Helping Build A Sustainable Future By Constructing Roadways with Portland Cement Concrete Pavement

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Abstract

Portland cement concrete pavement (PCCP) has long been known as a long lasting, durable pavement surface with low maintenance costs.

Although Life Cycle Cost analysis components are being considered by some DOTs when tendering pavement construction jobs, sustainability issues are generally not considered as part of the analysis. Including the pavements sustainable performance, however, would provide government agencies with a better understanding of the true cost of the roadway structure. This paper will look at the sustainable performance characteristics of concrete pavement by examining and documenting some of its many social, economic and environmental advantages.

Some of the social benefits of concrete pavement that are identified in this paper include: reduced potential for hydroplaning; good night time visibility; improved stopping distance and enhanced ride and comfort. Several environmental benefits of PCCP are examined and presented including: findings of the Athena Sustainable Materials Institute on the Life Cycle embodied Energy for concrete and asphalt roadways; findings of several studies on truck fuel savings from traveling on PCCP compared to asphalt concrete pavement (ACP) and the resulting reduction in greenhouse gas (GHG), as well as, and research on concrete pavement as a potential CO2 sink. The recyclable nature of PCCP will also be addressed including reuse of recycled PCCP as base material for a new pavement or aggregate for a new pavement. Typical PCCP structures will be presented to demonstrate the aggregate savings realized when utilizing PCCP pavement systems. Use of supplementary cementing materials (SCM) will also be discussed to show how industry by-products such as fly ash, blast furnace slag and silica fume can be used in the concrete to improve the PCCP performance characteristics and divert their disposal at landfill sites. Finally, economic benefits such as life cycle cost, two pavement system and potential for reduced lighting requirements for PCCP will be provided.

1.0 **Introduction**

Portland cement concrete pavement (PCCP) has long enjoyed the reputation as a longer lasting, durable pavement surface with low maintenance costs. Cities such as Winnipeg, Windsor, Montreal and Toronto have been using PCCP and composite pavement for some time and have extensive networks of PCCP. In addition, many cities are also using PCCP at high traffic and high wear areas such as intersections and bus stops where turning movements and static loading are rutting and showing asphalt pavements. However, most Provincial and Municipal Government agencies in Canada choose pavement type on an initial cost bases and have traditionally tendered only asphalt pavements. With the need to stretch ever decreasing public funds some government agencies are beginning to look at the longer term to increase the life of their assets. This has lead to alternate bid tenders with both asphalt and concrete pavement structure options and associated life cycle cost analysis (LCCA) values for the two pavement types. A total of nine alternate bid tenders with a LCCA component have been called across Canada since 2000 of which eight projects went PCCP.

Although alternate bid tenders with a LCCA component are a step in the right direction in helping government agencies to determine the best pavement option for a particular job they do not provide the true cost of a paving project. To have a complete understanding of the cost of one pavement type compared to another one must consider the sustainability of each product. Everyone has their own definition of what sustainable development is. The key is to ensure we leave our children and their children with sufficient resources to have the same standard of living we enjoy today. This can be accomplished by ensuring that every government and corporate decision considers the impact of the triple bottom line – the effect on Social, Environmental and Economic (SEE) impacts of their decision.

This paper provides an overview of the benefits PCCP structures provide related to these key pillars of sustainability. Government agencies considering the sustainable benefits of the different pavement types will be better equipped to make informed decisions related to the impact new and rehabilitated roadways have on the general public.

2.0 **Social Benefits**

The Social benefits from utilizing PCCP are many and cover a variety of areas such as roadway safety issues and passenger ride and comfort. The following subsections explain how PCCP provides enhanced pavement qualities through the following attributes: decreased potential for hydroplaning, better night time visibility, improved stopping distance, smooth ride for long period, and quite ride.

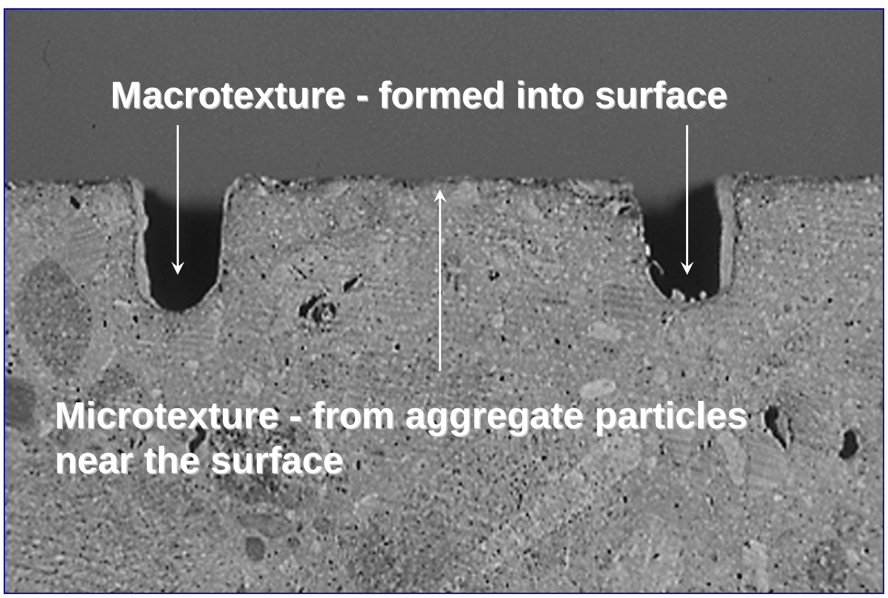
2.1 **Decreased Potential for Hydroplaning**

Hydroplaning of a vehicle occurs when there is tire separation from the pavement surface by a layer of water, which causes loss of vehicle steering and braking control. Several factors may contribute to hydroplaning potential such as tire wear, driver speed / experience and pavement surface characteristics. Since Government agencies have little control over the condition of tires and driver experience the following discussion focuses on the one area Government agencies do have control of - pavement surface characteristics.

All types of pavement whether gravel, asphalt or concrete have the potential for hydroplaning when it is raining or water is present on the surface. However, since concrete pavement is a mouldable material when it is first placed the pavement can be textured to provide good friction characteristics, as well as, good wet weather performance. As shown in Figure 1 texture created on the concrete surface is classified into two categories:

1) microtexture – which is the fine-scale roughness contributed by the fine aggregate (sand) in the concrete matrix and provides the dry weather friction. This texture is created in the concrete surface by dragging burlap or astro-turf over the surface of the plastic concrete prior to applying the curing compound.

2) macrotexture – which is the measurable striations or grooves formed in the plastic concrete by hand operated tining brooms or automated machines provides the wet weather friction. Macrotexture may also be formed by cutting or sawing grooves into the hardened concrete surface [ACPA 2000].



Source: Special Report Concrete Pavement Surface Textures by ACPA

Figure 1: Close-up of Microtexture and Macrotexture on PCCP

As identified in Figure 2 macrotexture is the main contributor to providing concrete pavement's superior performance in wet weather conditions. The grooves in the concrete pavement surface provide water with a channel to escape from underneath the vehicle's tires thereby greatly reducing the hydroplaning potential. Another contributor to PCCP's superior performance in wet weather conditions is its rigid structure. This quality prevents heavy vehicles from causing deformations such as ruts and washboarding in the pavement surface where water can accumulate and create increased hydroplaning potential. If studded tires are permitted to be used on provincial roadways higher strength concrete pavement can be used to virtually eliminate potential wear ruts in the vehicle wheel paths.

