A LIFE CYCLE PERSPECTIVE ON CONCRETE AND ASPHALT ROADWAYS: EMBODIED PRIMARY ENERGY AND GLOBAL WARMING POTENTIAL

Submitted to:
CEMENT ASSOCIATION OF CANADA

By:
ATHENA SUSTAINABLE MATERIALS INSTITUTE

September 2006

Executive Summary

This study presents estimates of embodied primary energy usage and global warming potential over a 50 year "life cycle" for the construction and maintenance of comparable flexible asphalt and rigid Portland cement concrete pavement structures across the following road types and regions:

- typical Canadian arterial roadways;
- typical Canadian high volume highways;
- a Quebec urban freeway; and,
- a section of the Highway 401 freeway in Ontario

The primary study units are two-lane kilometer (including inner and outer shoulders) lengths of roadway that are functionally equivalent in terms of accepted road design criteria. For the section of Highway 401 in Ontario, the study unit is a three-lane kilometer including shoulders. In all cases, the assumed study period is 50 years, a period which takes into account original road construction and major, material related, rehabilitation activities for both asphalt and concrete pavement types.

Study Scope and Boundaries

For all road type cases, the system analysis boundaries are set at the sub-grade and the finished road and shoulder surfaces. The study therefore takes account of material use and construction for the granular sub-base, base, shoulder and finished road and shoulder surfaces. Activities common to both concrete and asphalt roadways such a right-of-way clearing, sub-grade construction, lane divider painting, barrier construction and right-of-way restoration are excluded.

The asphalt and concrete Canadian average arterial and high volume roadway designs were developed in a separate report prepared for the Cement Association of Canada (CAC) by Applied Research Associates (December, 2003). The report considers two sub-grade foundation types for each road type and material design. Both the Quebec freeway and the Ontario Highway 401 asphalt and concrete pavement material quantity take-offs were developed by provincial Ministry of Transportation staff and were received from CAC offices in Montreal and Toronto, respectively.

Since the study deals with embodied primary (fossil) energy and greenhouse gas emissions for initial road construction and major rehabilitation activities, it primarily reflects the effects of producing and transporting materials and components e.g. concrete, asphalt, steel dowel and tie bars, granular materials, recycled materials.

The scope does not include operational considerations that may differ by road type for example, energy use by trucks and lighting in urban areas. These uses of energy should be taken into account in any decisions predicated on life cycle environmental effects, but they are beyond the scope of this study and should be the subject of a separate investigation.

Method

Regionally specific estimates were developed for the primary energy and greenhouse gas emissions associated with the production and transportation of a unit (i.e. cubic metre or tonne) of each of the materials identified as potentially significant during pavement design. The primary energy estimates include the upstream or pre-combustion energy necessary to extract, process or manufacture and transport primary fuels to their point of use. In the case of electricity generation, the study also accounts for regional generation efficiency by fuel type and transmission line losses to estimate the net primary energy and greenhouse gas emissions associated with delivering a unit of electricity.

In the asphalt cases, separate energy and greenhouse gas emissions estimates were developed for 0% and 20% recycled asphalt pavement (RAP) in the final asphalt hot mix. Also, the asphalt concrete energy estimates include the inherent or feedstock energy attributable to new asphalt (as opposed to RAP).1 The feedstock energy component of total embodied primary energy is depicted separately in all of the results so that its significance can be readily seen.

All greenhouse gas emissions estimates (CO2, CH4 and N2O) are converted to a measure of direct global warming potential (GWP) using the well-accepted CO2 equivalence method as developed by the International Panel on Climate Change.

The energy and GWP estimates per unit of material are then combined with the pavement structure design and rehabilitation quantity take-off scenarios to develop comparative embodied primary energy and GWP estimates per roadway functional unit for each of the asphalt and concrete pavement scenarios.

Results

Chart 1 below shows the embodied primary energy results for flexible asphalt concrete (AC) and rigid Portland cement concrete (PC) pavement designs for a two-lane kilometer of the Canadian high volume highway for two sub-grade foundation support classes (California Bearing Ratios 3 and 8). Although the absolute numbers change from one road class and region to another, the pattern of results is similar for the other four roadway designs.

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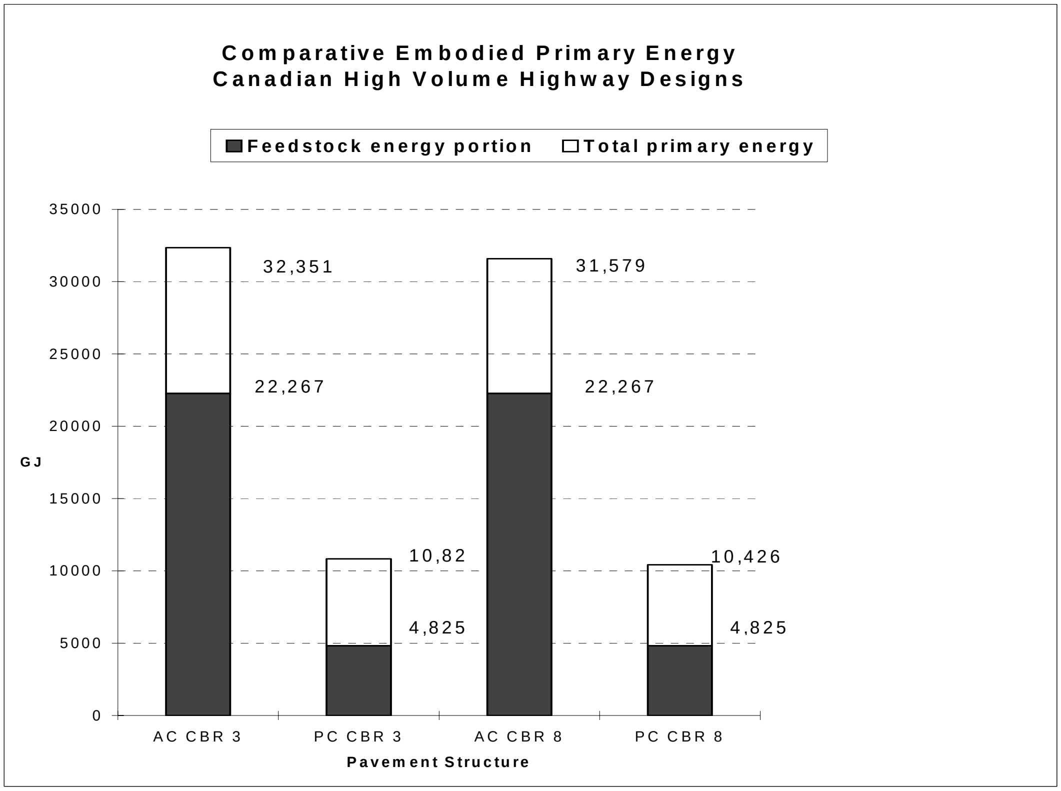
[1] Feedstock energy is the gross combustion heat for any material input to a product system which may be considered as an energy source, but is not being used as such. Bitumen clearly falls into this category. The Alberta tar sands are an example of bitumen being extracted and refined for energy production purposes.

Chart 1: Comparative Embodied Primary Energy, Canadian High Volume Highway Designs



Note: Displayed results are for 0% RAP case and 2-lane km

For all six pavement structural design comparisons, the asphalt concrete alternatives clearly require significantly more energy than their Portland cement concrete pavement counterparts from a life cycle perspective. Table ES1 identifies the additional primary energy used by the various asphalt pavement designs relative to their alternative concrete pavement designs. The feedstock energy component is the largest contributor to total energy for all of the asphalt concrete pavement structures. Even when feedstock energy is excluded, Portland cement concrete pavements still shows a significant energy advantage relative to their asphalt counterpart. Across the two-lane kilometer designs, the energy advantage of Portland cement concrete roadways grows as soil bearing capacity declines or as the class of roadway increases.

The inclusion of 20% RAP in the binder course mix for the Canadian arterial and high volume highway designs reduces the embodied primary energy estimates. For the concrete highway option which included asphalt shoulders and asphalt overlay as part of the maintenance and rehabilitation schedule, the embodied primary energy usage would be 3.5 to 5% less. The asphalt pavement option would be 5.0% to 7.5% less. While these reductions in energy use for asphalt narrow the gap between asphalt and concrete, the remaining differences are still significant.

Table ES1
Additional Embodied Primary Energy Used by
Asphalt Pavement Design Alternatives

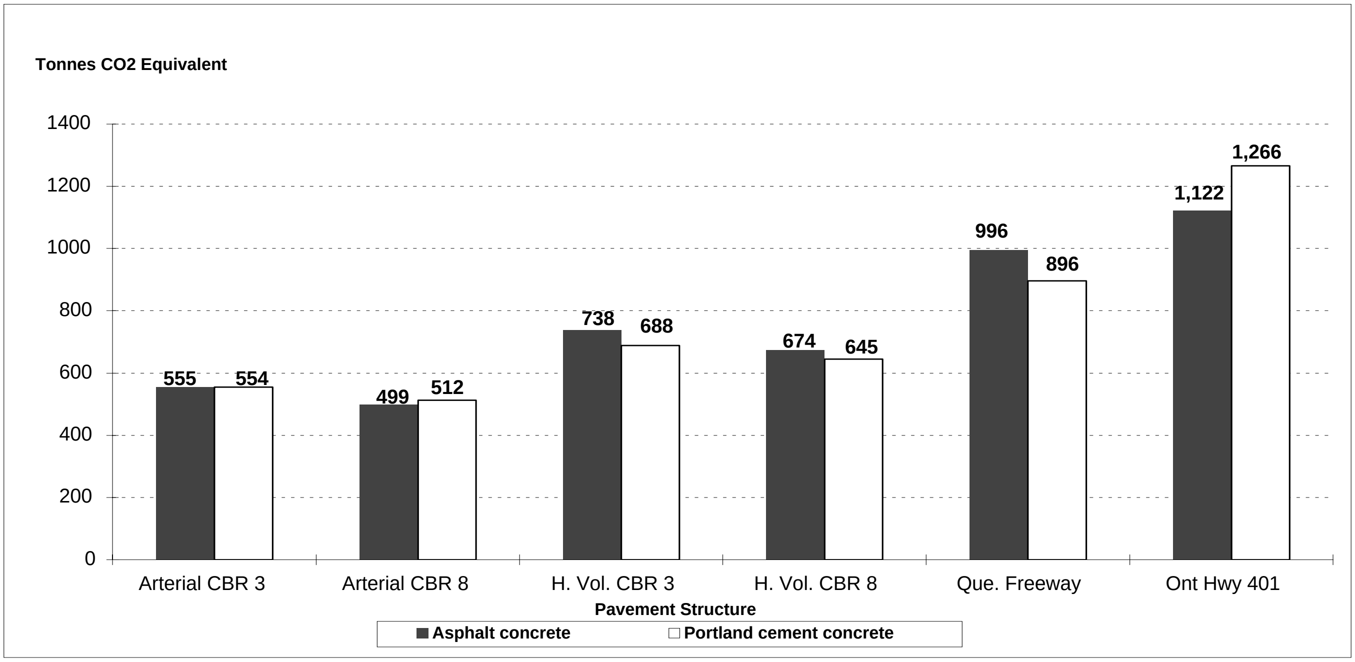
Highway Classification	Additional Embodied Primary Energy Used by Asphalt Pavement Design Alternatives	
	Including feedstock energy	Excluding feedstock energy
Canadian Arterial Highway		
- CBR 3	3.9 times more	67 % more
- CBR 8	4.1 times more	68 % more
Canadian High Volume Hwy		
- CBR 3	3.0 times more	66 % more
- CBR 8	3.0 times more	67 % more
Quebec Urban Freeway	5.3 times more	81% more
Ontario Highway 401 Urban Freeway	2.3 times more	31 % more

The global warming potential (GWP) results for the Canadian high volume highway design cases are shown in Chart 2 below. Across both subgrade foundation classes, the concrete pavement design has a small advantage over its asphalt counterpart. The study results indicate that neither material design has a distinct advantage across the two-lane kilometer roads. The GWP differences in favour of concrete range from less than 1% to as much as 7% and increase as one moves from arterial to high volume designs. However, they are generally within the 10% error or confidence interval of the life cycle inventory (LCI) study and should be considered insignificant.

Of the two-lane kilometer designs, it is only the Quebec urban freeway design that shows a marginally significant difference between the two alternative material designs – the flexible asphalt concrete design's global warming potential emissions are some 11% higher than that of the rigid, Portland cement concrete pavement design. This higher GWP result for the flexible asphalt concrete is primarily a function of two factors: (1) the need to resurface the asphalt concrete road more frequently and the requirement to reconstruct the flexible asphalt concrete roadway some 17 years earlier than the rigid Portland cement concrete roadway.

The Ontario Highway 401, three-lane kilometer roadway also demonstrated a marginally significant difference in GWP between the two material designs, with the flexible asphalt concrete design showing a 11% lower GWP over the 50-year planning cycle. The result is a function of the greater use of materials in the initial road construction (3 lanes rather than two) and the greater use of Portland cement concrete relative to the asphalt concrete in the initial designs. Chart 2 underscores these observations, whereby the difference in direct energy use for the two alternatives is the lowest for the Ontario Highway 401 road design.

Chart 2: Comparative GWP at 0% RAP



The report also investigated the sensitivity of the energy and GWP results to increased haul distances for granular materials used in both roadway material designs and the replacement of asphalt concrete pavement shoulders with Portland cement concrete pavement for the Canadian high volume highway. Because asphalt concrete roadways incorporate higher amounts of granular materials than their Portland cement pavement counterparts, any additional haul distance for granular materials would favour Portland cement concrete pavement options. However, these haul distances would need to be in the order of 80 km greater than assumed in this study before they would make an appreciable difference in the results for either roadway material design.

