9th. International Conference on Concrete Block Paving. Buenos Aires, Argentina, 2009/10/18-21
Argentinean Concrete Block Association (AABH) - Argentinean Portland Cement Institute (ICPA)
Small Element Paving Technologists (SEPT)

LIFE-CYCLE COST COMPARISON FOR MUNICIPAL ROAD PAVEMENTS

HEIN, David K., P.Eng.
Applied Research Associates, Inc., 5401 Eglinton Avenue West, Suite 105, Toronto, ON, CANADA, M9C 5K6. Tel: 416-621-9555 Ext 1 Fax: 416-621-4719, dhein@ara.com

SMITH, David R., Technical Director
Interlocking Concrete Pavement Institute (ICPI)
13921 Park Center Road, Suite 270, Herndon, VA, 20171, USA.
Tel: +1-703-6576900 Ext 201, Fax.: +1-703-6576901. dsmith@icpi.org, www.icpi.org

Note: The following is the notation used in this paper: (.) for decimals and (   ) for thousands.

Summary

Life-cycle cost analysis (LCCA) is an essential component of modern roadway infrastructure design and system selection. LCCA embraces maintenance and rehabilitation costs, not just initial construction costs when evaluating pavement alternatives. The actual service life of initial pavement construction and rehabilitation treatment depends on a variety of factors including type and composition of the traffic, timeliness of maintenance treatments, and environmental factors such as temperature and precipitation. In order to develop comparative cost estimates to determine LCCA of the different pavement types, it is necessary to know the timing, type and quantities of repairs and their service life. LCCA quantifies all of the costs necessary to construct and maintain a pavement over a set analysis period, typically between 25 and 50 years. Future costs are discounted to today's dollars by using a discount rate derived from the combination of expected future inflation and interest rates. These inputs help determine the net present value of future costs. By comparing the total life-cycle cost of two or more pavement options, it is possible to make informed decisions on selecting the best pavement alternative for a particular application.

The development of LCCA tool enables examination of various design options to determine which pavement type is the most cost effective over the total life-cycle of the pavement. Appropriate pavement design, maintenance and rehabilitation (M&R) procedures to document the life-cycle costs of interlocking concrete pavements are described. These tools and procedures can be used to document the life-cycle cost benefits of interlocking concrete pavements compared to conventional flexible asphalt and rigid concrete pavements. This is becoming increasingly important as asphalt prices fluctuate. This paper outlines guidelines and an easy-to-use software spreadsheet model that assists in developing realistic LCCA comparisons for flexible, rigid and interlocking concrete pavements for low traffic volume municipal pavements. The paper demonstrates life-cycle costs for interlocking concrete pavement can be lower than conventional asphalt and concrete pavements. The comparisons assume common design lives, typical base materials and anticipated traffic loads.

1. INTRODUCTION

Life-cycle cost analysis (LCCA) has become an essential component of infrastructure design and asset management programs. It has long been realized that maintenance and rehabilitation costs, not just the immediate initial construction costs should be considered when evaluating pavement alternatives. In order to assist owners and practitioners in comparing pavement whole life costs, a spreadsheet model for life-cycle cost procedures was developed to compare flexible, rigid, and interlocking concrete pavements for low traffic volume pavements. The tools and procedures can be used to document the life-cycle cost benefits of interlocking concrete pavements (ICP) compared to flexible and rigid pavements.

1.1 Life-Cycle Costing Overview

The U.S. Federal Highway Administration [Walls, et al, 1998] describes LCCA as "an analysis technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between competing alternative investment options". Comparing life-cycle costs has become standard for selecting among different pavement types, but also to evaluate different, feasible rehabilitation plans over the service life of pavement alternatives.

Pavement service life is defined as the time between initial construction and the time when the pavement reaches a minimum acceptable service level. Actual service life with required rehabilitation treatment depends on a variety of factors. These can include the traffic/wheel loads, timeliness of maintenance treatments, and environmental factors such as temperature and precipitation. In order to develop comparative cost estimates over the pavement life, the timing, type and quantities of repairs and the corresponding "activity" service life must be known or estimated with reasonable accuracy.

Life-cycle costing quantifies initial construction and activity costs such as maintenance and rehabilitation for a pavement over an "analysis period", typically between 25 and 50 years (see Figure 1). Future costs are discounted to today's dollars by selecting a discount rate i.e., the difference between bank financing rates and inflation rates. The discount rate is a key factor in determining the net present value of future costs. Lower discount rates tend to favor pavements with long service lives and higher initial costs such as interlocking concrete pavement.