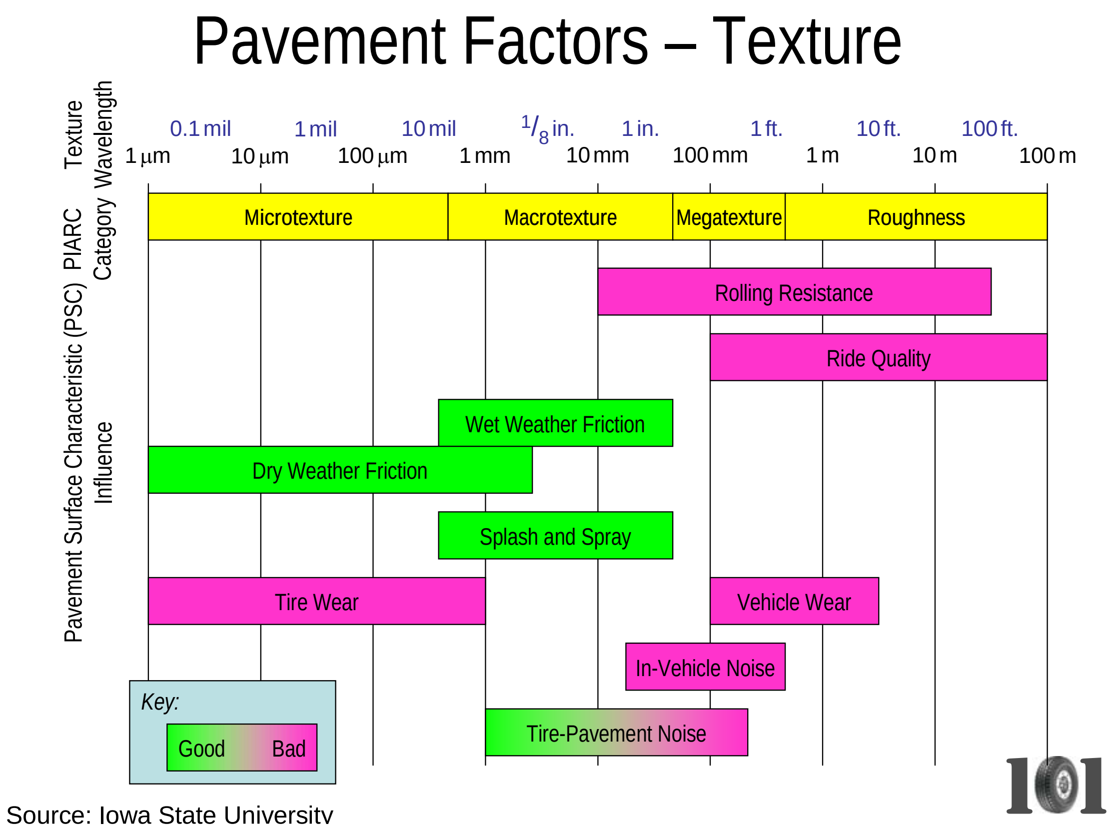


Figure 2: Effect of Texture on Pavement Surface Characteristics

2.2 **Superior Night Time Visibility**

Concrete pavement's light reflective surface not only provides a pavement surface that minimizes heat island effect in urban areas but also provides better night time visibility in urban and rural environments. This is accomplished due to the light coloured (high albedo) surface of concrete pavement. Table 1 below shows the Albedo (solar reflectance) ratings for various pavement types. As shown in the table concrete pavement has superior albedo to asphalt concrete pavement (ACP) in both new and weathered conditions- concrete pavement (0.35 – 0.40 new PCCP and 0.20 – 0.30 weathered concrete) and asphalt (0.05 -1.0 new ACP and 0.10 – 0.15 weathered ACP). Figure 3 below is a picture of Highway Castello Branco - São Paulo State which has several lanes of pavement including from left to right: four (4) lanes of concrete (with concrete shoulders), three (3) lanes of asphalt, three (3) lanes of asphalt and four (4) lanes of concrete (with concrete shoulder). As can be seen form the picture the concrete lanes have superior reflectance characteristics to the asphalt surface providing better night time visibility.

Table 1: Albedo for Various Pavement Types

Pavement Type	Albedos (solar reflectance)
Asphalt	0.05-0.10 (new) 0.10-0.15 (weathered)
Gray Portland Cement Concrete	0.35-0.40 (new) 0.20-0.30 (weathered)
White Portland Cement Concrete	0.70-0.80 (new) 0.40-0.60 (weathered)

Source: ACPA R&T Update Concrete Pavement Research & Technology June 2002

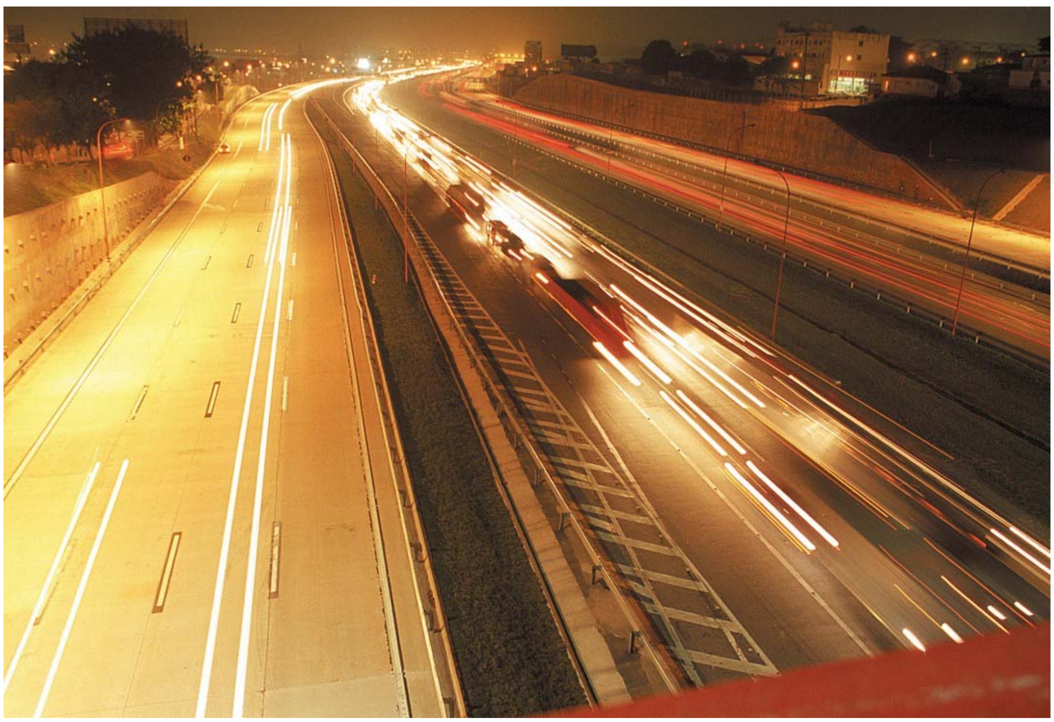
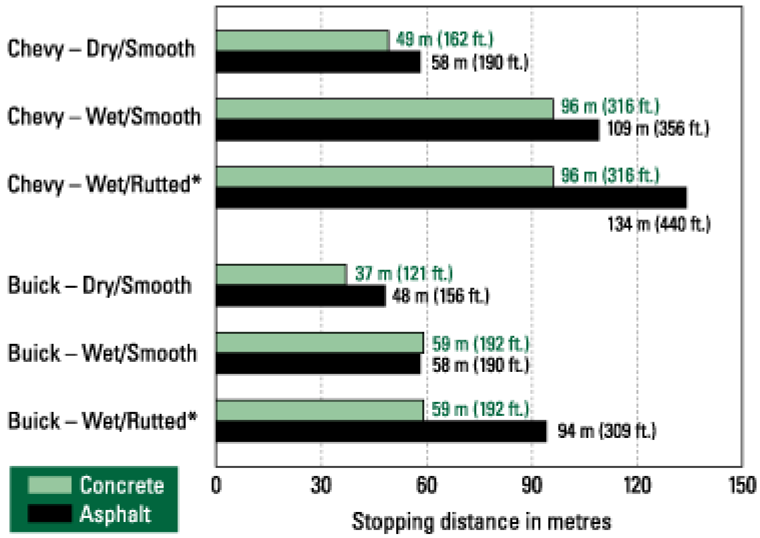