Replacing asphalt concrete shoulders with Portland cement concrete pavement in the concrete pavement design for the Canadian high volume highway indicated a 83% reduction in embodied primary energy, but a 7% increase in GWP, compared to the asphalt pavement design.

GLOSSARY OF TERMS

TERM	DEFINITION
Primary Energy	Fossil fuel resources required by system processes including pre-combustion fossil energy (see pre-combustion energy below).
Pre-combustion Energy	Fossil fuel resources used to extract, process and deliver fossil fuel resources to their point of use (also referred to as “indirect primary energy” or “upstream energy” use).
Feedstock Energy	The gross combustion heat value of any fossil hydrocarbon material input to a product system which is an energy source, but is not being used as an energy source (e.g, bitumen) including its related pre-combustion energy.
Embodied Primary Energy	Sum of primary energy and feedstock energy.
California Bearing Ratio	(CBR) is a penetration test for evaluation of the mechanical strength of road sub-grades. It was developed by the California state highways department to measure the load-bearing capacity of soils supporting roads.

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A LIFE CYCLE PERSPECTIVE ON CONCRETE AND ASPHALT ROADWAYS: EMBODIED PRIMARY ENERGY AND GLOBAL WARMING POTENTIAL

1. INTRODUCTION

Over the past 20 years, environmental issues have assumed an increasing priority for both government and private industry alike. Here in North America, the emphasis has gradually broadened from a site-specific focus on environmental degradation to include the characterization of product attributes. With Canada's signing of the Kyoto Protocol, greenhouse gases and their effect on the climate have taken centre stage with respect to policy and legislation, as well as general concern voiced by the public. Similarly, many private companies have placed increasing emphasis on environmental information and often share this information with their customers.

The Cement Association of Canada (CAC) commissioned the Athena Sustainable Materials Institute to update the previously completed 1999 study estimating the embodied primary energy and global warming potential associated with initial construction and maintenance of various types of concrete and asphalt roadways. This study reflects new or updated information concerning both pavement design and life cycle inventory data for various road construction materials. Because of the changes that have occurred on several fronts over the last half-decade, this study bears little resemblance to the earlier one and they should not be compared.

Although it deals only with two selected environmental effects, CAC emphasized that the study should be comprehensive and that it should adhere to accepted Life Cycle Assessment (LCA) standards and guidelines. LCA, and especially its most developed component, life cycle inventory analysis (LCI), is a tool that provides quantitative and scientific analyses of the environmental impacts of products and systems. By providing an unbiased analysis of entire industrial systems, LCA has shown that the reality behind widely held beliefs regarding environmental issues is often more complex than expected. In order for LCA to be an effective and accepted approach, standard guidelines have been developed and have evolved over time, with the most recent standards developed by the International Organization for Standardization (ISO). The Institute's own LCA methodology has evolved over time and adheres to LCA standards as set out by ISO; most notably, to clearly list all the assumptions and data sources used in the LCA in an objective and transparent manner. We have therefore been concerned from the proposal stage onward about ensuring transparency, the definition of functionally equivalent units, and appropriate scope and system boundary conditions.

1.1 PROJECT PLANNING

The audience for this report is likely to include individuals and organizations outside CAC and may be used for promotion or marketing purposes.

1.1.1 Definition of Functionally Equivalent Units

We examined the following three types of concrete and asphalt road systems:

- arterial roads or conventional unrestricted access highways (treated as one type of road as they typically require similar materials and are constructed using similar equipment and techniques);

- high volume highways; and
- urban freeways (in Quebec and Ontario).

For the Canadian and Quebec road types, the study unit is a two-lane kilometer of functionally equivalent road with functional equivalence defined in terms of accepted road design criteria (see Section 2). The Ontario road design was studied on a functionally equivalent three-lane kilometer basis; i.e., one side of a six-lane freeway with three lanes in either direction, but we studied only three lanes with traffic in one direction.

1.1.2 Scope and System Boundaries

The scope is restricted to a life cycle inventory (LCI) analysis of embodied primary (fossil) energy and greenhouse gas emissions, with the latter combined in a CO_2 equivalence or characterization measure to show global warming potential.

The following are additional scope and system boundary conditions specific to this study.

1. For the purposes of this study, the road system analysis boundaries are set at the sub-grade and at the finished road surface, inclusive of road shoulder materials. The study therefore takes account of material use and construction for the granular sub-base, base, shoulder and finished road and shoulder surfaces. It excludes right-of-way clearing, sub-grade construction[2], lane divider painting, barrier construction, right-of-way restoration and other activities common to both concrete and asphalt roads.

   With this definition of system boundaries, the study focuses on those aspects that affect comparative or relative results for the two road systems as opposed to estimating the absolute environmental effects of either type.

2. To make the results broadly applicable across Canada, we first examined two basic cases for each of two types of asphalt and concrete road, each with two soil foundation options (eight cases in total), with the cases differing primarily in terms of the amount of material required. We also assessed two additional “as built” freeway designs specific to Quebec (two cases in total) and Ontario (two cases in total). For all 12 cases, we conducted our analysis using regionally specific information, making adjustments for electricity grids, regional manufacturing technologies, and fuel use.

3. For the general Canadian designs, a base case study period of 50 years was selected to ensure inclusion of activities from original construction through major rehabilitation for both pavement types. In addition, we used the Ontario Ministry of Transportation’s rehabilitation schedule to determine the timing of each rehabilitation activity; the ministry also employs a 50-year planning cycle. A 50-year planning cycle was applied to the Quebec freeway design as well; we used the Quebec Ministry of Transportation’s rehabilitation schedule to determine both the timing and material quantities involved in rehabilitation. A 50-year planning cycle was also applied to the Ontario Highway 401 case study for both road material types. The Ontario

[2] Recent literature indicates that Portland cement concrete pavements may require between 5-7% less sub-grade construction energy due to their reduced width and depth relative to asphalt concrete roadways of comparable design.

Ministry of Transportation's rehabilitation schedule for deep strength asphalt concrete and doweled Portland cement concrete pavements were used to develop the timing and material quantities for the major rehabilitation activities.

4. As noted, the study deals with embodied primary energy and greenhouse gas emissions; i.e., energy and emissions associated primarily with the production and transportation of materials and components for initial road construction and major maintenance or rehabilitation (e.g., cement/pavement grade Portland cement concrete, bitumen binder/hot mix asphalt, steel dowel and tie bars, granular materials, recycled materials, etc.).

5. The scope does not include operational considerations that may differ by road type; for example, energy use by trucks and energy use for lighting in urban areas. These types of effects should be taken into account in any decisions predicated on life cycle environmental considerations; however, such effects will be the subject of a separate analysis.

1.2 REPORT STRUCTURE

Separate LCI reports detailing the methods and results for individual materials and products are provided in the Appendices attached to this report. The road design reports used to determine material quantities are also included in the Appendices.

The main body of this report is structured as follows.

Section 2 summarizes the roadway designs and related study cases; pavement materials and quantities; construction equipment; maintenance and rehabilitation schedules, materials and equipment.

Section 3 presents the basic regional per unit LCI data for granular materials, Portland cement concrete, asphalt concrete and steel dowel and tie bars.

Section 4 draws all of the preceding information together to develop the energy use and greenhouse gas emission profiles for the roadway types and cases.

Section 5 summarizes the results.

2. ROADWAY DESIGN, CONSTRUCTION, MAINTENANCE AND REHABILITATION

The material presented in this section is a summary of the detailed report prepared by Applied Research Associates, Inc. (Appendix A), referred to as the Canadian road designs. The Cement Association of Canada's (CAC) Montreal office provided the Quebec Ministry of Transportation urban freeway road design information and rehabilitation schedule. The CAC's Toronto office provided Ontario Ministry of Transportation Highway 401urban freeway road design information and rehabilitation schedules.

2.1 CANADIAN DESIGN CASES

The Applied Research Associates report provides typical rigid Portland cement concrete and flexible asphalt concrete pavement designs for three classes of roadways/highways constructed in Canada. Two roadbed sub-grade foundation support types were considered for each of the three roadway types, yielding 12 pavement section designs. All pavement designs were developed using the most commonly used design procedures. This included the AASHTO 1993 design methodology for flexible pavements and the AASHTO 1993 and Cement Association of Canada method for rigid pavements (i.e. PCAPAV). In addition, example trial pavement designs were completed for comparison purposes using the draft models developed as part of the National Cooperative Highway Research Program (NCHRP) 1-37a project better known as Mechanistic - Empirical Pavement Design Guide (M-EPDG). The design report (Appendix A) sets out quantities of asphalt concrete, Portland cement concrete and granular base and sub-base materials for each pavement structure on a two-lane kilometer basis, including outside and inside shoulders. This study draws on the design data for arterial and high volume highway roadways[3], and uses one two-lane kilometer, including shoulders, as its functional unit. Table 2.1 below summarizes the basic dimensional information for each material road design. The rigid road design employs an overall two-lane width that is wider than its flexible roadway counterpart. This 0.5m widened lane design facilitates better edge load transfer from the lane to the shoulder. In all cases, the overall roadway width is the same for the two roadway types. Each roadway employs an asphalt concrete (flexible) pavement shoulder.

Table 2.1
CANADIAN ROADWAY DESIGN DIMENSIONS

Pavement Design	2-Lane width	Inner shoulder width	Outer shoulder width
Rigid – Portland cement concrete	8.0m	1.0m	2.5m
Flexible – Asphalt concrete	7.5m	1.0m	3.0m

[3] The design report also provides design parameters and roadway quantities for collector type roadways; however, rigid Portland concrete pavement collector roads are not typically constructed in Canada, and therefore have not been considered in this report.

These designs represent typical arterial and high volume roadway types across Canada. The design traffic characteristics by roadway class are detailed in Appendix A, which also provides the pertinent traffic analysis and design parameters used in each design case as well as the final pavement structures for each of the eight sections considered in this report.

Table 2.2 below summarizes the initial construction material pavement quantities for the two roadway types for a given foundation support. The Appendix explains how these estimates were calculated.

Table 2.2
DESIGN MATERIAL QUANTITIES BY ROADWAY TYPE AND SUB-GRADE SUPPORT

Roadway Type	**Arterial Roadway/Highway**				**High Volume Highways**			
Sub-grade Support	**Low-CBR 3**		**Medium-CBR 8**		**Low-CBR 3**		**Medium-CBR 8**	
Pavement Type	**PC**	**AC**	**PC**	**AC**	**PC**	**AC**	**PC**	**AC**
Lanes								
Thickness (mm)	200		190		225		215	
Quantity (m^3)	1600		1520		1800		1720	
Dowel Bars (tonnes)	21		21		21		21	
HMA Surface (mm)		50		50		50		50
HMA Binder (mm)		120		120		155		155
HMA Surface (tonnes)		919		919		919		919
HMA Binder (tonnes)		2205		2205		2848		2848
Shoulders								
HMA Surface (mm)	40	40	40	40	40	40	40	40
HMA Binder (mm)	50	50	50	50	50	50	50	50
Gran A Shoulder (tonnes)	886	1564	805	1564	1087	1886	1006.	1886
HMA Surface (tonnes)	343	392	343	392	343	392	343	392
HMA Binder (tonnes)	429	490	429	490	429	490	429	490
Granular Base								
Base (mm)	150	150	150	150	150	150	150	150
Base (tonnes)	3968	3968	3968	3968	3968	3968	3968	3968
Granular Sub-base								
Sub-base (mm)	150	585	0	165	150	700	0	225
Sub-base (tonnes)	3300	12870	0	3630	3300	15400	0	4950

AC – flexible Asphalt Concrete or flexible pavement design
CBR – California Bearing Ratio
HMA – Hot Mix Asphalt
PC – rigid Portland Cement concrete pavement design
Steel dowel and tie bar estimates provided by T Smith, CAC Ottawa office

2.2 QUEBEC ROAD DESIGN CASE

The Quebec roadway design case applies to a four-lane divided freeway. The design was provided by the CAC's Montreal[4] office in consultation with Quebec's Ministry of Transportation. The freeway design considers a two-lane kilometer with shoulders in one direction (or one half of the complete four lane design). Each lane is 3.7m wide, for a combined two-lane width of 7.4m. In the case of the Portland cement concrete design, the shoulder surfaces are also specified to be concrete, while the asphalt concrete design employs asphalt concrete shoulders. The inner shoulder is 1.3m wide and the outer shoulder is 3m wide. The dimensional information specific to each of the material designs is summarized in Table 2.3 below.

Table 2.3
QUEBEC FREEWAY DESIGN DIMENSIONS

Pavement Design	2-Lane width	Inner shoulder width	Outer shoulder width
Rigid – Portland concrete	7.4m	1.3m	3.0m
Flexible – Asphalt concrete	7.4m	1.3m	3.0m

Source: Ministry of Transportation Quebec

Table 2.4 below summarizes the initial construction material quantities for the rigid Portland cement concrete and flexible asphalt concrete designs for the Quebec freeway.

[4] Personal correspondence with Pierre-Louis Maillard, March, 2006. Design values quoted from "Revisions de L'Orientation Ministerielle, Sur Le Choix des Types de Chaussees 2001-2006. Presentation des parametres LCCA par le sous-comite technique LCCA. Association Canadienne du Ciment, Bitume Quebec, Association des Constructeurs de Routes et Grand Travaux du Quebec," April 2006, p5-6.