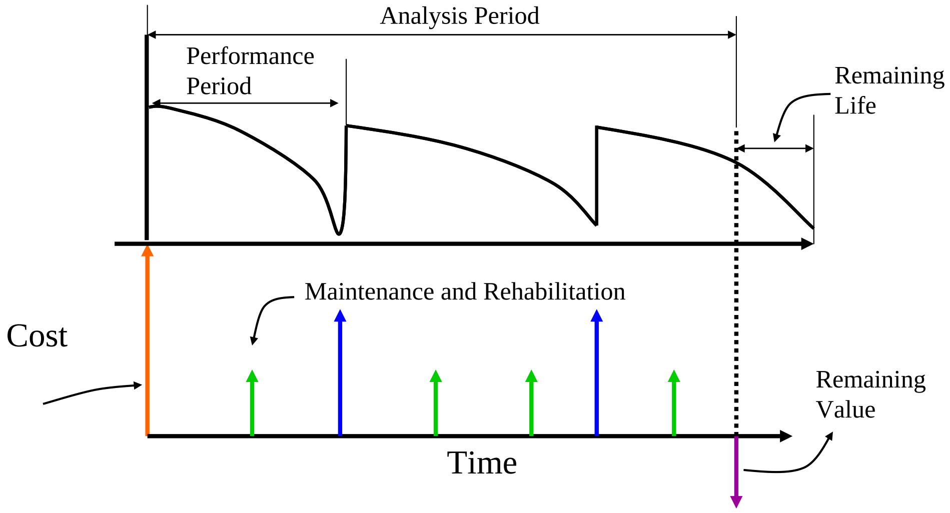

Figure 1. Schematic of Life-Cycle Costs.

Municipal pavements in the United States and Canada are typically designed for an initial service life of between 15 and 30 years. At the end of the service life, major rehabilitation is conducted such as a mill and overlay for asphalt pavements, concrete pavement restoration treatment (e.g. slab repairs, crack sealing, etc.) for rigid pavements, or removal and resetting of interlocking concrete paving units. By comparing the total life-cycle costs among pavement options, it is possible to make informed decisions on the least overall pavement cost for a particular application.

Life-cycle cost analysis is particularly important in answering the question; can municipalities afford to continue to replace deteriorated asphalt pavements with more asphalt pavements given that its future costs will inevitably rise? [Machado, 2006] recognized this by conducting a life-cycle analysis for a small town in central California and concluded that interlocking concrete pavement would incur a lower cost. In this case, the municipality adopted interlocking concrete pavement the standard for all residential streets.

1.2 Life-Cycle Cost Analysis Components

To evaluate the life-cycle cost, it is important to evaluate the costs in terms of several key parameters. These include the overall life-cycle costing assumptions such as the analysis period and the discount rate. Initial cost plus the types and timing of maintenance and rehabilitation activities are also inputs. All of these factors should be considered when comparing interlocking concrete, flexible, and rigid pavements. To facilitate comparisons among these pavements, the Interlocking Concrete Pavement Institute developed A Microsoft© Excel based tool to assist agencies and practitioners to compare total costs.

2. INITIAL DESIGN LIFE OF INTERLOCKING CONCRETE PAVEMENTS

The initial design of pavements is a critical factor in pavement performance and in the life-cycle cost evaluation. The service life of a pavement is usually established during the initial design. Service life considers the subgrade, pavement layer materials, their thicknesses, and the anticipated traffic on the roadway. This service life depends on the pavement’s environmental and loading conditions. By monitoring and rating the pavement performance using standard pavement management tools such as the pavement condition index (PCI), it is possible to establish typical pavement performance curves for the pavement [ICPI, 2007].

To determine the expected life of a pavement, the measured condition with a minimum acceptable level of service is used. To estimate expected life, the typical path of deterioration is monitored over the life a pavement type until the pavements reach a typical terminal serviceability level at which point field data are not available. Regression analysis that plots condition rating against age is commonly used to generate a deterioration path that estimates when a pavement will end its service life and require major rehabilitation.