Figure 3: Night Time Picture of PCCP and ACP on Highway Castello Branco - São Paulo State, Brazil

2.3 **Improved Stopping Distance**

For the user, a concrete pavements rigid surface is important when considering personal safety. A study by the University of Illinois entitled, "Safety Considerations of Rutting and Washboarding Asphalt Road Surfaces" demonstrates that overall stopping distances on concrete surfaces are shorter than for asphalt surfaces, especially when asphalt is wet and rutted, as shown in Figure 4. It should be noted, the values in this figure do not take hydroplaning into account, which would increase the asphalt stopping distance values even more [ACPA 1998].



Source: American Concrete Pavement Association Engineering Bulletin
- Whitetopping – State of the Practice, ACPA 1998

Figure 4: Measured Stopping Distances of Two Different Vehicles on Various Surface Conditions

2.4 **Quiet Ride**

Roadside noise levels are a public concern especially when the pavement is in an urban environment. Producers of the various pavement types are investing time and money to develop quieter pavements structures. In fact, the American Concrete Pavement Association (ACPA) is conducting research to develop quieter concrete pavements to better serve the transportation community. This effort involves standardization of tire/pavement noise assessment; establishment of acoustic performance curves for existing surfaces; development of new surface textures through a laboratory test program; a field validation program; and an implementation phase.

The development of new surface textures requires the ability to easily modify surface characteristics and to readily evaluate their impact on acoustic performance. To accomplish this, the ACPA has contracted with Purdue University to conduct laboratory testing using the Purdue Tire Pavement Test Apparatus (TPTA). The TPTA provides efficient evaluation of any surface that can be cast or formed. Efforts to date have focused on development of quieter diamond ground surfaces through alteration of the blade size, spacer arrangements, and by controlling fin profile.

When looking at the acoustic performance of different pavement types and macrotexture and microtexture finishes on the pavement surfaces one needs to consider the pavement characteristics throughout the pavements service life and not just the as-constructed or nearly new pavement condition.

Most research to date shows longitudinally tined, astro-turf drag textures, and diamond grinding provide the quietest new construction techniques for concrete pavement, while diamond grinding provides the quietest rehabilitation strategy. Most loud concrete pavements have been constructed using random transverse tining.

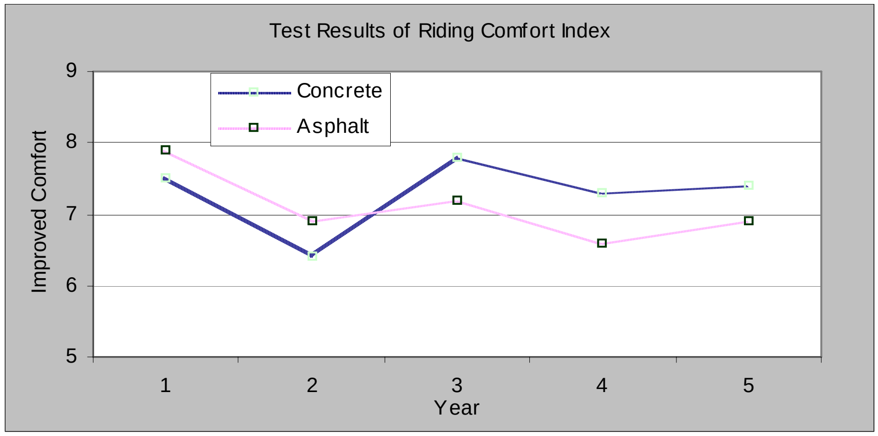
A report by the U.S. Department of Transportation in 1996 concluded that, "Properly constructed PCCP, with transversely tined surface, matches the performance of dense-graded asphalt considering both safety and noise factors" [FHWA 1996]. In addition, a report by the Wisconsin Department of Transportation concludes, "That it is possible (very simply and at no extra expense) to build a PCC pavement that does not "whine" and has the desired frictional properties. Such a pavement is a "good neighbour", is safe, provides user comfort and is durable" [WIDOT 1997]. Based on the comments of these two reports it is possible to build quiet PCCP similar to that of an ACP surface. Initial pavement smoothness can also affect the quietness of a highway as rougher pavements are noisier pavements. New paving equipment and construction techniques have allowed paving contractors to construct smoother concrete pavements.

2.5 **Smooth Ride for Long Period**

Advances in concrete paving construction equipment and techniques along with Government agencies' tenders having bonuses and penalties clauses have helped lead to PCCP being built smoother than previously accomplished. This initial smoothness decreases the dynamic loading on the pavement structure and helps the pavement stay smoother for a longer period of time. Concrete's natural rigid structure also helps the structure to stay smoother for a long period of time.

The Nova Scotia Department of Transportation and Public Works (NSTPW) completed a five-year study on an adjoining section of asphalt and concrete pavement built in 1994 on Highway 104 TransCanada Highway [NSTPW 1999]. Results of the study, which concluded in 1999, showed both pavements performed well over the evaluation period. However, the concrete pavement section outperformed the adjoining asphalt pavement in both riding comfort and road smoothness.

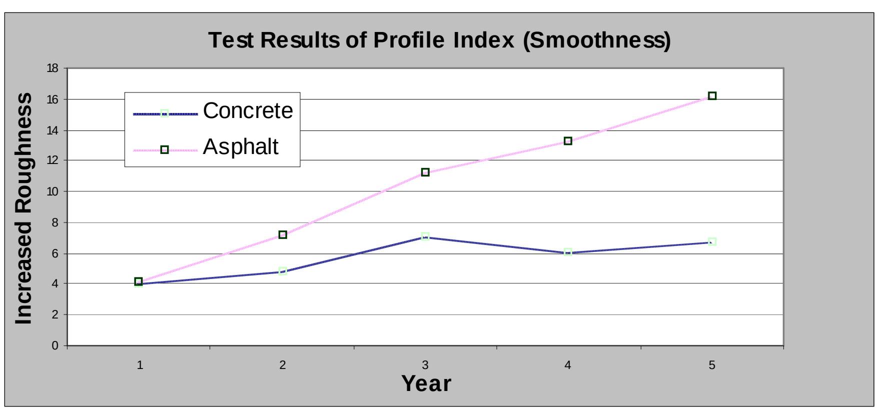
Data from the comparative study noted above indicated that although the new asphalt pavement had a higher initial riding comfort index (RCI), over time it deteriorated to a lower level than the adjoining concrete pavement. Figure 5 provides an illustration of how the RCI values changed over the 5-year evaluation period. Note, the higher the RCI value the more comfortable the ride. The RCI reading at year five was good for both pavements but the PCCP value was superior to the ACP number - 7.4 compared to 6.9 [NSTPW 1999].