Table 2.4
RIGID (PC) AND FLEXIBLE (AC) DESIGN MATERIAL QUANTITIES FOR TYPICAL QUEBEC FREEWAY

Roadway Type	**Freeway**	
Sub-grade Support	**Typical**	
Pavement Type	**PC**	**AC**
Lanes		
Thickness (mm)	240	
Quantity (m^3)	1776	
Dowel Bars (tonnes)	22	
HMA Surface (mm)		240
HMA Surface (tonnes)		4298
Shoulders		
Concrete Surface (mm)	150	
HMA Surface (mm)	0	150
Gran A Shoulder (tonnes)	0	0
Concrete Surface (m3)	645	0
HMA Surface (tonnes)	0	1561
Granular Base		
Base (mm)	150	286
Base (tonnes)	7121	11867
Granular Sub-base		
Sub-base (mm)	689	553
Sub-base (tonnes)	31277	25949

AC – flexible asphalt concrete pavement design
PC – rigid Portland cement concrete pavement design,
Steel dowel and tie bar estimates provided by T Smith, CAC Ottawa office
All other quantities from MTQ – see footnote 4

2.3 ONTARIO ROAD DESIGN CASE

The Ontario roadway design case applies to a six-lane divided freeway. The design was provided by the CAC's Toronto office as per Ontario's Ministry of Transportation contract specification 2005-3001. The freeway design considers a three-lane kilometer with shoulders (one side of the six-lane freeway). Two lanes are 3.75m wide, with a 3.5m speed lane for a total three-lane width of 11m. In the case of the rigid Portland cement concrete design, the outer shoulder lane is 0.5m wider to facilitate edge loud transfer to shoulder surfaces. Both the inner and outer shoulder surfaces for both roadway types are composed of flexible asphalt concrete. The inner shoulder is 3.4m wide and the outer shoulder is 3m wide (2.5m wide in the case of the rigid Portland cement concrete design). The dimensional information specific to each of the material designs is summarized in Table 2.5 below.

Table 2.5
ONTARIO HWY 401 FREEWAY DESIGN DIMENSIONS

Pavement Design	3-lane width	Inner shoulder width	Outer shoulder width
Rigid – Portland concrete	11.5m	3.4m	2.5m
Flexible – Asphalt concrete	11.0m	3.4m	3.0m

Source: as per Ontario's Ministry of Transportation contract specification 2005-3001

Table 2.6 below summarizes the initial construction material quantities for the rigid Portland cement concrete and flexible asphalt concrete designs for the Highway 401 freeway design.

Table 2.6
RIGID (PC) AND FLEXIBLE (AC) PAVEMENT MATERIAL QUANTITIES FOR ONTARIO HWY 401 FREEWAY

Roadway Type	**Freeway**	
Sub-grade Support	**Typical**	
Pavement Type	**PC**	**AC**
Lanes		
Thickness (mm)	260	
Quantity (m^3)	2990	
Dowel Bars (tonnes)	29.9	
HMA Surface (mm)		300
HMA Surface (tonnes)		7986
Shoulders		
HMA Surface (mm)	90	90
HMA Surface (tonnes)	1243	1307
Granular OGDL		
OGDL Base (mm)	100	100
OGDL Base (tonnes)	2926	2684
Granular Sub-base		
Sub-base (mm)	300	500
Sub-base (tonnes)	17575	27742

AC – flexible Asphalt Concrete pavement design
PC – rigid Portland Cement concrete pavement design
Steel dowel and tie bar quantities calculated by Athena Institute
All other quantities calculated by MTO

2.4 CONSTRUCTION EQUIPMENT

2.4.1 Rigid Concrete Pavements

For arterial roads and urban highways, it is usual to erect a portable ready-mixed concrete batching/mixing plant. A plant consists of silos and bins for material storage, conveyors to move the material, and a concrete mixer. After mixing, the concrete is delivered to the site in dump trucks.

Most concrete is placed using a slip form paver, which consolidates the concrete and forms it in the correct location with a smooth surface. Mechanical equipment is used to texture and cure the surface. As the concrete hardens, joints are sawn to delineate the lanes and divide the pavement into panels about 3.5 to 6m long. Hot pour joint sealers are heated on site using special kettles to melt the material prior to application.

Aggregates and cement are normally delivered by truck, and while the haul distances for aggregates and cement vary from project to project, the delivery differences between flexible and rigid pavements may not be significant. When haul distances exceed 200 km, materials may be partially hauled by train or boat. Other materials such as curing compounds, steel, and joint sealers are delivered by truck.

2.4.2 Flexible Hot Mixed Asphalt Pavements

For urban areas, the hot mixed asphalt usually comes from permanent plants, and for rural projects, from a portable plant(s) erected at a suitable central location. The raw materials, coarse and fine aggregates and asphalt cement are delivered by truck to the plant, with the asphalt cement usually delivered hot in a liquid condition and used while still hot. Unlike concrete aggregates, the aggregates for hot mix asphalt are dried and heated prior to mixing. After the hot materials are mixed, they may be stored in an insulated silo or loaded directly into trucks for delivery to the site.

The delivery trucks discharge the hot mix into an asphalt paver, which spreads the material on the road. The hot mix is compacted and smoothed by steel wheel and rubber tired rollers. The number and size of the rollers depends on the weather, the material quantities, and the type of hot mix, but it is common to have two steel wheel and one rubber tired roller. When a tack coat is used, the emulsion is often delivered to the site in a truck equipped with a spray bar to spread the material.

2.4.3 Granular Base and Sub-base

Granular base and sub-base materials are produced in pits and quarries using the same equipment as for concrete aggregates, and are usually delivered and placed by the same trucks. Special spreaders are available, but seldom used. The material is spread and leveled using dozers and graders, and then compacted by vibratory rollers, which vary in size depending on the material depths and quantities. In hot weather, water may be added by a water truck to assist in the compaction process. After compaction, the surface is fine graded by graders or by specialized fine grading equipment.

2.5 MAINTENANCE AND REHABILITATION

Minor or routine roadway maintenance includes activities such as joint and crack sealing and patch repairs. We have not included embodied energy or greenhouse gas emission estimates for these maintenance items for two reasons:

1. the material quantities for both kinds of pavement are small and unlikely to have any significant effect on the relative estimates; and

2. estimation of related material quantities is difficult because the frequency and extent of this type of maintenance for any given roadway depends on location and weather conditions as well as on the practices of the responsible jurisdiction.

The focus, then, is on rehabilitation of the two types of pavement for the various roadway designs.

2.5.1 Rehabilitation of Rigid Concrete Pavements

For the Canadian rigid Portland cement concrete arterial and high volume highway designs, rehabilitation includes diamond grinding at years 20 and 35, and load transfer restoration at year 35. For the high volume highway only, rehabilitation also includes, at year 40, the addition of an 80mm asphalt concrete overlay covering both the roadway and shoulders (see Table 2.7).

Diamond grinding is a rehabilitation procedure used to restore or improve pavement rideability. Diamond grinding equipment uses diamond saw blades, which are gang mounted on a cutting head and work like a wood plane. Bumps and faults are planed off when the equipment passes over the defect. In some cases, it may be necessary to make multiple passes over a specific defect to restore rideability. Diamond grinding is not a material intensive activity; given its limited impact from an embodied energy perspective, we have elected to exclude it from this study.

The ability of a transverse crack or joint to distribute load is fundamental to the structural integrity of pavement. Load transfer restoration to improve load transfer across transverse joints and cracks involves two basic options: retrofit dowel bars and double-vee shear devices. However, the related material quantities should be relatively small over the life of a well-designed concrete pavement; like diamond grinding, load transfer restoration may be considered to have no significant impact on the overall embodied life cycle energy and greenhouse gas emissions of rigid pavements.

The high volume rigid Portland cement concrete roadway will require an 80mm asphalt overlay at year 40. The overlay would span both the roadway and shoulders; therefore, 2,226 tonnes of asphalt would be used in the rehabilitation of a two-lane kilometer of roadway. At year 40, the roadway is only 10 years away from the end of the first 50-year planning cycle. In keeping with standard LCA practice, we have accounted for 59% of the materials used (10 years/17-year expected life of the new overlay) to allow for the additional life of the overlay beyond the 50-year cycle (see Table 2.7).

In contrast, the Quebec rigid Portland cement concrete freeway design will receive a 50mm asphalt overlay over both the roadway and shoulders at year 39, and complete reconstruction down to the base at year 49 – just one year short of the 50-year planning cycle (see Table 2.8). During the intervening years, the roadway will be subject to minor rehabilitation activities such as crack and joint resealing, diamond grinding to restore rideability, and patch repairs to various depths of the roadway (less than 5% of the total road surface area). These minor rehabilitation activities are again ignored in this analysis as they are not particularly material intensive. The major reconstruction of the concrete slab has been pro-rated to the end of the 50-year planning cycle; i.e., at year 49, the complete roadway slab and shoulder materials are removed to the base layer and replaced. However, we only account for 2% of the materials required (one year remaining/49-year life) to bring the material quantities in line with the initial 50-year planning cycle.

The Ontario Highway 401, rigid Portland cement concrete design will also undergo minor rehabilitation activities and, again, these are ignored in this analysis. According to Ontario's Ministry of Transportation life cycle cost analysis procedures, the only major, material intensive, rehabilitation activity is the application of an 80mm flexible asphalt concrete overlay over the entire road and shoulder surfaces at year 38 (see Table 2.9). This analysis assumes that the overlay has a life expectancy of about 12 years, which takes it to the end of the 50-year planning cycle.

Table 2.7
CANADIAN RIGID (PC) ROAD DESIGN
REHABILITATION MATERIAL QUANTITIES

	Arterial Highway	High Volume Highway
Year **40** (asphalt overlay roadway and shoulders)		
New asphalt thickness mm	n/a	80
New asphalt tonnes		2226
Quantity applicable to 50 yr study period (59% = 10yrs/17years of expected life) tonnes		1309

Source: Arterial Highway Table 8 (p 71) original 1999 report; High Volume Highway, MTO life cycle model reference, rigid pavement design maintenance/rehabilitation schedule.

Table 2.8
QUEBEC RIGID (PC) FREEWAY DESIGN
REHABILITATION MATERIAL QUANTITIES

	Urban Freeway
Year **39** (asphalt overlay roadway and shoulders)	
New asphalt thickness mm	50
New asphalt tonnes	520
Year **49** (base up reconstruction)	
New PC roadway thickness mm	240
New PC shoulder thickness mm	150
New PC tonnes	5568
New Steel dowels and tie-bars tonnes	22
Yr **49** quantities applicable to 50-yr planning period	
New PC tonnes	111
New Steel dowels and tie-bars tonnes	0.44

Source: Ministry of Transportation, Quebec (see footnote 4 for source)

Table 2.9
ONTARIO HWY 401 RIGID (PC) FREEWAY DESIGN REHABILITATION MATERIAL QUANTITIES

	Urban Freeway
Year **38** (asphalt overlay roadway and shoulders)	
New asphalt thickness mm	80
New asphalt tonnes	3369

Source: Benefits of new technologies and their impact on life-cycle models, MTO, 2000 (pg 10-24, fig 10-7)

2.5.2 Rehabilitation of Flexible Asphalt Pavements

For arterial and high volume highways, asphalt overlay is required for the Canadian flexible asphalt concrete pavement designs at years 18 and 35

The procedure for this typical rehabilitation consists of grinding the entire roadway surface, followed by the application of tack coat to the milled surface, machine placement of a new hot-mix asphalt surface, and compaction of the hot-mix asphalt using smooth steel wheel and pneumatic wheel rollers. The materials include tack coat[5] and hot-mix asphalt. The depth of grinding and the thickness of the new pavement materials are dependent on the existing pavement performance combined with various design requirements and specified paving materials.

For the purpose of this study, the first overlay applied to the Canadian flexible asphalt concrete pavement road designs is assumed to involve removing 40 mm of the existing asphalt from the roadway and replacing it with one 50 mm lift of hot-mix asphalt. The second overlay (at year 35) is assumed to involve removing 80 mm of the existing asphalt from both the roadway and shoulders and replacing it with 100 mm of hot-mix asphalt (placed in two lifts). The year-47 asphalt overlay quantity is pro-rated to the 50-year study period. The associated material quantities are shown in Table 2.10.

The Quebec flexible asphalt concrete pavement freeway design calls for asphalt removal and application of a 50mm asphalt overlay to the roadway at years 12 and 22, and complete replacement of all asphalt (roadway and shoulder) from the base granular layer up at year 32, followed by an additional 50mm asphalt overlay of the road surface at year 44. The last overlay is assumed to have a life of 10 years, but will only be in service six years of the remaining 50-year study period; the analysis therefore accounts for 60% of the final overlay. See Table 2.11 for the timing and material quantities associated with the various rehabilitation activities.

[5] Note: material and application aspects associated with the tack coat are excluded in the energy and global warming assessment of flexible pavements. These energy and material aspects have been deemed to be very small in relation to material and energy associated with applying an asphalt overlay.

The Ontario Highway 401 flexible asphalt concrete pavement freeway design rehabilitation schedule includes asphalt removal and application of an 80mm asphalt overlay to the roadway surface at years 19 and 31. At year 42, there is another removal and an 80mm overlay is applied to the complete roadway and shoulders. This final overlay is assumed to have a life expectancy of at least 12 years; at year 42, however, there are only eight years left before the end of the first 50-year planning horizon — as a result, only 67% of the last rehabilitation overlay is considered in the analysis calculations (see Table 2.12 for the timing and material quantities involved with each rehabilitation activity).