2.1 Data Sources

For the development of a North American LCCA tool, pavement performance data was collected from 83 interlocking concrete pavement roads located in 19 cities across Canada and the United States. The detailed pavement condition assessments were completed based on the procedure outlined in the *Standard Practice for Pavement Condition Index Surveys for Concrete Pavement* [ICPI 2007]. The survey procedure is modelled on the U.S. Army Corps of Engineers MicroPAVER distress guide as published by the American Society for Testing Materials D6433, *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.*

Condition surveys were completed in 2007 and 2008 on interlocking concrete pavements in the following cities:

- Baltimore and Rockville, Maryland.
- Calgary, Alberta.
- Colma, California.

- Boston, Massachusetts.
- Eugene and Portland, Oregon.
- Hamilton, Port Elgin, and North Bay, Ontario.
- Houston and San Antonio, Texas.
- Syracuse, New York.
- Tampa, Daytona and Lake Mary, Florida.
- Vancouver, British Columbia.
- Winnipeg, Manitoba.

To compare the various pavements and their stage of deterioration, construction history was determined through local knowledge of the various projects. Construction history included the initial construction date as well as any information regarding maintenance and rehabilitation treatments. The pavement age was plotted against pavement condition to develop a deterministic regression model and deterioration path.

The result of the performance modeling is shown in Figure 2 (note that outliers have been removed in the trend line). This data indicates some variability in the PCI measured in the field. This type of variability is common among all pavement types and reflects many factors, other than age, that affect the service life of the pavement. A general trend can be seen from the regression indicating the typical path of deterioration.

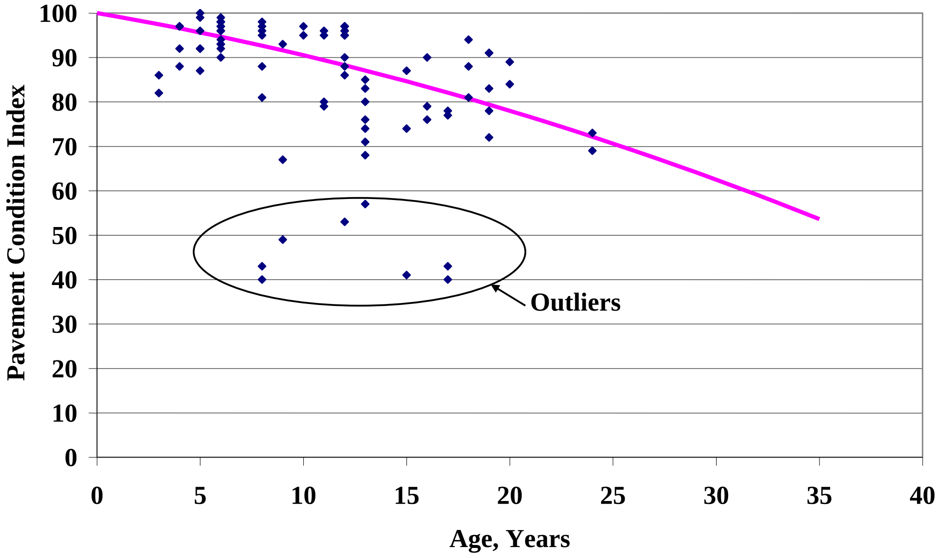

Figure 2. PCI and General Performance Model for Interlocking Concrete Pavements.

The deterioration path shown in Figure 2 indicates that a typical interlocking concrete pavement exhibits slow deterioration in the first eight years of service. This agrees with field observations. Pavement sections that showed reduced performance (identified as outliers) typically had design or construction related issues that accelerated the relative deterioration of the pavement. These were excluded from the deterioration path regression model.

2.2 Level of Service

The minimum acceptable level of service is an important decision made by a designer. The maximum state of deterioration that a pavement is expected to reach can greatly influence service life. The service level can be described by condition indicators such as structural capacity, ride quality, or visual distress. For most municipal roads, the visual condition is typically used because it can represent the other indicators in an overall condition-rating scheme. With the low operating speed of most low traffic volume pavements, the impact of the other indicators is reduced.

Figure 3 illustrates a rating scale for visual condition common to the PCI method.

Figure 3. Level of Service Based on Pavement Condition Index.

Based on the condition descriptions in Figure 3 and the level of service measured during the field inspections, a typical rating of a PCI of 60 is recommended as a minimum level of service for a municipal road. A threshold value of PCI 60 is commonly used in condition rating of asphalt and concrete pavements. Once a rated pavement passes this value, substantial repairs or major rehabilitation throughout a section are likely required to bring the pavement up to an excellent condition level.