Source: Asphalt Concrete Pavement and Portland Cement Concrete Pavement, Highway 104, Cumberland County, Year 5 of 5 Year Study, October 1999.

Figure 5: Comparison of Test Results of Riding Comfort Index

Profile ride index (PRI) which is a measure of the pavement smoothness was also collected during the NSTPW study. Unlike the RCI measurement, an increase in the PRI value represents increased roughness in the pavement. Figure 6 illustrates how the two pavement structures performed over the 5-year evaluation period. As can be seen in the diagram both pavements were constructed quite smooth with the ACP having a slightly better IRI reading than the PCCP – 4.0 compared to 4.1. However, over the next four years, the concrete pavement maintained close to its original smoothness, while the asphalt section showed increased roughness. In fact, the roughness of the ACP more than doubled that of the PCCP after five years of service (i.e., 6.8 mm/100 metres on concrete versus 16.2 mm/100 metres on asphalt) [NSTPW 1999].



Source: Asphalt Concrete Pavement and Portland Cement Concrete Pavement, Highway 104, Cumberland County, Year 5 of 5 Year Study, October 1999.

Figure 6: Comparison of Test Results of Profile Ride Index

3.0 **Environmental Benefits**

Concrete pavement also provides many environmental advantages compared to other pavement structures. This section of the report looks at the many environmental benefits including: reduced energy consumption when using PCCP, reduced carbon dioxide emissions from operating on PCCP, reusable and recyclable paving material, reduction in the use of granular materials, use of industrial by-products, and use of pervious pavements.

3.1 **PCCP Reduced Energy Consumption**

The Athena Sustainable Materials Institute was commissioned by the Cement and Concrete Industry to research the Life Cycle Embodied Energy and Global Warming Emissions for PCCP and ACP Roadways. The study presents embodied energy and global warming potential (GWP) estimates for the construction and maintenance of equivalent PCCP and ACP pavement structures for three different classes of roadway: Class 1 – secondary highway/local collectors; Class 2 – major highways/arterial roads; and Class 3 – major urban freeways [Athena 1998]. The Athena study investigated 12 different pavement structures, each one lane kilometer over an assumed study period of 40 years. This takes into account activities from original construction through major rehabilitation for both roadway types. Two subgrade strengths were analyzed for each pavement class (i.e. California Bearing Ratios (CBR) of 3 and 8) to make the results broadly applicable across Canada. The study and analysis took into account material use and construction of the granular subbase, base and finished surface for both PCCP and ACP roadways, but eliminated items common to both (i.e. right-of-way clearing).

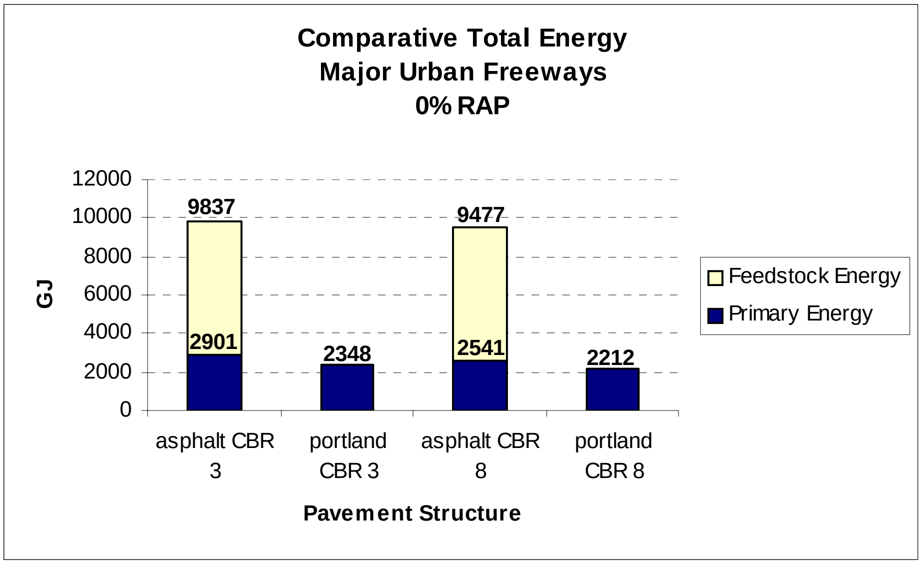
The report shows the PCCP pavement has lower total primary energy results for all roadway classes analyzed. The results ranged from a low of 2.4% less for the secondary highways / local collector roads (Class 1 CBR = 8) to as high 30% less for major highways / arterial urban roads (Class 2, CBR = 3). Figure 7 shows an example of the comparative total energy results for the urban freeway at 0% RAP. If feedstock energy (i.e. liquid asphalt in the asphalt pavement) is also considered in the analysis the total energy differences between the PCCP and ACP structures increases from a range of 245% to 349% (PCCP favour) [Athena1998].

Other findings from the report Include:

1) For all 12-pavement structures investigated, the asphalt concrete alternatives require significantly more energy from a life cycle assessment perspective.

2) The inclusion of 20% RAP in the ACP mix for roadways in areas where it is likely to be permitted (i.e. excluding urban freeways) reduces the total energy estimates for the asphalt but the remaining differences are still significant.

3) Increases in transportation hauling distances for granular materials tend to increase the advantage of PCCP construction. This is due to the need for substantially more granular material being required under most ACP pavement compared to PCCP [Athena1998].



Source: Athena Sustainable Materials Institute, Life Cycle of Embodied Energy and Global Warming Emissions for Concrete and Asphalt Roadways

Figure 7: Comparative Total Energy ACP versus PCCP - Major Urban Freeways – 0% RAP

Since the study deals with embodied energy and greenhouse gas (GHG) emissions for initial road construction and major maintenance or rehabilitation, it primarily reflects the effects of producing and transporting materials and components. The scope did not include operational considerations such as truck fuel savings by operating on different pavement types and energy savings due to the different light reflectance properties of the pavement types. The report does, however, recommend these types of issues be taken into account in any decisions predicated on life cycle environmental effects. The report also notes Athena took:

"A conservative stance from the perspective of the Portland cement alternatives to avoid any perception of bias in the client's favour. In fact, if anything we may have biased results in the other direction [Athena1998]*."*

The report notes several areas where Athena was conservative with PCCP data including: ignoring the subgrade benefits of narrower PCCP structure, using only 10 % fly ash in PCCP mix, PCCP design may be conservative on amount of granular, RAP treated as free of environmental burdens, and no salvage value given to PCCP option [Athena1998].

3.2 **Reduced Carbon Dioxide (CO_2) Emissions from Operating on PCCP**

Differences in fuel consumption as a function of pavement structure are an important consideration for users and government agencies. Heavy vehicles cause greater deflection on flexible pavements than on rigid pavements. This increased deflection of the pavement absorbs part of the vehicles rolling energy that would otherwise be available to propel the vehicle. Thus, the hypothesis can be made that more energy and therefore more fuel is required to drive on flexible pavements [Zaniewski 1989].