Table 2.10
CANADIAN FLEXIBLE ROAD DESIGN
REHABILITATION MATERIAL QUANTITIES

	Arterial Highway	High Volume Highway
Year **17** rehabilitation (excludes shoulders)		
Mill and replace asphalt thickness mm	50	80
New asphalt tonnes	908	1452
Year **28** rehabilitation (excludes shoulders)		
Mill and replace asphalt thickness mm	n/a	80
New asphalt tonnes	n/a	1452
Year **38** rehabilitation (includes shoulders)		
Mill and replace asphalt thickness mm	80	80
New asphalt tonnes	2226	2226
Year **47** rehabilitation (excludes shoulders)		
Mill and replace asphalt thickness mm	50	80
New asphalt tonnes	908	1452
Yr. 47 quantities applicable to 50 yr. study period (27%)		
New asphalt tonnes (3 yrs/11yrs of life)	245	396

Source: Arterial highway Table 8 (p 71), original 1999 report; High Volume Highway, MTO life-cycle cost analysis procedures, DSAC pavement design maintenance/rehabilitation schedule (figure 10-1).

Table 2.11
QUEBEC FLEXIBLE FREEWAY DESIGN REHABILITATION MATERIAL QUANTITIES

	Urban Freeway
Year **12** rehabilitation overlay (excludes shoulders)	
New asphalt thickness mm	50
New asphalt tonnes	895
Year **22** rehabilitation overlay (excludes shoulders)	
New asphalt thickness mm	50
New asphalt tonnes	895
Year **32** reconstruction from granular base layer up (includes shoulders)	
New roadway asphalt thickness mm	240
New shoulder asphalt thickness mm	150
New roadway asphalt tonnes	4298
New shoulder asphalt tonnes	1561
Year **44** rehabilitation overlay pro-rated (excludes shoulders)	
New asphalt thickness mm	30
New asphalt tones	537

Source: Ministry of Transportation, Quebec.

Table 2.12
ONTARIO HWY 401 FLEXIBLE FREEWAY DESIGN REHABILITATION MATERIAL QUANTITIES

	Urban Freeway
Year **19** rehabilitation overlay (excludes shoulders)	
New asphalt thickness mm	80
New asphalt tonnes	2130
Year **31** rehabilitation overlay (excludes shoulders)	
New asphalt thickness mm	80
New asphalt tonnes	2130
Year **42** rehabilitation overlay (includes shoulders)	
New asphalt thickness mm	80
New asphalt tonnes	3369
Year **42** rehabilitation overlay pro-rated quantity (at 67%)	
New asphalt thickness (equivalent) mm	54
New asphalt tones	2257

Source: Benefits of new technologies and their impact on life-cycle models, MTO, 2000, (figure 10-3, pg10-16)

3.0 PRIMARY ENERGY AND GREENHOUSE GAS EMISSIONS PER UNIT OF MATERIAL

This section presents estimates of the per unit embodied primary energy and greenhouse gas emissions associated with the production and transportation of materials for road construction and rehabilitation. These per unit life cycle inventory estimates are applied in Section 4 to derive the embodied energy and global warming potential values per two or three-lane kilometer of each pavement structure.

For the purposes of this study, embodied primary energy is deemed to include all fossil fuel energy used in material manufacturing and related transportation for road construction and rehabilitation. Upstream or pre-combustion energy — the energy required to extract, process and transport fossil fuels to the point of their combustion — is also included in the primary energy estimates. Embodied primary energy also includes the 'inherent' or 'feedstock' energy value of materials. Feedstock energy is defined as the gross combustion heat for any material input to a system which may be considered as an energy source but is not being used as an energy source (e.g., bitumen asphalt). Similarly, fossil fuel use in the production of electricity is included, and takes into consideration fuel pre-combustion energy, fuel conversion efficiency in generating electricity, and transmission line losses associated with distribution of electricity for the country as a whole and for Quebec and Ontario.

Direct greenhouse gas emissions considered in the study include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). While there are a large number of possible direct and indirect greenhouse gases, these three gases account for 98.9% of the greenhouse gas inventory recognized by Environment Canada[6]. Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "CO_2 equivalence effect", which is simply a multiple of the greenhouse potential (heat trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time. The Athena Institute has adopted the International Panel on Climate Change's 100-year time horizon factors as the basis for CO_2 equivalence for this study, as shown in the Global Warming Potential Index (GWPI) equation below. [7]

$$\text{GWPI (kg)} = CO_2\text{ kg} + (CH_4\text{ kg} \times 23) + (N_2O\text{ kg} \times 296)$$

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modeling manufacturing process stages. One example in which process CO_2 emissions are significant is in the production of cement and lime (calcination of limestone). The detailed life cycle modeling methodology adopted for this study

[6] Canada's Greenhouse Gas Inventory 1990-2002. Prepared by Greenhouse Gas Division, Environment Canada 2004.
[7] International Panel on Climate Change (2000) – Third Assessment Report (Technical Summary) Working Group 1, p47.

includes all relevant process greenhouse gas emissions in the global warming potential index calculation.

Appendices B, C and D contain updated reports providing the underlying details for the Portland cement concrete, asphalt concrete and granular base and sub-base energy and greenhouse gas estimates on a regional basis. Comparable estimates for steel reinforcing materials are from a recently published Athena Institute report. The estimates for steel reinforcing materials include regional electricity related primary fossil fuel use, upstream pre-combustion effects and associated greenhouse gas emissions.

3.1 PORTLAND CEMENT CONCRETE

The energy and greenhouse gas estimates were developed for one cubic meter of Portland cement based roadway concrete mix with each region having a specific composition[8] as specified in Table 3.1 below.

Table 3.1
REGIONAL PORTLAND CEMENT CONCRETE ROADWAY MIX DESIGNS
(t/m^3)

Material	Canada Average	Quebec Average	Ontario Average
Cement	0.26686	0.25500	0.26250
Blast furnace slag	0.04814	0.07700	0.08750
Fly ash	0.03500	0.00000	0.00000
Silca Fume	0.00000	0.01750	0.00000
Coarse aggregate	1.10000	1.10000	1.10000
Fine aggregate	0.70000	0.70000	0.70000
Water	0.15000	0.15000	0.15000
TOTAL	2.30000	2.26500	2.30000

The above concrete pavement mix designs are similar across the three regions considered in this study. Across the country, both fly ash and blast furnace slag (supplementary cementing materials — SCMs) are used to varying degrees, depending on availability and the design specifications posed by the various provincial transportation ministries. Typically, both fly ash and ground granulated blast furnace slag are used to some extent across the country, but both Ontario and Quebec favour slag mixes, with Quebec favouring Turnery blended cements. Although these supplementary cementing materials are included in the mix, we continue to refer to the final concrete as Portland cement concrete in order to maintain a clear distinction from asphalt concrete.

For this part of the analysis, the system boundaries encompass the following:

- extraction and processing of aggregates;
- processing of ground granulated blast furnace slag (GGBFS);

[8] The Canadian concrete mix design is the same as used in the earlier 1998 study. Quebec and Ontario mix designs were taken from McLeod, N.F. 2005, A Synthesis of Data on the Use of Supplementary Cementing Materials (SCMs) in Concrete Pavement Applications Exposed to Freeze/Thaw and Deicing Chemicals.

- regional production of Portland cement;
- transportation of aggregates, GGBFS, fly ash and cement to the ready-mixed concrete plant; and
- ready-mixed (concrete mixture) processing.

The boundary ends with ready-mixed concrete mixture ready for transportation at the concrete plant gate. As noted previously, all of the underlying assumptions, transportation distances, calculation methods and other details are set out in Appendix B. Basic energy and emission estimates for the production of Portland cement were taken from a previously published and recently updated Athena Institute report referenced in the Appendix.

The final regional primary energy and greenhouse gas results from Appendix B are summarized below in Table 3.2. The Appendix provides a more detailed breakdown of these estimates, including input material quantities by unit processes. Table 3.2 also shows the overall global warming potential (GWP) of the three greenhouse gases combined.

Table 3.2
REGIONAL PRIMARY ENERGY AND GHG EMISSIONS PER CUBIC METER OF PORTLAND CEMENT CONCRETE

	Canada	Quebec	Ontario
Primary energy (GJ)	1.858	1.7269	2.0178
GHG emissions (kg)			
Carbon dioxide (CO_2)	273.75	260.11	272.2
Methane (CH_4)	0.063	0.058	0.425
Nitrous oxide (N_2O)	0.0002	0.000003	0.0002
GWP (kg CO2 equiv.)	275	261	282

3.2 ASPHALT CONCRETE

The energy and greenhouse gas emissions for the production and transportation of one cubic meter of asphalt concrete vary depending on the amount of recycled asphalt pavement (RAP) used in the mix. Starting with the basic composition specified in Appendix C, Table 1, the amount of asphalt and aggregates required per cubic meter of asphalt concrete decreases as the amount of RAP is increased; estimates have therefore been developed assuming 0 and 20% RAP. In terms of the road designs, RAP use is typically relegated to the binder course for arterial and high volume highways, while freeway designs typically do not allow the use of RAP at all. As a result, the development of a RAP energy and greenhouse gas profile has been limited to the Canadian regional analysis of arterial and high volume highways.

RAP is assumed to be recycled hot at the asphalt plant and to consist of the same components in the same proportions as the asphalt concrete it is replacing. For the purposes of this study the RAP is assumed to enter the process free of any environmental burdens, but with the energy required to mill a road surface, transport and stockpile RAP included.

The system boundaries for this part of the analysis include the following:

- production and transportation of crude oil;
- production of asphalt at the refinery;
- transportation of asphalt to the asphalt plant;
- aggregate production and RAP removal;
- aggregate and RAP transportation to the asphalt plant; and
- production of asphalt concrete.

The boundary ends with material ready for shipment at the asphalt concrete plant gate. Appendix C contains the underlying assumptions, data sources, calculation methods and other details.

The primary energy and greenhouse emissions associated with the production and transportation of crude oil to the refinery and the production of asphalt at the refinery were derived from a separate study undertaken for the Athena Institute by Franklin Associates, as referenced in the Appendix.

A critical issue for this part of the study is the inclusion of the 'inherent' or 'feedstock' energy value of asphalt. Feedstock energy is defined as the gross combustion heat for any material input to a system which may be considered as an energy source but is not being used as an energy source. A well accepted LCA guideline is to include the inherent energy value of a material if that material is derived from a generally used energy source. For example, the inherent energy value of petrochemicals (e.g., bitumen) should be included in an LCI because they are derived from crude oil. In fact, Alberta's oil (tar) sands are made up of bitumen (10% to 12%), mineral matter (80% to 85%), and water (4%). These bitumen deposits through rigorous treatment become gasoline and other fuels. Assigning a feedstock energy value accounts for the energy implications associated with the decision to forego use of the resource as a fuel and to instead use it as a material input.[9] The feedstock energy value of asphalt has therefore been calculated and included in the analysis as explained in Appendix C. However, we also show results in Section 4 without feedstock energy so that its overall influence can be easily assessed.

The basic energy and greenhouse gas results from Appendix C are summarized in Table 3.3 below for the two RAP cases, with the feedstock energy contribution to primary energy shown separately.

Table 3.3
REGIONAL PRIMARY ENERGY AND GHG EMISSIONS PER CUBIC METER OF ASPHALT CONCRETE

	Canada		Quebec	Ontario
	0% RAP	**20% RAP**	**0% RAP**	**0% RAP**
Primary energy (GJ)	7.613	6.410	7.516	7.637
Feedstock portion	5.610	4.488	5.610	5.610
GHG emissions (kg)				

[9] For a more complete discussion of this issue, see Canadian Standards Association, *Life Cycle Assessment*, Z760-94, pg44.

Carbon dioxide (CO_2)	135	130	128	135
Methane (CH_4)	0.323	0.296	0.310	0.328
Nitrous oxide (N_2O)	0.0002	0.0002	0.0001	0.0002
GWP (kg CO2 equiv.)	142	137	135	143

3.3 GRANULAR BASE AND SUB-BASE

Appendix D details the energy and emission calculations for the granular base and sub-base materials. The system boundaries encompass the following:

- extraction and processing of aggregates; and
- transportation of aggregates to the road building site.

Table 3.4 shows the primary energy and greenhouse gas emissions for both categories of granular material.

Table 3.4
REGIONAL PRIMARY ENERGY AND GHG EMISSIONS PER CUBIC METER OF BASE AND SUB-BASE

	Canada		Quebec		Ontario	
	Base	**Sub-base**	**Base**	**Sub-base**	**Base**	**Sub-base**
Primary energy (GJ)	0.197	0.163	0.152	0.151	0.208	0.165
GHG emissions (kg)						
Carbon dioxide (CO_2)	15.8	13.2	12.5	12.4	16.5	13.4
Methane (CH_4)	0.009	0.0036	0.0019	0.0018	0.0111	0.0041
Nitrous oxide (N_2O)	0.0007	0.0005	0.0005	0.0005	0.0008	0.0006
GWP (kg CO2 equiv.)	16.2	13.4	12.7	12.6	17.0	13.7

3.4 STEEL DOWEL AND TIE BARS

The rigid concrete pavement designs for the Canadian arterial and high volume highways and the Quebec and Ontario freeways include the use of steel dowel and tie bars. The corresponding energy, greenhouse gas emissions and resulting global warming potential presented here have been derived from an updated (2002) Athena Institute report,[10] using the data for reinforcing bar (rebar). In Canada, electric arc furnace (EAF) steel making accounts for over 90% of total rebar production. EAF mills (mini-mills) rely primarily on scrap steel as their primary raw material (all scrap steel enters the LCI free of any embodied effects other than those associated with its collection, bailing

[10] *Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Steel Products*. Aug./93 Prepared by Stelco Technical Services Limited for the Athena Institute. Updated March 2002 by Markus Engineering Services.

and transportation). The complete LCI boundary for steel primary energy and greenhouse gas estimates encompasses the following:

- scrap metal transportation and preparation;
- rebar production; and
- transportation to the road construction site.

EAF mills are located across the country but, like their virgin integrated steel making counterparts, are concentrated in Ontario. For the purposes of this study, we used the generalized LCI profile for EAF steel making adjusted to reflect electricity grids in Ontario, Quebec and Canada as a whole, to arrive at specific profiles for steel dowel and tie bars for each concrete road design in each of these region.