Using a typical minimum serviceability value PCI of 60, the condition data collected indicates a typical ICP service life of 20 years. Variability increases significantly after eight years into the service life. The condition data also shows a group of pavement sections with relatively low PCI values (between 40 and 60) which do not seem to be grouped with the remainder of the pavement sections. If these sections (outliers) are removed from the population, the initial performance curve (deterioration path or line) would cross the PCI of 60 trigger value for major rehabilitation at 32 years.

In addition, reduced service level requirements for very low volume roads or parking areas can influence when rehabilitation is required. Due to the low speed of vehicles and the limited use, consideration could be given to setting the minimum acceptable PCI at 50 for these types of pavements. This would result in an initial service life of 37 years.

3. MAINTENANCE AND REHABILITATION NEEDS FOR ICP

There is little doubt as to the importance of the initial construction cost of a pavement. However, the on-going maintenance and rehabilitation costs can be a significant cost over the entire life-cycle of a pavement. To account for these costs, pavement maintenance and rehabilitation activities are typically scheduled to maintain and improve the serviceability of the pavement. The timing of the activities, in conjunction with the cost to perform the activities is then combined to estimate the total life-cycle cost.

3.1 Initial Interlocking Concrete Pavement Design

Initial design and construction costs are typically the largest expenses over the life-cycle, for ICPs. Like other pavements, initial ICP design and related costs depend greatly on traffic level, environment, and materials. For the purpose of life-cycle costing, typical asphalt, concrete and ICP structures are designed using the American Society of Civil Engineers *Draft Standard for the Structural Design of Interlocking Concrete Pavement* [ASCE, 2009]. The design methodology is based on the 1993 American Association of State Highway and Transportation Officials *Guide for Pavement Design* [AASHTO, 1993]. The traffic loads are characterized as 80 kN equivalent single axle loads or ESALs. Two cost scenarios are examined, a lightly trafficked road subject to 300 000 ESALs over its service life and another subject to 5 000 000 ESALs, a heavily used urban thoroughfare.

Design Details

Design Traffic: 300,000 ESALs.
Drainage Type: Fair.
Subgrade Type: CL (M_r = 20 MPa).

- Concrete pavers: 80 mm thick.
- Bedding sand: 25 mm thick.
- Granular base: 150 mm thick.
- Granular subbase: 350 mm thick.

3.2 Estimating Maintenance Activity Costs

One of the key components for the evaluation of total costs over the pavement life-cycle is in estimating maintenance and rehabilitation costs. This is typically accomplished by reviewing the potential activities that will occur throughout the service life of a pavement, their frequency, and costs.

The maintenance and rehabilitation costs used in the analysis are based on current dollars, but adjustments due to inflation and discounting are taken into account so that they are expressed in terms of net present value. The unit costs represent the entire expense to complete a maintenance and rehabilitation activity including labor, equipment, and materials. Table 1 lists an example of the estimated unit costs for the expected activities on the ICPs for a Canadian location, and based on 2006 Canadian dollar construction prices. It should be noted that unit costs would vary depending on regional pricing, size of the project, availability of materials and contractor experience.

Table 1. Example of Unit Costs for Maintenance and Rehabilitation of ICP.

ACTIVITY	TYPICAL UNIT COST (US$)	UNIT
Bedding Sand and Paver Installation	50	m^2
Granular Base	15	t
Granular Subbase	7.5	t
Replace Cracked Pavers	60	m^2
Replace Worn/Rutted Pavers (wheelpath)	60	m^2

3.3 Maintenance and Rehabilitation Plan

The maintenance and rehabilitation (M&R) plan is established as a typical scenario to maintain the pavement in a cost-effective and serviceable manner. It reflects the maintenance and rehabilitation activities as well as the timing and quantity for each activity. These activities typically include mill and overlay for flexible pavement, concrete pavement restoration (e.g. slab repairs, crack sealing, etc.) for rigid pavement and replacement and for an ICP they include replacing cracked or worn pavers.

A typical plan for maintenance and rehabilitation expected for ICP is listed in Table 3. This plan should be evaluated on a project-by-project basis before implementation in the field to ensure the correct timing of activities.