Several studies have been completed that support these findings. The first study was part of a larger 1989 study to update vehicle operating costing tables by the Federal Highway Administration (FHWA) for the World Bank. In this study, the FHWA found that the savings in fuel consumption for heavy vehicles traveling on concrete versus asphalt pavements was up to 20% [Zaniewski 1989].

Considering the results of the FHWA work, the Cement Association of Canada (CAC) initiated its own series of studies to investigate the potential truck fuel savings when operating on concrete pavement compared to asphalt pavement. In the fall of 1998 a small test study was undertaken to verify the findings of the FHWA work. Based on the findings of the Phase I study CAC contracted NRC to perform a second and much more detailed study during 1999 and 2000 comparing several PCCP, ACP and composite pavements roadways in Quebec and Ontario. This Phase II study also included several other variables in the analysis including:

- Pavement roughness (IRI<1.5, IRI>2)
- Vehicle type (Semi-trailer, Straight, B-train)
- Load (Empty, Half, Full)
- Speed (100, 75, 60 km/h)
- Seasons (Spring, Summer, Fall and Winter)
- Temperature (<-5,-5 to 10, 10 to 25, >25 ° C)
- Grade < 0.5%
- Ambient wind (< 10km/h average)

In-cab state-of-the-art real time computerized data collection equipment along with Cummins supplied in-site software was used in the tractor trailer unit to collect and calculate instantaneous fuel flow while traveling over the desired pavement locations. The tanker semi-trailer data was analyzed using a multivariate linear regression analysis tool to determine the potential savings and the statistical significance of the results. The results of the Phase II MVA Study entitled, "Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption" showed statistically significant fuel savings for heavy vehicles operating on PCCP versus ACP as follows:

- 4.1 to 4.9 % compared to ACP at 100 km/hr
- 5.4 to 6.9 % compared to ACP at 60 km/hr [Taylor et al 2002]

Based on the request of several Government agencies a third fuel study was undertaken by NRC to verify the Phase II study findings. This study, however, was funded under the Government of Canada Action Plan 2000 on Climate Change with some dollars from the Cement and Concrete Industry. Terms of reference for the study were set by a government committee that included people form various organizations including Natural Resources Canada, the Ministry of Transportation of Ontario (MTO), Ministère des Transport du Quebec (MTQ) and others. Like the Phase II study this was a year long study comparing fuel consumption data for ACP, PCCP and composite pavements. The main difference with this Phase III study and the Phase II study was the test vehicle was a van semi-trailer and the DOTs chose the sections to test in Ontario and Québec.

The results of the Phase III Fuel Study show statistically significant fuel savings for heavy vehicles traveling on PCCP compared ACP ranging as follows:

- 0.8 to 1.8 % savings compared to ACP pavement at 100 km/h.*
- 1.3 to 3.9 % savings compared to ACP pavement at 60 km/h.*

* This excludes summer night data which was not statistically significant [Taylor 06].

Based on the finding of these two detailed studies one can confidently say there is statistically significant fuel savings from operating on PCCP compared to ACP ranging from 0.8 to 6.9 %. Using this information one can estimate the potential CO_2 savings of operating a heavy vehicle on PCCP by calculating the fuel savings realized over a year of driving and converting it into CO_2 values. For example, a tractor - trailer with a diesel engine travelling 160 000 km / year and averaging 43 litres / 100 km, the CO_2, NOx, SO_2 savings for each motor unit would be the following:

- 0.8% fuel savings = ↓1.40 t of CO_2; ↓19.82 kg of NOx; ↓2.51 kg of SO_2;
- 4% fuel savings = ↓7.03 t of CO_2; ↓59.45 kg of NOx; ↓7.52 kg of SO_2;
- 6.9% fuel savings = ↓12.3 t of CO_2; ↓99.08 kg of NOx;↓12.53 kg of SO_2

Another way of showing the potential savings is to provide an example of what the effect of converting a section of highway from asphalt to concrete pavement would be. For example, if Highway 20 from Montreal to Quebec City, which carries approximately 2,290,000 trucks per year, was all concrete pavement, the annual reduction in fuel consumption and associated reduction in CO_2 would be as follows:

- Total fuel and CO_2 reduction at 0.8 % savings – 2,089,318 litres and 4,618 tonnes
- Total fuel and CO_2 reduction at 6.9 % savings – 18,020,369 litres and 49,783 tonnes

Based on the evidence identified above it is conservative to say that there are significant GHG savings when operating tractor-trailers on PCCP versus ACP, which also means less pollutants being emitted into the environment. Furthermore, the reduced fuel consumption decreases trucking firms' operating costs, thereby, possibly reducing cost of goods to consumers.

3.3 Reusable and Recyclable Paving Material

Concrete pavement can be placed over deteriorated asphalt pavement to provide a new pavement structure. This type of paving process is known as "whitetopping" and utilizes the existing asphalt pavement structure as a strong base for the new concrete overlay. In fact, the known performance of the asphalt pavement will minimize the potential for pumping, faulting and loss of support in the new concrete pavement. No repairs are required to the existing ACP unless there are large areas of soft spots or the pavement ruts are over 50 mm. The key point is that the asphalt pavement is reused and becomes part of the new PCCP structure.

Concrete pavement is also a versatile product which can be reused by performing concrete pavement restoration (CPR) techniques on the damaged areas. Repair techniques such as full depth / partial depth repairs and load transfer restoration combined with diamond grinding will restore the pavement to an almost new state. Pavements in an advanced state of deterioration may be able to be left in tack and used as a base for a new PCCP. In these cases a thin layer of asphalt of 25 to 50 mm is placed over the old PCCP and then over laid by a new PCCP.

Another possible reuse option for PCCP is a bonded overlay. When traffic patterns change and a roadway is receiving substantially more traffic than originally designed for a bonded overlay can be used to increase the PCCP thickness. As long as the underlying pavement is in good condition a new layer of concrete pavement can be placed over the existing PCCP by bonding the new layer to the old surface and matching joints locations. This effectively increasing the amount of traffic the pavement structure can handle and increases the pavements expected life.

Concrete pavement is also a 100 percent recyclable material and provides government agencies an attractive option at reconstruction time. If subgrade or pavement condition does not allow the older PCCP to be reused in its existing state it can be rubblized and used as granular fill, base course for new pavement and / or as an aggregate for new concrete pavement. In addition, the steel in the PCCP such as dowels and tie bars can be recycled [ACPA 1993]. In fact, a company in the United States is developing a prototype machine called Paradigm which is an in-place recycling system for concrete pavements. This machine breaks and crushes the concrete into the desired aggregate sizes and collects the reinforcing steel. The system is still in the experimental stage of development.