The distance factor used by the Institute to cover average steel transportation from the mill to the market is 400 km roundtrip, a figure that may be high for most road construction. We have nevertheless retained that factor in the calculations.

Rebar and the steel materials used in road construction differ somewhat (e.g., epoxy coating); our approach is therefore an approximation that may slightly understate production energy and emissions. The alternative would have been to conduct a separate assessment of the specific steel products. Such a major expansion in the study scope was not justified in view of the overall significance of the steel products in the context of total road construction and the marginal improvement in accuracy that would have resulted.

The primary energy and greenhouse gas results are shown in Table 3.5, below.

Table 3.5
Primary Energy and GHG Emissions
per Tonne of Steel Dowel and Tie Bars

	Canada	Quebec	Ontario
Primary energy (GJ)	**11.29**	**9.08**	**11.85**
GHG emissions (kg)			
Carbon dioxide (CO_2)	**565.00**	**402.00**	**648.00**
Methane (CH_4)	**1.24**	**0.90**	**1.46**
Nitrous oxide (N_2O)	**0.02**	**0.02**	**0.03**
GWP (Kg CO_2 equiv.)	**599.44**	**428.62**	**690.46**

4 ENERGY USE AND GLOBAL WARMING POTENTIAL BY PAVEMENT STRUCTURE

This section combines the life cycle inventory estimates from the previous section with the pavement structure design and rehabilitation scenarios described in Section 2, to develop comparative embodied primary energy and global warming potential (GWP) estimates for the asphalt and Portland cement concrete alternatives for Canadian arterial and high volume roads and the Quebec and Ontario freeway designs.

The functional unit for this part of the analysis is a two-lane kilometer of each pavement structure, including inner and outer shoulders for Canada and Quebec designs and a three-lane kilometer of each pavement structure, including inner and outer shoulders for the Ontario Highway 401 design.

Section 4.1 describes how the calculations were made, Section 4.2 presents the results, and Section 4.3 explains why we excluded the energy associated with on-site equipment usage and concrete transportation. This last section also demonstrates the sensitivity of the results to changes in the haul distances for granular material for the Canadian pavement designs and the significance of substituting Portland cement based shoulder surfaces for asphalt concrete shoulders on Portland cement based pavement designs.

4.1 CALCULATION METHOD

The calculation method is relatively straightforward, as explained in the following points.

1. The cubic meters of concrete (asphalt or Portland cement) and granular material, as well as the tonnes of steel dowel and tie bars (for Portland cement concrete alternatives), were taken from Section 2, Table 2.2, for initial construction of each Canadian pavement structure. Table 2.4 was used as the source for the Quebec, and Table 2.6 for the Ontario Highway 401, initial freeway construction values.

2. The volumes of asphalt or Portland cement concrete required for rehabilitation of the roadway alternatives were taken from Tables 2.7 to 2.12 for each material alternative and region. In each case, the final rehabilitation quantities were adjusted (as per the Tables) to reflect the assumed 50-year operating period of each roadway alternative.

3. The regional primary energy and GWP estimates for Portland cement concrete, asphalt concrete (0% RAP and 20% RAP), granular materials, and steel bars were taken from Section 3, Tables 3.2, 3.3, 3.4 and 3.5, respectively.

4. For the Canadian flexible asphalt concrete design cases using 20% RAP, the primary energy, feedstock energy and GWP estimates per cubic meter of asphalt concrete were reduced to account for the RAP component which displaces new asphalt. RAP was assumed to be used only in the binder course of the Canadian asphalt concrete roadway designs. RAP employed in the rehabilitation schedules was also limited to the binder course. For example, in year 17, 80mm of asphalt concrete is milled and then a new 80mm overlay is applied to the flexible asphalt concrete arterial road. The initial surface thickness is 50mm and the binder course thickness is 120mm; thus the 80mm removal completely strips away the surface layer, but only 30mm of the binder course. The 20% RAP rehabilitation maintains the original surface and binder course distinction and, thus, 67.5% of the 80mm overlay is assumed to be 0% RAP, while

the remaining 32.5% is assumed to be comprised of 20% RAP. The 80mm overlay is assumed to be put down in two lifts with no tack coat between lifts.

5. The primary energy use and GWP values attributed to the RAP include its collection (milling), transport, and stockpiling at the asphalt concrete plant. No inherent or feedstock value is applied to RAP, thus understating its embodied primary energy value.
6. For each initial construction and rehabilitation line in the tables in Section 4.2 below, the quantities of materials were simply multiplied by the relevant energy or GWP values and the results were summed for the specific pavement structure design. For example, the primary energy calculation for initial construction of the rigid Portland cement (PC) concrete Canadian arterial highway (CBR3) pavement structure is as follows.

   Primary energy = 1600 m^3 of concrete x 1.858 GJ/m^3 + 1803 m^3 of base granular x 0.163 GJ/m^3 + 1500 m^3 of sub-base x 0.197 GJ/m^3 + 21 tonnes of steel x 11.29 GJ/m^3
   (Result does not exactly match the table because the above energy values are rounded from the values in the spreadsheet used for the calculations.)

4.2 RESULTS

Tables 4.1, 4.2, 4.3 and 4.4 present the final results for the Canadian arterial road, Canadian high volume highway, Quebec urban freeway designs and the Ontario Highway 401 designs, respectively. Each table is sub-divided into asphalt and Portland cement concrete alternatives, with two design cases reflecting different sub-grade foundation support for the two Canadian road types. In total, the three tables cover the 12 pavement structure designs set out in Section 2.

Comparisons should only be made between flexible asphalt concrete and rigid Portland cement concrete roads of the same type and California Bearing Ratio (CBR) values (where specified).

For all 12 cases, the tables show the embodied primary energy and GWP subdivided between initial construction and rehabilitation effects. The tables also show feedstock (inherent) energy for new asphalt (but not for RAP) as a separate primary energy input so that readers can easily assess the importance of feedstock energy in the total calculation. Estimates of embodied primary energy are shown with feedstock energy included; these should be viewed as the base case assessment, since all life cycle assessments should include feedstock energy in their results.

In the case of the initial construction of the Canadian rigid Portland cement concrete roadways, there is no feedstock energy associated with concrete or steel materials, but the shoulder surface is specified as flexible asphalt concrete, which does include feedstock energy. Rehabilitation schedules for the high volume highway call for asphalt concrete overlays, which also carry a feedstock energy value. The rigid Portland cement concrete arterial roadway has no significant energy or material input associated with its maintenance or rehabilitation during the 50-year study period.

The flexible asphalt concrete arterial and high volume highway design cases are further sub-divided in Tables 4.1 and 4.2 to show the effects of using 20% RAP in the binder course for both initial construction and rehabilitation. The 20% figure was selected as an example, recognizing that the actual amount of RAP allowed or used in the binder course may vary from one jurisdiction to another as well as from one construction project to another. Neither the Quebec nor Ontario flexible asphalt concrete freeway designs includes RAP, since the use of RAP is usually not permitted in urban freeways.

Table 4.1
Comparative Embodied Primary Energy and GWP
Canadian Arterial Highways
(per 2-lane kilometer, including inner and outer shoulders)

	Flexible Asphalt Concrete		**Rigid Portland Cement Concrete**	
Pavement Support Structure	(CBR 3)	(CBR 8)	(CBR 3)	(CBR 8)
		0% RAP		
Initial Construction				
Embodied primary energy (GJ)	14,049	13,366	6,319	5,919
- feedstock portion (GJ)	9,287	9,287	1,790	1,790
GWP (tonnes)	355	299	554	512
Rehabilitation				
Embodied primary energy (GJ)	10,630	10,630	NA	NA
- feedstock portion (GJ)	7,833	7,833	NA	NA
GWP (tonnes)	200	200	NA	NA
Totals (50-year life cycle)				
Embodied primary energy (GJ)	24,679	23,996	6,319	5,919
- feedstock portion (GJ)	17,120	17,120	1,790	1,790
GWP (tonnes)	555	499	554	512
		20% RAP		
Initial Construction				
Embodied primary energy (GJ)	12,645	11,962	6,096	5,696
- feedstock portion (GJ)	8,037	8,037	1,591	1,591
GWP (tonnes)	299	243	545	503
Rehabilitation				
Embodied primary energy (GJ)	10,195	10,195	NA	NA
- feedstock portion (GJ)	7,446	7,446	NA	NA
GWP (tonnes)	182	182	NA	NA
Totals (50-year life cycle)				
Embodied primary energy (GJ)	22,840	22,157	6,096	5,696

- feedstock portion (GJ)	15,483	15,483	1,591	1,591
GWP (tonnes)	481	425	545	503

NA — not applicable

Table 4.2
Comparative Embodied Primary Energy and Global Warming Potential
Canadian High Volume Highways
(per 2-lane kilometer, including inner and outer shoulders)

	Flexible Asphalt Concrete		**Rigid Portland Cement Concrete**	
Pavement Support Structure	(CBR 3)	(CBR 8)	(CBR 3)	(CBR 8)
	0% RAP			
Initial Construction				
Embodied primary energy (GJ)	14,967	14,195	6,708	6,308
- feedstock portion (GJ)	9,457	9,457	1,790	1,790
GWP (tonnes)	411	347	611	568
Rehabilitation				
Embodied primary energy (GJ)	17,384	17,384	4,118	4,118
- feedstock portion (GJ)	12,810	12,810	3035	3035
GWP (tonnes)	327	327	77	77
Totals (50-year life cycle)				
Embodied primary energy (GJ)	32,351	31,579	10,826	10,426
- feedstock portion (GJ)	22,267	22,267	4,825	4,825
GWP (tonnes)	738	674	688	645
	20% RAP			
Initial Construction				
Embodied primary energy (GJ)	14,548	13,776	6,485	6,086
- feedstock portion (GJ)	9,230	9,230	1,591	1,591
GWP (tonnes)	341	278	602	559
Rehabilitation				
Embodied primary energy (GJ)	16,254	16,254	3,753	3,753
- feedstock portion (GJ)	11,805	11,805	2,714	2,714
GWP (tonnes)	281	281	63	63
Totals (50-year life cycle)				
Embodied primary energy (GJ)	30,802	30,030	10,238	9,839
- feedstock portion (GJ)	21,035	21,035	4,305	4,305
GWP (tonnes)	622	559	665	622

NA — not applicable

Table 4.3
Comparative Embodied Primary Energy and Global Warming Potential
Quebec Major Urban Freeways
(per 2-lane kilometer, including inner and outer shoulders)

	Flexible Asphalt Concrete	**Rigid Portland Cement Concrete**
Pavement Structure	typical	typical
Initial Construction		
Embodied primary energy (GJ)	20,935	7,120
- feedstock portion (GJ)	13,582	0
GWP (tonnes)	540	854
Rehabilitation		
Embodied primary energy (GJ)	25,425	1,702
- feedstock portion (GJ)	18,977	1,205
GWP (tonnes)	456	42
Totals (50-year life cycle)		
Embodied primary energy (GJ)	46,359	8,823
- feedstock portion (GJ)	32,559	1,205
GWP (tonnes)	996	896

NA — not applicable

Table 4.4
Comparative Embodied Primary Energy and Global Warming Potential
Ontario Highway 401 Urban Freeway
(per 3-lane kilometer, including inner and outer shoulders)

	Flexible Asphalt Concrete	**Rigid Portland Cement Concrete**
Pavement Structure	typical	typical
Initial Construction		
Embodied primary energy (GJ)	31,664	11,903
- feedstock portion (GJ)	21,543	2,878
GWP (tonnes)	738	1,067
Rehabilitation		
Embodied primary energy (GJ)	20,566	10,632
- feedstock portion (GJ)	15,108	7,810
GWP (tonnes)	384	199
Totals (50-year life cycle)		
Embodied primary energy (GJ)	52,231	22,535
- feedstock portion (GJ)	36,650	10,632
GWP (tonnes)	1,122	1,266

NA — not applicable

4.3 MISCELLANEOUS EXCLUDED ENERGY AND GWP CONTRIBUTORS

There are some other contributors to energy use and greenhouse gas emissions for both types of roads that have been excluded from the analysis for the reasons noted below.

4.3.1 Concrete Transportation

The analysis boundaries stated in Section 3 for asphalt and Portland cement concrete are the concrete plant gates. As discussed in that section, the plants may be either permanent or portable, depending on the specific construction project. As a result, the requirement for transportation to move both types of concrete from the plants to the site is uncertain. Since the focus of this study is comparative, and since both materials can be affected in essentially the same way and with similar transportation distances involved, we elected to omit this uncertain element from the calculations.

4.3.2 Construction Equipment

We excluded energy use and related emissions for construction equipment used for initial construction and rehabilitation for all of the cases for the following reasons:

- a rough calculation indicates that total equipment energy use during initial construction would be less than 1% of the total embodied energy of materials for the road types;
- heavy equipment is used for both types of initial road construction and only the difference in energy use and emissions would have a bearing on the results of this study; therefore, we would be dealing with only a fraction of 1%; and
- the differences in equipment energy use for rehabilitation of both types of roads would be even smaller than for initial construction.

We also excluded transportation of construction equipment to and from the job site because the differences between the types of construction are unlikely to be significant in the context of total embodied energy or GWP and it is, again, a very uncertain aspect.

4.3.3 Transportation Sensitivity Analysis – Canadian Arterial and High Volume Highways

The basic energy and global warming potential estimates presented in Section 3.3 for granular materials assume a 30 kilometer round trip for trucks moving base and sub-base granular materials from quarries to the construction site. Of course, actual transportation distances may vary greatly from one project to another and from one end of a given project to another. In an effort to reveal how primary energy use changes as granular material transportation distance increases, we conducted a sensitivity analysis around granular material travel distance using the Canadian arterial and high volume highways as test cases.