Table 2. Unit Costs for Maintenance and Rehabilitation

YEAR	ACTIVITY	QUANTITY (%)
8	Replace Cracked Pavers	2
20	Replace Worn/Rutted Pavers (wheelpath)	5
28	Replace Cracked Pavers	2
35	Replace Worn/Rutted Pavers (wheelpath)	5

4. COMPARABLE FLEXIBLE AND RIGID STRUCTURE AND M&R PROGRAM

The key benefit of a life-cycle cost analysis is the ability to compare multiple pavement structures that have the same structural design but different initial cross-section and hence different maintenance strategies. Flexible and rigid pavement designs have been developed based on equivalent geometric and traffic conditions to the ICP example. An example of unit costs for the flexible and rigid pavement structures can be found in Table 4 [Applied, 2006]. These will also vary depending on regional pricing, size of the project, availability of materials and contractor experience.

Table 3. Typical Unit Costs for Maintenance and Rehabilitation.

ACTIVITY	TYPICAL UNIT COST ($)	UNIT
Doweled Jointed Concrete Pavement (200 mm)	60	m^2
Plain Jointed Concrete Pavement (200 mm)	45	m^2
Asphalt Concrete (Surface)	115	t
Asphalt Concrete (Base)	100	t
Granular Base	15	t
Granular Subbase	7.5	t
Rout and Seal Crack	2	m
Reseal Joints	2	m
Asphalt Patching	7	m^2
Mill and Overlay Pavement	125	t
Concrete Pavement Restoration	160	m^2

4.1 Flexible Pavement Structure

Flexible pavement structures are typically composed of an asphalt concrete surface over granular base and subbase combination. A typical flexible pavement structure, based on the 1993 AASHTO *Guide*, with a comparable traffic and subgrade condition equivalent to the ICP example in Section 3 is:

$$SN_{Design} - 97\ mm \quad \textbf{(1)}$$

- Asphalt Concrete: 100 mm thickness.
- Granular base: 150 mm thickness.
- Granular subbase: 375 mm thickness.

This structure is a typical for a municipal pavement. A typical maintenance and rehabilitation plan for this flexible pavement structure is given in Table 4.

Table 4. Flexible Pavement Maintenance and Rehabilitation Plan.

YEAR	ACTIVITY	QUANTITY (%)
4	Rout and Seal Cracks	5
8	Machine Patching	5
15	Mill and Overlay (50 mm)	100
19	Rout and Seal Cracks	10
22	Machine Patching	10
25	Mill and Overlay (90 mm)	100
27	Rout and Seal Cracks	10
30	Machine Patching	10
37	Mill and Overlay (50 mm)	100

4.2 Rigid Pavement Structure

Rigid pavement structures are typically composed of a Portland Cement Concrete (PCC) layer over a granular base material. A typical PCC design for the same conditions as the ICP, and assuming jointed plain concrete pavement is provided below:

- PCC Pavement: 200 mm thickness.
- Granular subbase: 150 mm thickness.

Table 5. Rigid Pavement Maintenance and Rehabilitation Plan.

YEAR	ACTIVITY	QUANTITY (%)
5	Reseal Joints	5
15	Minor Concrete Pavement Repair	2
18	Reseal Joints	15
25	Major Concrete Pavement Repair	5
30	Reseal Joints	5
40	Minor Concrete Pavement Repair	2
43	Reseal Joints	15

5. ESTIMATING TOTAL LIFE-CYCLE COST

Total life-cycle cost combines estimated initial costs and the future maintenance and rehabilitation costs for each alternative. The inputs used for evaluating the total life-cycle cost are handled by a spreadsheet tool to provide accurate and consistent costs expressed in today’s dollars as a net present value.

The required inputs include:

General inputs.
- Analysis period.
- Discount rate.
- Site description/dimensions.

All pavement types.
- Unit costs.
- Initial pavement layer thickness.
- Maintenance and rehabilitation plan and quantities.

5.1 Calculation of Net Present Value

The costs distributed over the pavement are typically translated into a Net Present Value (NPV). The NPV represents the total cost today that would be required, accounting for the interest and inflation expressed as the discount rate. The NPV of all activities are summed up to estimate the total maintenance and rehabilitation cost.

$$\text{Total M\&R Cost} = \sum_i \frac{(M\,\&\,R\ Cost_i)}{(1 + Discount\ Rate)^{Age}} \quad \textbf{(2)}$$

where:

$$\textit{Discount Rate (\%) = Interest Rate (\%) – Inflation Rate (\%)} \quad \textbf{(3)}$$

The discount rate used in the analysis represents the expected rate over the life of the project. In public sector projects, the discount rate depends primarily on the current economic environment, cost of borrowing, bank interest rates, market risk and opportunity costs to the public agency or government. In North America the discount rate is usually 3% to 5%. For the examples shown in this paper a discount rate of 4 % is used.

