Crack Sealing (280m/km)	32
Rout and Crack Sealing (280m/km)	37
15% Mill and Patch 40 mm	41
Rout and Crack Sealing (560m/km)	45
Mill 50mm Asphalt Pavement	50
SMA- 50 mm	50
Tack Coat	50
Rout and Crack Sealing (280m/km)	55
Rout and Crack Sealing (280m/km)	60
15% Mill and Patch 40 mm	64
Rout and Crack Sealing (560m/km)	68

The LCCA total Net Present Value (NPV) of a perpetual pavement is calculated using 3%, 4% and 5% discount rates, for an analysis period of 70 years. The deterministic NPV results were $2,197,039, $2,035,463 and $1,919,548 respectively. While the LCCA total NPV cost results of the conventional pavements were $2,902,167, $2,376,661 and $2,022,611 respectively for the same discount rates. The LCCA results show the perpetual asphalt pavement is more cost effective over the life cycle. Although the construction costs of the perpetual pavement design is expected to be 37 percent more expensive compared to the conventional design, the overall LCCA NPV costs of the perpetual pavement is lower than that of the conventional design by 5.4 percent. However if user delay costs are included, the difference would be closer to 30 percent. The main reason for this is believed to be the partial reconstruction of conventional design that is scheduled on year 40. This partial reconstruction activity projects a reconstruction of the asphalt layers (surface HMA, intermediate HMA and HMA base layers). The alternative to this partial reconstruction activity is usually a thick asphalt overlay to increase the pavement thickness. Based on the structural and economic evaluation of both alternatives, the overlay solution will overcome some structural deformations but it will not be able to treat the bottom-up cracks. These cracks will continue to propagate due to load repetitions and frost-thaw cycles and the pavement deterioration after the overlay is expected to be faster than the partial reconstruction alternative. Thus the partial reconstruction rehabilitation treatment alternative is expected to be more cost effectively in the long run.

9.0 CONCLUSION

The results and analysis of the ELSYM 5, WESLEA for Windows, MEPDG and LCCA presented in this paper allow the following conservative conclusions to be made.

1. Conventional pavement design is expected to be subjected to higher fatigue stresses than those in perpetual pavement design. This causes rapid propagation of fatigue cracking and high structural deterioration rates in the conventional design compared to the perpetual pavement.

2. The overall structural evaluation of the two design methods through the various simulation software shows that the perpetual pavement design is performing more efficiently and thus requires less maintenance and rehabilitation activities through its lifetime.

3. Although the perpetual and conventional pavement designs were designed for a 30 year service life, a well designed maintenance and rehabilitation program can ensure the extension of the service life of the conventional design to 40 years or more. The perpetual pavement design lifetime can be extended to 70 years provided that a well designed preventative maintenance program is being implemented.

4. Although the conventional asphalt pavement structure is about 37 percent cheaper than the perpetual pavement design – based on current cost data. However, the LCCA over the 70 year period have shown that the perpetual pavements will not only overcome the remarkable difference in construction costs, but also will tend to have a NPV of 5.4% lower than that of the conventional pavements. This significant LCCA result is due to the lower maintenance and rehabilitation activities needed for perpetual pavements when taking into account its structural performance.

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