Since we have no real basis for distinguishing differences in transportation distances for granular materials destined for asphalt versus Portland cement concrete roads, it is reasonable to assume that similar quarrying decisions would be made for both types of construction and that travel distances would therefore be similar.

The key difference that arises, then, is the difference in quantities of granular material required for asphalt in comparison with Portland cement concrete roads. Since transportation energy use and related emissions are a function of the number of tonne-kilometers of transportation by a given mode, the energy use and emissions will vary in direct proportion to the tonnage differences for the same distances.

For the CBR 3 roads, asphalt concrete construction requires 86% to 125% more granular material (base, sub-base and shoulder granular) per two-lane kilometer than the Portland cement concrete alternatives[11]. For CBR 8 roads, the asphalt concrete designs use between 117% and 154% more granular materials. At 0.0018 GJ per tonne-kilometer, these percentages translate into 12 to 15 GJ more energy use per 2-lane kilometer of asphalt concrete, compared with the Portland cement concrete alternative for the CBR 3 roads, and from 5 to 7 GJ per 2-lane kilometer for the CBR 8

[11] Note that all arterial and high volume highways specify the same quantity of base materials regardless of foundation support levels.

roads. Therefore, every additional kilometer of granular material transport incurs another 0.4 to 0.5 GJ and 0.17 to 0.23 GJ of additional energy use for CBR 3 and CBR 8 asphalt concrete roads, respectively, relative to their Portland cement concrete counterparts.

While these per kilometer energy use and associated emission differences are not large relative to total embodied energy and emissions per 2-lane kilometer of roadway, they can nevertheless mount rapidly and become more significant if haul distances for granular materials increase appreciably. Table 4.5 below shows the relative increase in transportation energy for the asphalt versus Portland cement concrete alternatives when the granular material haul distance is increased from 30 to 60 kilometers and from 30 to 80 kilometers (i.e., net increase in transportation energy for the difference in granular usage for the asphalt concrete alternative over the Portland cement concrete alternative).

Table 4.5
Increase in Energy for Asphalt Concrete
Relative to Portland Cement Concrete Alternatives
(GJ per 2-lane kilometer including inner and outer shoulders)

Pavement type & structure	Increased haul distance	
	30 km	50 km
Arterial – CB3	12	20
Arterial – CB8	5	8
High volume– CB3	15	25
High volume– CB8	7	11

The relative increases in greenhouse gas emissions will be proportional to the relative changes in transportation energy use.

4.3.4 Shoulder Material Sensitivity Analysis – Canadian High Volume Highways

Both the Portland cement concrete pavement designs of the Canadian arterial and high volume highways incorporate asphalt concrete shoulders. In addition, the high volume highway receives a 80mm asphalt overlay over the roadway and shoulder at year 40. This section explores the material effects of replacing the initial asphalt concrete pavement shoulder with Portland cement based concrete pavement and eliminating the asphalt concrete pavement overlay entirely at year 40 with improved surface maintenance (diamond grinding) and load transfer restoration.

Table 4.6 sets out a number of scenarios and their primary energy and global warming potential effects during the 50-year life cycle of the Canadian high volume highway. The first part of the two-part table displays the original design results as determined in this study – i.e., the 0% RAP base case results or both the asphalt and Portland cement based pavement designs. The second part of the table shows the impact of replacing the original asphalt concrete shoulder pavement with Portland cement based concrete and reinforcing dowels and tie bars with no asphalt overlay at year 40; this scenario presumes a different maintenance approach which is less material intensive over the 50-year study period. This alternative maintenance approach known as, concrete pavement restoration (CPR), includes maintenance activities such as full / partial depth joint repair, load transfer restoration, and diamond grinding to restore rideability. The second scenario in part two of the Table indicates the effects of assuming that 10% of the all Portland cement based roadway pavement will undergo full-depth repairs during the 50-year planning period, which entails removal and placement of new Portland based concrete and steel reinforcing.

Table 4.6 (Part 1)

Shoulder Material Sensitivity Case Study Results

Canadian High Volume Highway

	Flexible Asphalt Concrete Base Case w/ AC Shoulders (Scenario 1)		**Rigid Portland Cement Concrete Base Case w/ AC Shoulders (Scenario 2)**	
Pavement Support Structure	(CBR 3)	(CBR 8)	(CBR 3)	(CBR 8)
Initial Construction				
Total Primary Energy (GJ)	14,967	14,195	6,708	6,308
- feedstock portion (GJ)	9,457	9,457	1,790	1,790
GWP (tonnes)	411	347	611	568
Rehabilitation				
Total Primary Energy (GJ)	17,384	17,384	4,118	4,118
- feedstock portion (GJ)	12,810	12,810	3035	3035
GWP (tonnes)	327	327	77	77
Totals (50-year life cycle)				
Total Primary Energy (GJ)	32,351	31,579	10,826	10,426
- feedstock portion (GJ)	22,267	22,267	4,825	4,825
GWP (tonnes)	738	674	688	645

Per two-lane kilometer, 0% RAP

Table 4.6 (Part 2)

Shoulder Material Sensitivity Case Study Results

Canadian High Volume Highway

	Rigid Portland Cement Concrete W/ PC Shoulders* (Scenario 3)		**Rigid Portland Cement Concrete (w/ PC Shoulders & 10% full depth repair**) (Scenario 4)**	
Pavement Support Structure	(CBR 3)	(CBR 8)	(CBR 3)	(CBR 8)
Initial Construction				
Total Primary Energy (GJ)	5,745	5,297	5,745	5,297
- feedstock portion (GJ)	0	0	0	0
GWP (tonnes)	780	728	780	728
Rehabilitation				
Total Primary Energy (GJ)	0	0	358	344
- feedstock portion (GJ)	0	0	0	0
GWP (tonnes)	0	0	51	49
Totals (50-year life cycle)				
Total Primary Energy (GJ)	5,745	5,297	6,103	5,641
- feedstock portion (GJ)	0	0	0	0
GWP (tonnes)	780	728	831	777

Per two-lane kilometer, 0% RAP
*no asphalt concrete overlay- assumes only load transfer restoration and diamond grinding to restore ride-ability.

**no asphalt concrete overlay- assumes only load transfer restoration and diamond grinding to restore ride-ability with 10% of road surface receiving full depth repairs.

As discussed previously in section 4.2, the rigid Portland cement based concrete pavement design with asphalt concrete shoulders and an asphalt overlay at year 40, embodies only a third of the primary energy and less than 90 to 95% of GWP of that of the original flexible asphalt concrete design.

The effect of substituting Portland cement concrete pavement for the asphalt concrete shoulders and changing the maintenance and restoration approach negates having to add an asphalt concrete overlay over the Portland cement concrete pavement design is displayed in Scenario 3 in part two of Table 4.6. Relative to the base case Portland cement based design with asphalt shoulders with an asphalt overlay at year 40 (Scenario 2), the results (averaged across the two pavement support structures) indicates that by substituting Portland cement concrete pavement for asphalt concrete pavement shoulders the 50-year construction primary energy use decreases by 48%, but GWP increases by 13%. However, relative to the base case asphalt concrete pavement design (Scenario 1), the substitution of the shoulder materials and reduced rehabilitation material associated with the all Portland cement based pavement design is more significant with the primary energy showing a reduction of 83% and only a 7% increase in the GWP effect when averaged across the two given pavement support structures.

Assuming a 10% full depth repair of the all Portland cement concrete pavement design (Scenario 3) as depicted in Scenario 4 has a small impact on the overall results. Relative to the asphalt concrete base case (Scenario 1), adding the 10% full depth repair effects to the all Portland cement pavement design case results in a 82% reduction in total primary energy use and a 14% increase in the overall GWP effect (see Table 4.7 below for net percent difference between design cases).

Table 4.7

Shoulder Material Sensitivity Case Study Results
Canadian High Volume Highway
Average Percent (%) Differences Between Cases

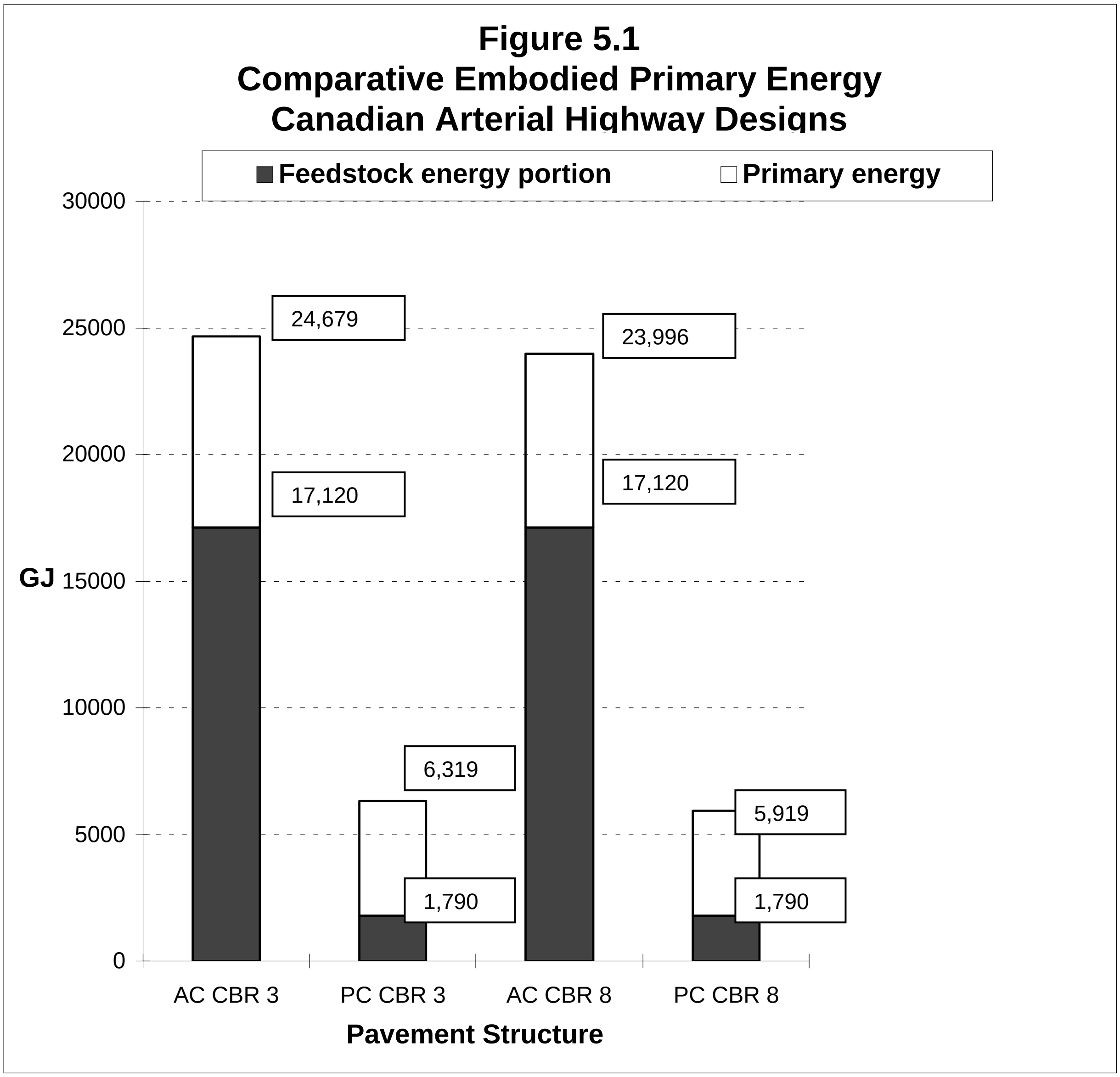
% DIFFERENCES REPORTED RELATIVE TO BASE CASE DESIGNS	AC BASE CASE DESIGN		PC BASE CASE DESIGN	
	Total Primary Energy	GWP	Total Primary Energy	GWP
PC BASE CASE DESIGN W/ PC SHOULDERS (NO AC OVERLAY)	- 83%	+ 7%	- 48%	+13%
PC BASE CASE DESIGN W/ PC SHOULDERS (NO AC OVERLAY) + 10% FULL DEPTH REPAIR	- 82%	+ 14%	- 45%	+21%