5.2 Pavement Residual Value

To ensure fair comparison of the alternatives, residual value of any unused pavement rehabilitation activity at the end of the analysis period must be included in the life-cycle cost analysis. The residual value is estimated by linear depreciation of the last capital activity cost. The prorated life method is used in the LCCA procedure to estimate the residual value. The recoverable cost is estimated by dividing the remaining life of the last rehabilitation treatment, by the expected life of the treatment.

$$\textit{Residual Value = Last Rehab Cost x [(Service Life - Activity Age) / Service Life]} \quad \textbf{(4)}$$

To determine the salvage value, the last major rehabilitation activity is used. Based on the year of implementation of the last rehabilitation, the expected service life (from the Unit Costs table) and the activity cost, a proportion of the initial cost is determined. The residual value, at the end of the design period is then discounted to a net present value. The residual value is then subtracted from the other costs.

5.3 Life-Cycle Cost (LCC)

The total cost to construct and maintain each design option is the key focus of a LCCA. To accomplish this, the total sum of all costs, in equivalent NPV is required. The total cost is thus calculated as:

$$\textit{LCC = (Initial Cost + Total Discounted M\&R Cost – Residual Value)} \quad \textbf{(5)}$$

This value can then be used to benchmark other potential options and determine which is the most cost effective.

A summary of the overall results is provided in Table 6. This table indicates that the pavement with the lowest life-cycle cost based on 300 000 ESALs and the unit prices shown is the asphalt concrete (flexible) pavement. In this case, the ICP has a life-cycle cost of only eight percent higher than the asphalt concrete pavement. The key observation here is that the initial cost variance between asphalt and ICP is 47 %.

The initial and life cycle costs were recalculated for equivalent pavement structures with design traffic of 5 000 000 ESALs. The results of the analysis are provided in Table 7.

Table 6. Summary of Present Worth of Example Life-Cycle Cost Analysis (Design Traffic = 300 000 ESALs).

PAVEMENT TYPE	INITIAL COST (US$)	MAINTENANCE AND REHABILITATION COSTS (US$)	TOTAL PRESENT WORTH OF COSTS (US$)
Asphalt Concrete	271,688	171,523	443,211– Rank 1
Concrete	524,625	36,790	561,415 – Rank 3
ICP	455,438	23,205	478,642 – Rank 2

Table 7. Summary of Present Worth of Example Life-Cycle Cost Analysis (Design Traffic = 5 000 000 ESALs).

PAVEMENT TYPE	INITIAL COST (US$)	MAINTENANCE AND REHABILITATION COSTS (US$)	TOTAL PRESENT WORTH OF COSTS (US$)
Asphalt Concrete	414 000	166 299	580 299 – Rank 3
Concrete	524 625	36 790	561 415 – Rank 2
ICP	517 313	20 012	537 325 – Rank 1

In this example, the higher traffic level pavements show a life-cycle cost advantage of the ICP design with ICP having the lowest overall cost by 4.5% compared to the concrete design.

5.4 Comparison of Life-Cycle Cost Versus Design Traffic

The results of a life-cycle cost analysis are dependent on a number of input variables including pavement structural design, construction quality, maintenance and rehabilitation practices, design life and the cost of money. Typically, lower traffic volumes result in thinner pavements and the life-cycle costs favour asphalt concrete surfaced whose sections are thinner. Higher traffic volumes tend to favour concrete and ICP. For comparison purposes, the total present worth of costs for a two (2) lanes roadway, over a 40-year design period were calculated for design traffic levels from 10 000 to 10 000 000 ESALs for two subgrade types. The first, is a silt subgrade with poor drainage and the second a clay subgrade with fair drainage. The results of the analysis are shown in Figures 4 and 5. In Figure 4, it can be seen that for lower traffic levels, the flexible pavement has a lower life-cycle cost up to a traffic level of 5 000 000 ESALs. In Figure 5, the ICP section has lower life-cycle costs for design ESALs of 2 000 000 or higher.