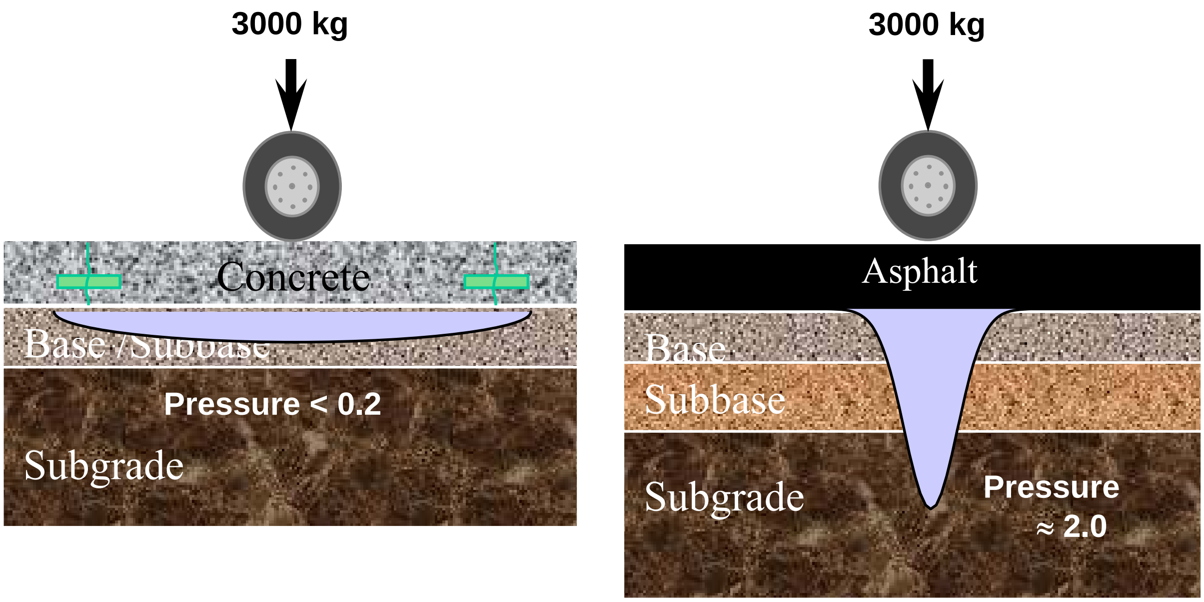
Reusing the concrete pavement minimizes the amount of non-renewable resources required for a new pavement structure and eliminates potential material going to landfill sites. In addition, the short hauling distance for the aggregate reduces the cost of providing aggregates to the job.

3.4 **Utilize Less Granular Material**

The essential difference between flexible and rigid pavements is the manner in which they distribute the load over the subgrade. Figure 8 below illustrates how PCCP and ACP carry heavy vehicles loads. Because of concrete's rigidity and stiffness, the slab itself supplies the major portion of a rigid pavement's structural capacity and distributes the heavy vehicle loads over a relatively wide area of the subgrade. On the other hand, flexible pavement which is built with weaker and less stiff material does not spread loads as well as concrete. Therefore, more of the heavy vehicle's load is distributed into the base and subbase layers of the flexible pavement structure. This results in the flexible structure usually requiring more layers and greater thickness to the layers for optimal transmission of the vehicle load to the subgrade [ACPA 2004]. An exception to this is when Government agencies specify granular thicknesses based solely of frost protection.

Applied Research Associates, Inc. ERES Consultants Division prepared an analysis on equivalent pavement designs for flexible and rigid pavements. In this paper ERES identifies the amount of granular material required in the base, subbase and shoulders for the PCCP and ACP structures. For arterial roads on low strength subgrade the report recommends the following pavement structures: PCCP (200 mm, 150 mm base and 150 mm subbase) and

ACP (175 mm ACP, 150 mm base and 585 mm subbase) [ERES 2003]. Based on these structures there is approximately twice as much granular material used in the asphalt structure. The environmental effect of this increased usage of granular material is magnified as the hauling distance to job sites increases due to depletion of suitable aggregate sources, thereby, increasing the fuel consumed by the gravel haul trucks and the CO_2 emitted from them. Therefore, a concrete pavement structure provides a more sustainable pavement when considering aggregate use.



Concrete acts more like a bridge over the subgrade. cm for cm much less pressure is placed on materials below concrete than on asphalt pavements

Figure 8: Typical Load Distribution for Flexible and Rigid Pavement Layers

3.5 **Use of Industrial by-products**

Concrete pavement is a mixture of fine and coarse aggregate, cement, water and admixtures. However, it is possible to replace a portion of cement with a variety of industry by-products often referred to as supplementary cementing materials or SCMs. These materials if used in the proper proportions will enhance the properties of the concrete mix, as well as, stabilize the by-product material in the pavement structure rather than dumping them at local landfill sites. The three most commonly used SCMs are fly ash (by-product of coal burning), blast furnace slag (by-product of steel manufacturing) and silica fume (by-product of manufacture of silicon or ferrosilicon alloy). Some of the enhanced properties of using SCMs include improved concrete pavement durability, permeability and strength. Fly ash and blast furnace slag also increase workability of the concrete mixtures. Fly ash, blast furnace slag and silica fume can also control alkali - silica reactivity also known as ASR (a chemical reaction that occurs when free alkalis in the concrete combine with certain siliceous aggregates to form an alkali-silica gel. As the gel forms, it absorbs water and expands, which cracks the surrounding concrete) [Kosmatka et al 2002].

Another added benefit of utilizing SCMs in concrete pavement is the reduction of CO_2 emissions associated with the PCCP. The SCMs replace a portion of the cement in the concrete mixture and thereby decreases the total amount of CO_2 associated with the construction of PCCP structure. The amount of CO_2 reduction is related to the percentage of the SCM used in the mix design. Details on what is done on the use of SCMs across Canada and in the Northern States can be found in a report completed in March 2005 by Norman MacLeod entitled, "A Synthesis of Data on the Use of Supplementary Cementing Materials (SCMs) In Concrete Pavement Applications Exposed too Freeze / Thaw and Deicing Chemicals".

3.6 **Use of pervious pavements**

Pervious pavements have been around for some time and can be constructed of concrete or asphalt surfaces. The Green Building movement, however, has brought more of a focus on this technology as an environmentally friendly product. Pervious concrete pavements also known as "no fines concrete" or "porous concrete" are comprised of specially graded coarse aggregates, cementitious materials, admixtures, water, possibly fibres and little or no fines. Mixing these products in a carefully controlled process creates a paste that forms a thick coating around aggregate particles and creates a pavement with interconnected voids in the order of 12 to 35 percent. This provides a pavement that is highly permeable with drainage rates in the range of 100 to 750 litres per minute per square meter [Brown 2003]. The most common uses of this pavement are parking lots, low traffic pavements, and pedestrian walkways. Figure 9 shows a picture of a pervious pavement integrated with the existing trees and grass areas.

Figure 9: Pervious Concrete Pavement Integrated with Natural Vegetation

Pervious concrete pavements reduce storm runoff and minimize the amount of pollutants (car oil, anti-freeze and other automobile fluids) contained in storm water that is captured. By allowing the rainfall to percolate into the ground, soil chemistry and biology are allowed to naturally "treat" the polluted water [Brown 2003]. This allows for reduction in storm water retention areas. These pavements also recharge groundwater thereby, reducing the need to water trees and shrubs in the paved areas. The light coloured pavement surface is also a solution to the heat island effect.

Pervious concrete pavements have been used mainly in areas with minimal freeze-thaw (F/T) issues. However, a number of installations have been completed in Northern US states. In addition, experimental sections of pervious pavement have been placed in Halifax and Toronto and appear to be performing well. The National Concrete Pavement Technology Center at Iowa State University has produced a document on pervious pavement entitled "The Freeze-Thaw Durability of Pervious Concrete". This document can be obtained at the following URL: http://www.ctre.iastate.edu/reports/mix_design_pervious.pdf . Other studies are also underway to investigate the use of pervious pavements in F/T climates.