AC – ASPHALT CONCRETE   PC – PORTLAND CEMENT BASED CONCRETE

5 SUMMARY OF COMPARATIVE RESULTS

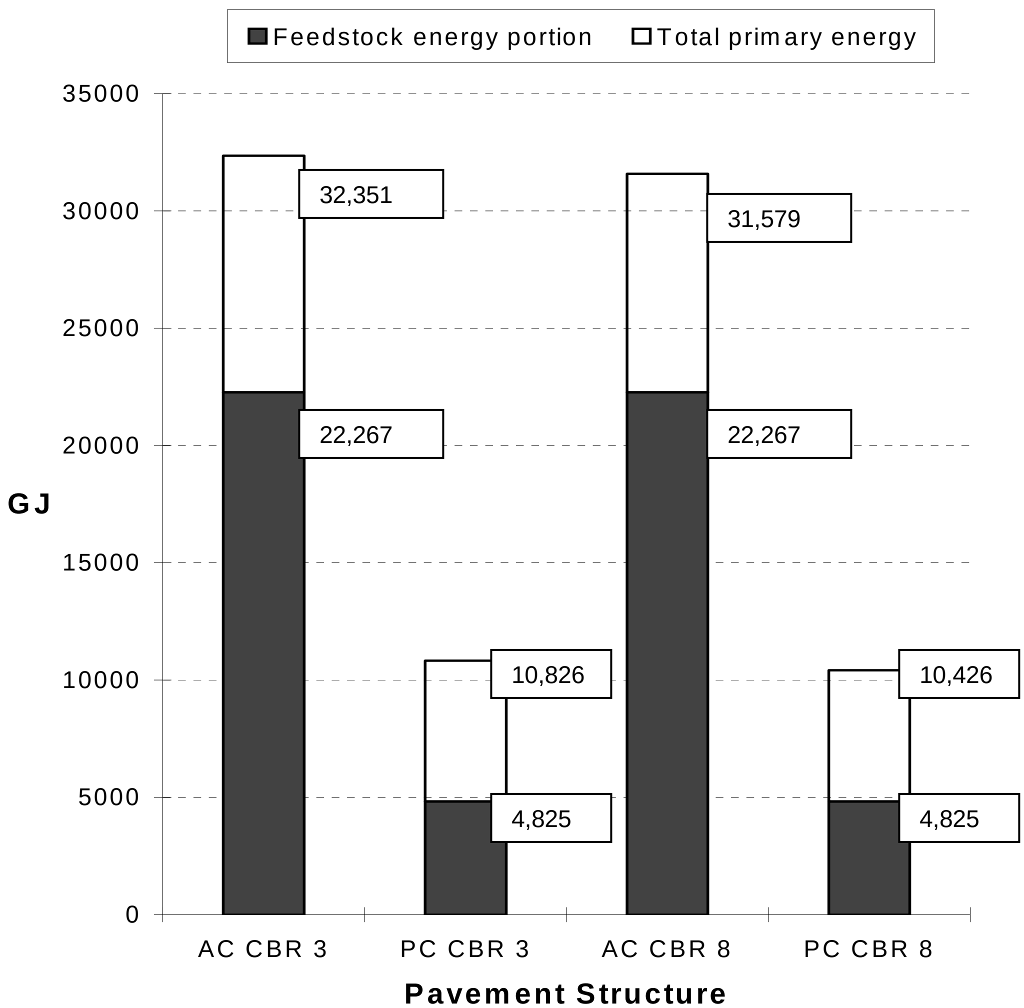
5.1 ENERGY USE

Figures 5.1, 5.2, 5.3 and 5.4 show the comparative embodied primary energy results for the Canadian arterial and high volume highways, the Quebec urban freeway and Ontario Highway 401 for the 0% RAP use case. Within each figure, the comparable asphalt and Portland cement concrete CBR pavement structures are shown side-by-side for ease of comparison. The charts show both the feedstock portion and primary energy use; summing the feedstock and direct energy use yields the embodied primary energy embodied in the road pavement structure.

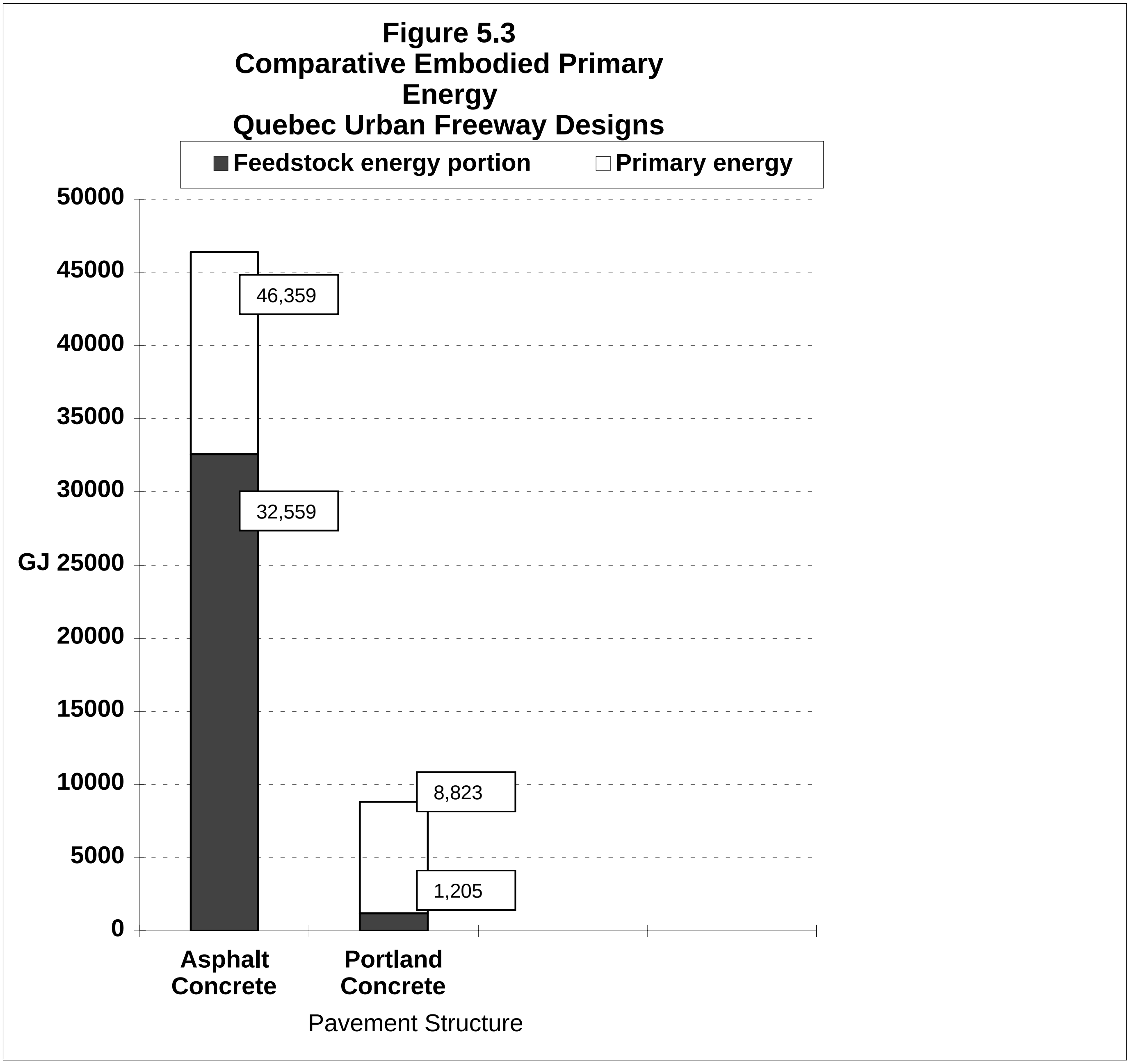


Note: Displayed results are for the 0% RAP case on 2-lane kilometer basis

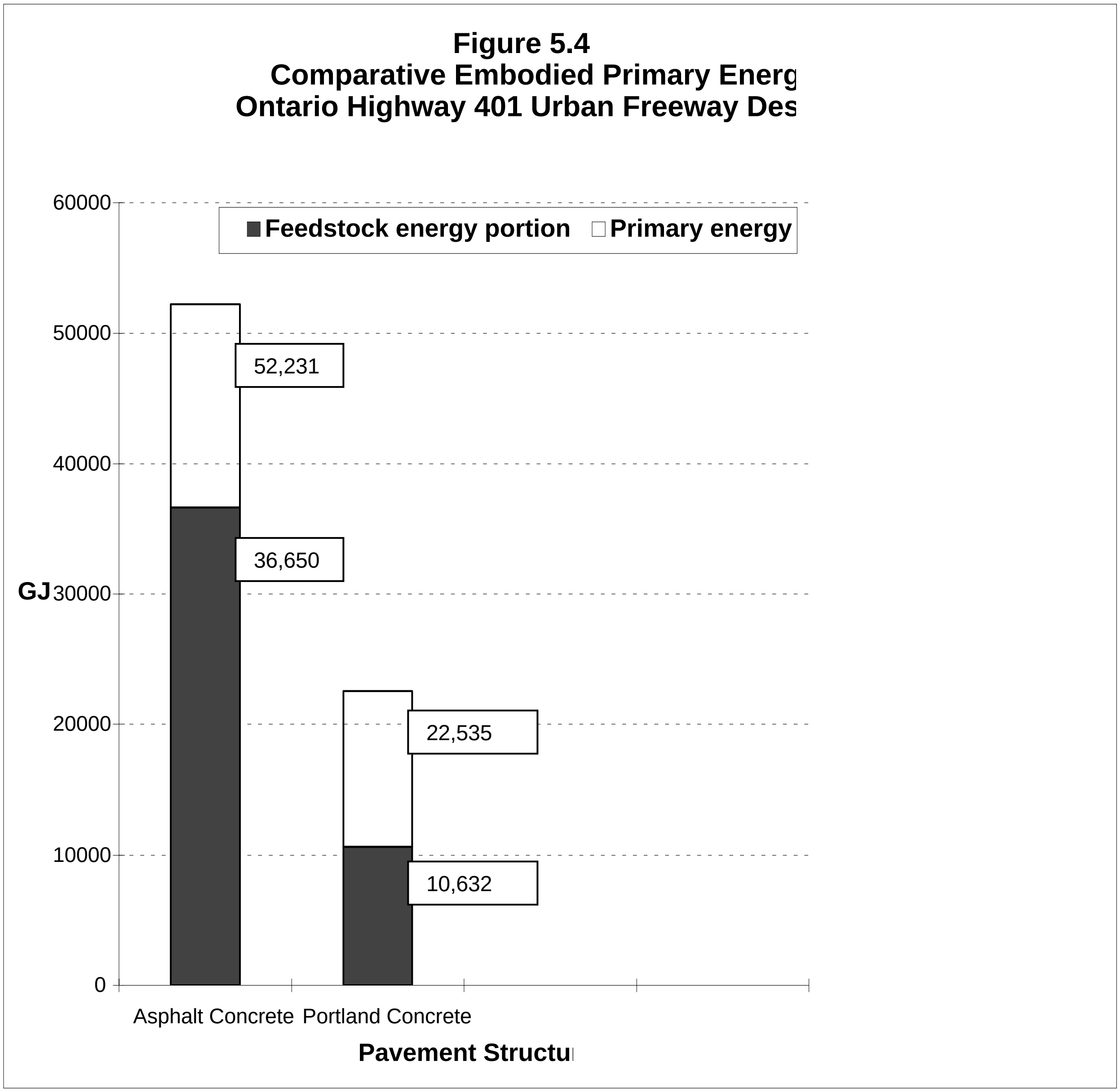
Figure 5.2
Comparative Embodied Primary Energy
Canadian High Volume Highway Designs



Note: Displayed results are for the 0% RAP case on 2-lane kilometer basis



Note: : Displayed results are for the 0% RAP case on 2-lane kilometer basis



Note: Displayed results are for the 0% RAP case on 3-lane kilometer basis

For all 12 pavement structures, the flexible asphalt concrete alternatives clearly embody more primary energy from a life cycle assessment perspective than their rigid Portland cement concrete counterparts. The absolute primary energy advantage gained from the use of Portland cement concrete pavement ranges from 131% to 425%, depending on the road type. For example, the differences between asphalt and Portland cement concrete construction with 0% RAP are as follows:

- 18,360 GJ per 2-lane kilometer for arterial highways (CBR 3) — 3.9 times more than the Portland cement concrete alternative;
- 21,525 GJ per 2-lane kilometer for high volume highways (CBR 3) — 3.0 times more than the Portland cement concrete alternative;
- 37,536 GJ per 2-lane kilometer for the Quebec urban freeway — 5.3 times more than the Portland cement concrete alternative; and
- 29,696 GJ per 3-lane kilometer for the Ontario Highway 401— 2.3 times more than the Portland cement concrete alternative.

As the figures indicate, the feedstock energy component is the largest contributor to total energy for all of the flexible asphalt concrete pavement structures. Portland cement concrete pavements still enjoy a significant energy advantage relative to asphalt if feedstock energy is excluded, but the gap narrows considerably (see Table 5.1 below).

These higher primary energy differences for the flexible asphalt concrete designs range from 2,734 GJ for the Canadian arterial CBR 8 highway to 6,182 GJ for the Quebec urban freeway per two-lane kilometer, values that are 66% to 77% higher than the corresponding alternative Portland cement concrete design primary energy use. The Ontario three-lane kilometer primary energy differences between asphalt and Portland cement concrete show the smallest difference (31%).

The inclusion of 20% RAP in the binder course mix for the Canadian arterial and high volume highway designs reduced the embodied primary energy estimates by 3.5 to 5% for the rigid Portland cement concrete highways and from 5 to 7.5% for the flexible asphalt concrete highways. While these reductions in energy use for flexible asphalt concrete narrow the gap with Portland cement concrete, the remaining differences are still significant, especially at the embodied primary energy level.

Table 5.1
Primary energy Use Comparison 0% RAP

Material & Highway Type by Pavement Structure	Primary Energy (excluding feedstock energy) GJ	Difference between AC and PC GJ	Per cent Difference (PC as basis)
AC Arterial CBR3	7,559	3,030	67
PC Arterial CBR 3	4,529		
AC H. Vol. CBR 3	10,084	4,083	68
PC H. Vol. CBR 3	6,001		
AC Arterial CBR8	6,876	2,747	67
PC Arterial CBR 8	4,129		
AC H. Vol. CBR 8	9,312	3,711	66
PC H. Vol. CBR 8	5,601		
AC Quebec Freeway	13,800	6,182	81
PC Quebec Freeway	7,618		
AC Ontario Hwy 401	15,581	3,678	31
PC Ontario Hwy 401	11,903		

As discussed in Section 4.3.3, increases in transportation distances for base and sub-base granular materials will tend to increase the advantage of Portland cement concrete pavement construction from an energy perspective. However, the relative increase in energy use for asphalt concrete compared to Portland cement concrete was not found to be significant when compared to the overall embodied energy of the given roadway.