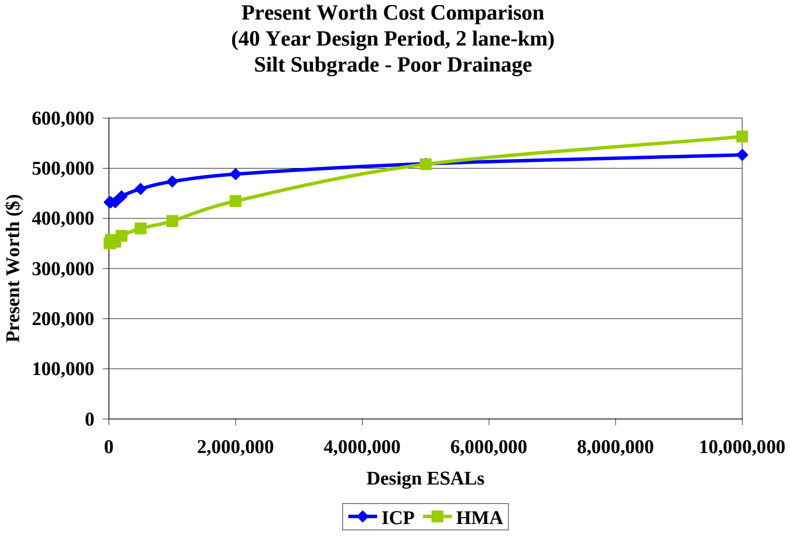
Present Worth Cost Comparison
(40 Year Design Period, 2 lane-km)
Silt Subgrade - Poor Drainage

Figure 4. Life-Cycle Cost Comparison for a Pavement with Silt Subgrade.

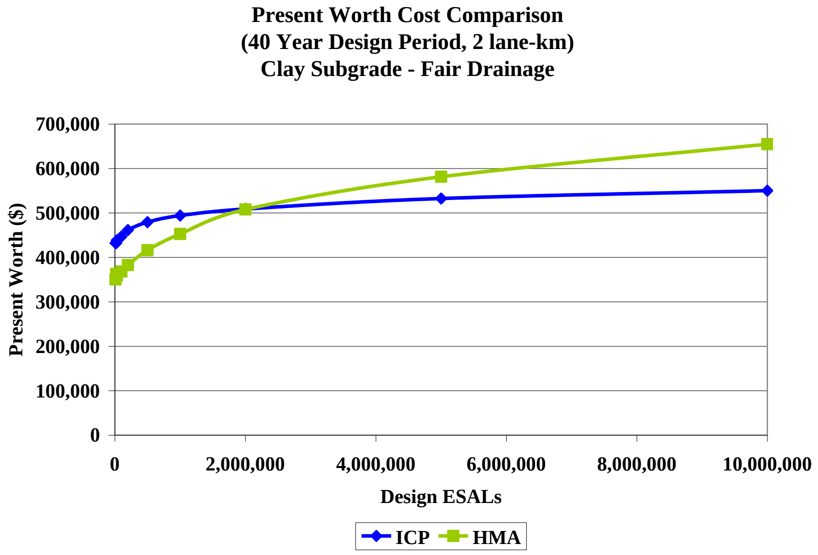

Figure 5. Life-Cycle Cost Comparison for a Pavement with Clay Subgrade.

6. CONCLUSIONS

The development of a life-cycle cost tool allows for the examination of various design options to determine which pavement type is the most cost effective over the total life-cycle of the pavement. The LCCA analysis outlined in this paper clearly shows the whole life cost advantage of using ICP as a pavement surface for municipal roadways.

7. REFERENCES

AMERICAN SOCIETY FOR TESTING MATERIALS, 2003. ASTM D6433-07 Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys, ASTM, Washington, D.C.

APPLIED RESEARCH ASSOCIATES, INC., 2006. Estimation of the Representative Annualized Capital and Maintenance Costs of Roads by Functional Class, March 31, 2006, http://www.tc.gc.ca/pol/en/aca/fci/menu.htm.

AASHTO, 1993. Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, Washington, DC.

ASCE, 2009. Draft Standard, Structural Design of Interlocking Concrete Pavement. American Society of Civil Engineers, Draft 02/15/09.

ICPI, 2007, Standard Practice for Pavement Condition Index Surveys for Concrete Block Pavement, Herndon, VA.

WALLS, JAMES III AND MICHAEL R. SMITH, 1998. Life-Cycle cost Analysis in Pavement Design – Interim Technical Bulletin. FHWA Report FHWA-SA-98-079, September 1998.