Clogging of pervious pavements can occur and in many cases is due to design issues. For example, where natural areas with grass or exposed soils is allowed to drain stormwater across the pervious pavement surface a fine material may be deposited in localized areas of the pavement. Routine sweeping or vacuuming of the pavement surface will remove this material or any vegetation matter that may collect on the pavement. In addition, pressure washing will restore the porosity of clogged pervious concrete to nearly new conditions.

3.7 **Potential CO_2 Sink**

The Portland Cement Association contracted Construction Technology Laboratories, Inc., to investigate the current state of understanding of the absorption of CO_2 by concrete (also known as carbonation) and estimate the amount of CO_2 removed from the atmosphere by the carbonation of concrete. Sixteen literature references were reviewed and summaries of the documents were provided. The report estimates 200,000 metric tons of CO_2 would be absorbed the first year after construction assuming a typical U.S. concrete production year and 13.6% fly ash in the mix. The concrete will continue to absorb CO_2 throughout its life and over 100 years this concrete would absorb nearly 2.1 million metric tons of CO_2. If no fly ash is used in the mix the amount of CO_2 absorbed by the concrete would increase by 32% [Gajda 00].

4.0 **Economic Benefits**

Concrete pavement provides many economic advantages compared to other types of pavement structure. Some of the advantages are of follows: life cycle cost analysis, two-pavement system, truck fuel savings, eliminates spring weight restrictions and reduced lighting requirements.

4.1 **Life Cycle Cost Analysis Advantage**

The concept of Life Cycle Cost Analysis (LCCA) is to combine the incurred cost and accrued benefits over different periods of service lifetime in a consistent manner. Whether the basis is the present value, annualized cost, future cost, salvage value or some rate of return measure, the heart of the reduction is the use of an appropriate discount rate.The decision to use LCCA as part of the alternate bid process provides government agencies with better knowledge of the true cost of a roadway rather than just consider the initial cost of the pavement. The greater the level of detail provided in the LCCA the better the agency is equipped to make an informed decision on which pavement type is the best for that particular job. The key points to consider in a LCC analysis are as follows:

1) Use of equivalent ACP and PCCP design sections
2) Selection of accurate maintenance and rehabilitation (M&R)activities schedules
3) Selection of appropriate discount rate
4) Inclusion of user costs such as user delay and accident costs
5) Inclusion of sustainability of pavement type

The American Concrete Pavement Association has prepared an in depth Engineering Bulletin entitled "Life Cycle Cost Analysis: A Guide for Comparing Alternate Pavement Designs" which gives a detailed review of the basic factors in the analysis such as Agency costs, user costs, and discount rate.

There have been nine alternate bid tenders called across Canada since 2000. Six of these projects were tendered in Ontario, two in Alberta and one in Nova Scotia. Table 2 below gives a summary of the projects with the year tendered, project length, concrete LCCA advantage, discount rate used in the analysis and pavement type selected.

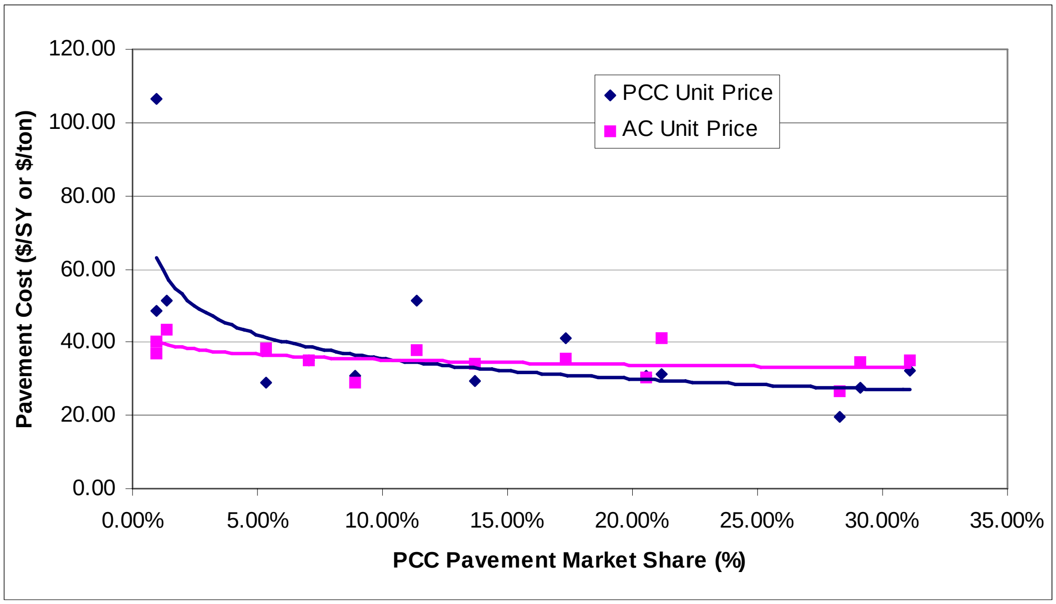
Table 2: Summary of Alternate Bid Tender Projects in Canada

Location	Tender Year	Project Length (Lane km)	Concrete LCCA Advantage ($)	Discount Rate	Pavement Tpye Selected (ACP / PCCP)
Highway 101, NS	2003	21.8	$1.5 M or 20% more than ACP	NA	PCCP
Highway 417 E, ON	2000-01	78.2	433,321	7	PCCP
Highway 417 W, ON	2004-05	73.8	860,719	5.3	PCCP
Highway 401, Chatham, ON	2004	63.6	620,219	5.3	PCCP
Highway 401, Chatham Ph2, ON	2005	75.6	588,969	5.3	PCCP
Highway 401, Chatham Ph3, ON	2006	93.6	548,551	5.3	PCCP
Highway 410, ON	2006	21.6	378,780	5.3	PCCP
Deerfoot Trail, AB	2002	44 + PCCP shoulders	3,522,000	4	ACP
Anthony Henday, AB	2004	58 + PCCP shoulders	2,372,800	4	PCCP

Source: tender documents

4.2 **Advantage of Two-Pavement System**

A study by ACPA of data from the Oman System, State data system, for 14 states confirmed that states who utilize a two-pavement system get a much larger "bang for the buck" than states that utilize only one pavement type. The research shows competition between the two paving industries lowers the average unit cost for both the PCCP and ACP, thereby, allowing the government agencies to place more pavement for the same dollars spent. Figure 3 below illustrates that as the market share becomes more balanced between the amount of ACP and PCCP being placed, the average unit cost of the asphalt and concrete pavements goes down. This translates into government agency being able to pave more roadways with the same amount of funding levels compared to a single pavement system [ACPA 2005].



States: 5-year average for data for GA, IL,IN,KS,KY,MD,MO,NC,OH,PA,TN,VA,WI,WV

Figure 3: Benefit of a Two-Pavement System on Pavement Costs

The ACPA article notes one way to use this graph above is a "break-even analysis." An agency can run "what if" scenarios as shown in Table 3, to find out what would happen if they had varying degrees of a two-pavement system. For example, assume a state spends $200 Million (M) US per year on pavement items and they spend 100% of their pavement dollars on ACP. At this level, with no competition *between* industries, the asphalt would cost approximately $40/ton US. Thus, the state is buying about 5M tons of asphalt for their $200M. Now assume the state makes a commitment toward using some PCCP. Assuming the state plans to spend the same amount of money (i.e. $200M US), but this time they will spend 10% on PCCP. In this scenario, the asphalt prices drop to approximately $35.25/ton US on the asphalt and $35.50/SY US on the concrete. For the same amount of money, the state can still afford the approximate 5 Million tons of asphalt, but because competition results in *lower* asphalt prices, they can use the balance ($20M US) to buy 560,000 SY of concrete (at $35.50/SY US). Essentially, by showing a commitment to concrete, an agency lowers the asphalt price enough to virtually get the concrete free. Therefore, committing to two pavement types allows the Government agencies to place more pavement surface for the same price when using only one type of pavement. Table 3 also shows that at 30% PCCP market share there is only a 15 % reduction AC tons, while the agency would get over 2.2M SY of long-life concrete pavement. Therefore, the agency and ultimately the taxpayer are provided with more paved roadways for the same investment [ACPA 2005].

Table 3- Break-even Analysis for $200M / year Pavement Expenditures

Investment Total	Concrete Market Share	Expenditures on Asphalt ($)	Asphalt Unit Price ($)	Tons of Asphalt	Expenditures on Concrete ($)	Concrete Unit Price ($)	Square Yards Concrete
$200,000,000	0%	$200,000,000	$ 40.00	**5,000,000**	-	-	-
$200,000,000	1%	$198,000,000	$ 39.87	4,966,009	$2,000,000	$ 62.48	32,012
$200,000,000	5%	$190,000,000	$ 36.63	5,186,919	$10,000,000	$ 42.12	237,427
$200,000,000	**10%**	$180,000,000	$ 35.24	**5,108,553**	$20,000,000	$ 35.54	**562,747**
$200,000,000	15%	$170,000,000	$ 34.42	4,939,181	$30,000,000	$ 32.18	932,281
$200,000,000	20%	$160,000,000	$ 33.84	4,728,210	$40,000,000	$ 29.99	1,333,815
$200,000,000	25%	$150,000,000	$ 33.39	4,492,341	$50,000,000	$ 28.39	1,760,956
$200,000,000	**30%**	$140,000,000	$ 33.02	**4,239,459**	$60,000,000	$ 27.15	**2,209,679**

Source: ACPA 2005

4.3 **Truck Fuel Savings Driving on Concrete Pavement Reduced Fuel Costs**

As discussed in the environmental benefits sections concrete pavement provides reduced CO_2 emissions due to heavy truck fuel savings. These fuel savings reduce trucking firms' or independent truckers' operating costs which could lead to reduced consumer prices if the savings are passed along. Using the same assumptions as in the environmental section an example of the magnitude for potential truck fuel savings can be shown. Based on a tractor - trailer with a diesel engine travelling 160,000 km / year, averaging 43 L / 100 km and diesel fuel cost of $ 0.80 per litre the fuel savings for truckers would be as follows:

- 0.8 % fuel economy the truck fuel savings would be $ 440 per year per truck.
- 4 % fuel economy the truck fuel savings would be $ 2,202 per year per truck.
- 6.9 % fuel economy the truck fuel savings would be $ 3,798 per year per truck.

This could provide substantial savings to company operating costs depending on the number of trucks the firm is operating.

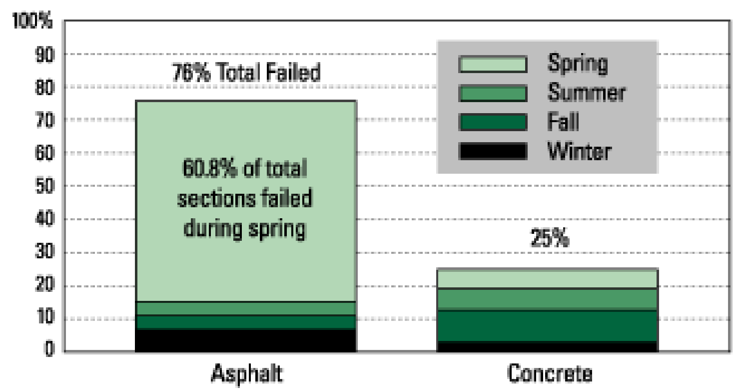
Taking the values calculated in the example in Section 3.2 on converting the heavily truck traveled (approximately 2,290,000 trucks per year) Highway 20 from Montreal to Quebec City to concrete one can also estimate the over all diesel fuel savings. In addition, assuming a $15 per tonne credit for CO_2 reduction one can calculate a dollar value for this too. Therefore, the over all savings (i.e. total fuel savings and CO_2 credit savings) for converting this section of highway to PCCP would be as follows:

- at 0.8 % fuel savings = $1,671,545 fuel saved + $69,270 CO_2 credits = $1,740,742
- at 6.9 % fuel savings = $14,416,295 fuel saved + $746,745 CO_2 credits = $15,163,040

4.4 **Eliminates Spring Weight Restrictions**

Concrete's durability is most evident during Canada's spring thaw season. Simply put, concrete is not affected by seasonal weakening of the subgrade during spring thaw, as are many asphalt pavements. A Study by the AASHO Road Test showed that 61% of asphalt roads fail during spring conditions compared to 5.5% for concrete as shown in Figure 8 [ACPA 98].

Although asphalt pavement design has changed since the original AASHO tests there is still concern with the strength of asphalt structures during spring thaw periods. This is evident in the fact that many provincial Departments of Transportation (DOTs) still put spring weight restrictions on truck traffic to minimize road damage during this period. In fact, the Ministère des Transports du Quebec (MTQ) employs spring weight restrictions on all their highway systems including the Trans Canada Highway (TCH). In addition, although the New Brunswick Department of Transportation does not reduce allowable weight on the TCH during the spring thaw period, it does not allow the extra axle tolerances that it does at other times of the year.



Source: American Concrete Pavement Association Engineering Bulletin - Whitetopping – State of the Practice, ACPA 1998

Figure 8: Example of the Weakening of Asphalt Roads During Spring Months in the Data from AASHO Road Test

4.5 **Reduced Lighting Requirements**

As stated in the environmental and social benefits section PCCP's light reflective surface provides a pavement surface that minimizes heat island effect in urban areas as well as provides better night time visibility for the driving public. These advantages can also translate into an economic savings. A report entitled "A Comparison of Six Environmental Impacts of Portland Cement Concrete and Asphalt Cement Concrete Pavements" notes that concrete pavement's mode of reflectance is mostly diffuse (R1 class) compared to asphalt pavement's mode of reflectance typically falling in slightly specular (R3 class). Therefore, ACP requires more lights per unit length of ACP pavement to achieve the same illumination as PCCP. The report goes on to identify the potential cost savings when utilizing concrete pavement compared to asphalt pavement based on a 1985 Chicago example. The results show the cost savings represent 31 % decrease in initial, energy and maintenance costs for lighting PCCP versus ACP pavement. [Gajda 97]

5.0 **Conclusion**

For the general public to get the most cost effective pavement structure Government agencies must look at more than just the initial cost of the pavement in the pavement selection process. It is clear from the preceding sections of this paper that concrete pavement has many sustainable benefits which should be considered by roadway decision makers when trying to compare the overall cost of one type of pavement alternative to another. Environmental benefits of PCCP include important issues such as reduced energy and aggregate consumption, reduced CO_2 emissions, reusable construction material, and use of industrial by-products in the concrete mix design. Social benefits of PCCP centre on roadway safety issues and passenger ride and comfort, while economic advantages include life cycle cost advantage, two- pavement system, truck fuel savings, elimination of spring weight restrictions, and reduced lighting requirements.

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