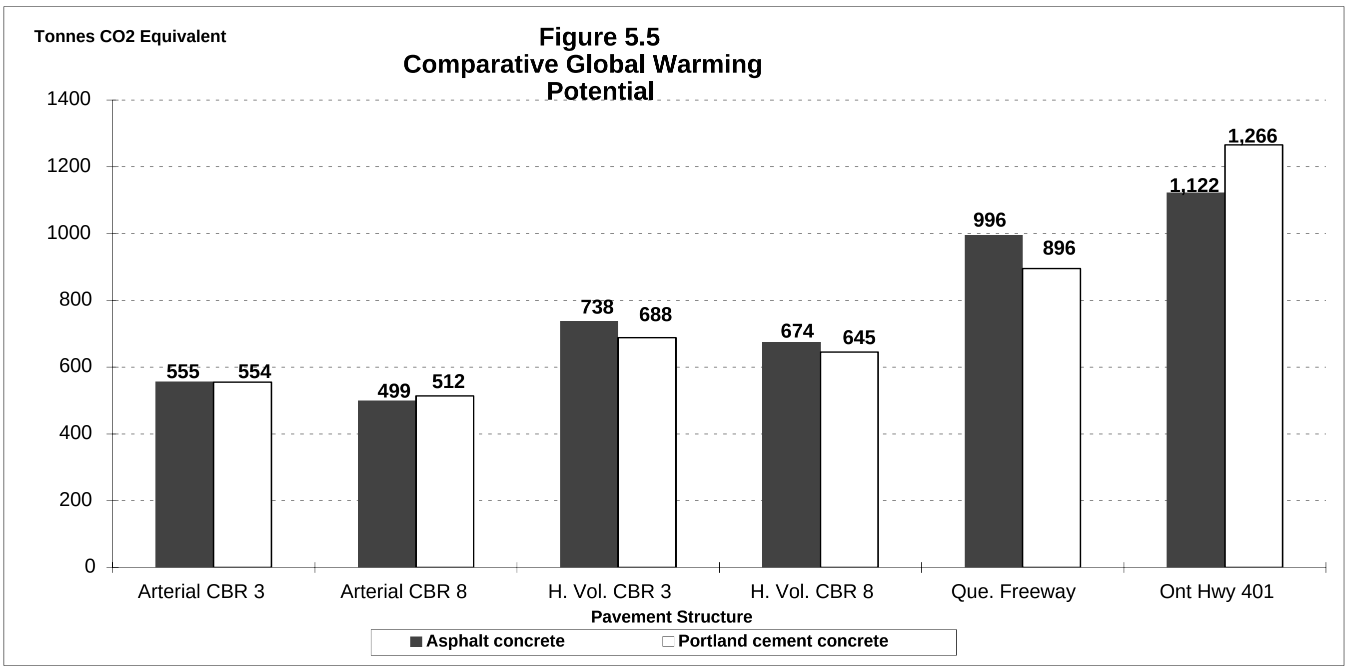
Other factors, such as construction equipment use and concrete transportation, are more likely to have similar energy use implications for the two kinds of construction.

5.2 GLOBAL WARMING POTENTIAL

Figure 5.5 shows the comparative global warming potential estimates for the 12 pavement structures with 0% RAP over the 50-year life cycle. The bar charts are organized by road class design and CBR (where applicable) to facilitate direct comparisons between the asphalt and Portland cement concrete alternatives.

For the Canadian arterial and high volume highways neither alternative material design has a distinct advantage in terms of GWP effects across the two-lane kilometer roads. These differences range from less than 1% to as much as 7%. And while these differences increase as one moves from the arterial to the high volume highway, the differences are generally regarded to be within the 10% acceptable error or confidence interval of the supporting life cycle inventory study and should be considered insignificant. Of the two-lane kilometer designs, it is only the Quebec urban freeway design that shows a marginally significant difference between the two alternative material designs – the flexible asphalt concrete design's global warming potential emissions are some 11% higher than that of the rigid, Portland cement concrete pavement design. This higher GWP result for the flexible asphalt concrete is primarily a function of two factors: (1) the need to resurface the asphalt concrete road more frequently and the requirement to reconstruct the flexible asphalt concrete roadway some 17 years earlier than the rigid Portland cement concrete roadway.

The Ontario Highway 401, three-lane kilometer roadway also demonstrates a marginally significantly difference in GWP between the two material designs, with the flexible asphalt concrete design showing a 11% lower GWP over the 50-year planning cycle. The result is a function of the greater use of materials in the initial road construction (3 lanes rather than two) and the greater use of Portland cement concrete relative to the asphalt concrete in the initial designs. Table 5.1 underscores these observations, whereby the difference in direct energy use for the two alternatives is the lowest for the Ontario Highway 401 road design.



APPENDIX A

CANADIAN DESIGN BACKGROUND DOCUMENT: PAVEMENT ENGINEERING TECHNICAL SERVICES EQUIVALENT PAVEMENT DESIGNS FLEXIBLE AND RIGID ALTERNATIVES

Prepared by:

Applied Research Associates, Inc.
ERES Consultants Division

December 2003

December 15, 2003

PAVEMENT ENGINEERING TECHNICAL SERVICES

EQUIVALENT PAVEMENT DESIGNS

FLEXIBLE AND RIGID ALTERNATIVES

Project No. 5687L

Submitted to:

Cement Association of Canada

By:

Applied Research Associates, Inc.
ERES Consultants Division
5409 Eglinton Avenue West
Suite 207
Toronto, Ontario M9C 5K6
Telephone: 416-621-9555 Facsimile: 416-621-4917
Web: www.eresconsultants.com

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PAVEMENT ENGINEERING TECHNICAL SERVICESEQUIVALENT PAVEMENT DESIGNS FLEXIBLE AND RIGID ALTERNATIVES

1.0 General

Applied Research Associates, Inc. – ERES Division was retained by the Cement Association of Canada for the provision of pavement engineering technical services related to the development of typical pavement designs for three classes of roadways/highways constructed in Canada.

The purpose of this study was to develop typical pavement designs for roadway/highway sections along with their associated typical initial construction costs. All pavement designs were developed using the most commonly used pavement design procedures. This included the AASHTO 1993 design methodology for flexible pavements and the AASHTO 1993 and Cement Association of Canada (CAC) method for rigid pavements.

In addition, example trial pavement designs were completed for comparison purposes using the draft models developed as part of the National Cooperative Highway Research Program (NCHRP) 1-37a project better known as AASHTO 2002 Guide.

Relative cost comparisons were also provided through the determination of the approximate quantities of hot mix asphalt (HMA), Portland cement concrete (PCC) and granular base/subbase materials for each pavement structure, applying typical unit costs and then totalling these values to provide the typical cost for each pavement type on a 2-lane kilometre section basis.

2.0 Methodology

The flexible pavements were designed using the AASHTO *Guide for the Design of Pavement Structures, 1993* which is the most predominate procedure for designing flexible pavements in North America. For rigid pavements, the designs were developed using the AAHSTO 1993 and the Cement Association of Canada (CAC) methods.

To develop pavement designs for this study, a number of assumptions were required. The pavement sections assumed a 2 lane roadway with traffic in two directions. The designs were developed assuming the roadbed soils provide foundation support equivalent to a CBR 3 and a CBR of 8. Three traffic levels were assumed for this assignment, collector roads and minor highways (5,000 AADT), arterial road and major highways (15,000 AADT), and high volume highways (50,000 AADT).

The NCHRP 1-37a pavement design method is based on mechanistic-empirical theory and is substantially different from the AASHTO and CAC methodologies. The procedure is not a thickness design method but rather relates pavement layer thicknesses and material properties to pavement performance indicators such as asphalt and PCC cracking, smoothness, etc. The mechanistic-empirical design of new rigid and flexible pavements requires an iterative hands-on approach by the designer. The designer must select a trial design and then analyze the design in detail to determine if it meets the performance criteria established by the designer. The flexible pavement performance measures considered include permanent deformation (rutting), fatigue cracking (both bottom-up and top-down), thermal cracking, and smoothness (International Roughness Index or IRI). Rigid pavement performance measures considered include mid-slab cracking, faulting and IRI. If the trial design does not satisfy the performance criteria, the design is modified and reanalyzed until the design does satisfy all criteria. The designs that meet the applicable performance criteria are then considered feasible from a structural and functional viewpoint.

The NCHRP 1-37a designs were completed for a typical pavement section located in southern Ontario. The highest traffic load pavement and low subgrade support were selected for the example trial pavement designs. Inputs were obtained from the LTPP and C-LTPP sections, weather station databases typical of southern Ontario type conditions and other information. The evaluation consisted of obtaining all needed inputs, prediction of key distress types and smoothness over a 20 year period, and the examination of those results as indicators of future performance of this rehabilitation. These steps are described briefly in the following sections.

Design Input Levels

For many of the design inputs for the AASHTO 2002 Guide, the designer can choose from multiple (generally three) levels of data quality.

Level 1—site and/or material specific inputs for the project obtained through direct testing or measurements. Examples of Level 1 data include material properties obtained through laboratory testing and measured traffic volumes and weights at the project site.

Level 2—the use of correlations to establish or determine the required inputs. Examples of Level 2 data include the resilient modulus of the subgrade or unbound base materials estimated from CBR or R-values using empirical correlations.

Level 3—the use of national or regional default values to define the inputs. Examples of Level 3 input include the use of AASHTO soil classifications to determine a typical resilient modulus value or the use of roadway type and truck type classifications to determine normalized axle weight and truck type distributions.

As the pavement designs developed for this assignment were intended to be 'typical' of three levels of traffic and two subgrade conditions, Level 2 inputs were used for the 2002 Guide designs.

Input Processing

The inputs were processed to obtain monthly values of the traffic, material, and climatic inputs required for damage/distress computations. Specific information used in the analysis was:

- Average daily number of single, tandem, tridem, and quad axles in each axle weight category for each month of the analysis period.
- Temperatures within the PCC and asphalt concrete layers for every hour of the design period.
- Average monthly relative humidity for each calendar month.
- HMA modulus versus temperature based on the program master curves.
- PCC strength and elastic modulus at each month of the analysis period.
- Monthly average moduli values of the base and subbase layers.
- Monthly average effective subgrade modulus of reaction (k-value) determined using subbase(s) and subgrade resilient modulus (the raw design input).

The monthly layer moduli and the hourly temperatures profiles were obtained using the Enhanced Integrated Climatic Model (EICM).

Structural Response Model

For the PCC pavement, the structural response model was based on the ISLAB2000 finite element (FE) software was used for the computation of pavement responses (i.e., stresses, strains, and deflections). The processed inputs were used to compute stresses and deflections on an incremental basis (e.g., month-by-month) for the entire design period. The computed stresses and deflections were then used to estimate damage and distress.

For flexible pavement, the structural response model is to determine the response of the pavement system due to traffic loads and environmental influences. Environmental influences may be direct (e.g., strains due to thermal expansion and/or contraction) or indirect via effects on material properties (e.g., changes in stiffness due to temperature and/or moisture effects).

The outputs from the pavement response model are the stresses, strains, and displacements within the pavement layers. Of particular interest are the critical response variables required as inputs to the pavement distress models in the mechanistic-empirical design procedure. Examples of critical pavement response variables for flexible pavement include:

- Tensile horizontal strain at the bottom/top of the HMA layer (for HMA fatigue cracking)
- Compressive vertical stresses/strains within the HMA layer (for HMA rutting)
- Compressive vertical stresses/strains within the base/subbase layers (for rutting of unbound layers)
- Compressive vertical stresses/strains at the top of the subgrade (for subgrade rutting)

Incremental Damage Accumulation

The trial designs were analyzed for adequacy by dividing the design analysis period into monthly time increments beginning with the traffic opening month. Traffic loads were also divided into types of axles and axle loads and distributed for each hour with a given monthly increment.

Within each increment (each month), all other factors that affect pavement responses and damage such as HMA modulus, PCC strength, PCC elastic modulus, base/subbase modulus, subgrade modulus, and joint load transfer (transverse and longitudinal) were held constant. Thus, within each increment the critical stresses and deflections were calculated along with the damage incurred in that increment. Damage was summed over all increments.

Distress Prediction

Cumulative damage (the mechanistic parameter that represents a relative index of load associated damage within the pavement structure) was used to estimate pavement distress. The incremental damage (accumulated month by month) was converted to physical pavement distresses (i.e., transverse cracking, fatigue cracking, joint faulting, etc.) using calibrated models that relate the calculated damage to observable distresses. Calibrated distress prediction models were developed using long-term pavement performance data located in a variety of climatic conditions and subject to various traffic and environmental loading situations.

Smoothness (IRI) Prediction

The IRI over the design period was estimated using initial IRI, subsequent development of distresses over time, and site factors. The site factors include subgrade and climatic factors that account for the roughness caused by shrinking or swelling soils and frost heave conditions. IRI was estimated incrementally over the entire design period on a monthly basis.

The distresses and smoothness (IRI) were predicted using the draft mechanistic-empirical models developed as part of the NCHRP Project 1-37A and incorporated in the 2002 Design Guide. At present, the AASHTO 2002 design software is only available in imperial units. Therefore, all input values were converted to imperial units prior to running the software.

3.0 Traffic Considerations

The AADT (Average Annual Daily Traffic (2-way)) volumes were assumed as follows: collector roads and minor highways (5,000 AADT), arterial road and major highways (15,000 AADT), and high volume highways (50,000 AADT). The percentage of commercial vehicles in the traffic flow was assumed to be 10 percent. To calculate the equivalent single axle loads (ESAL's) an average truck factor of 2.0 was assumed. This assumes that the commercial vehicle class distribution will comprise predominately 4 and 5 axle trucks. A 1.0 percent growth rate in truck traffic was assumed over the design period. The number of ESALs the pavements are expected to accommodate during the design life is the same for both the flexible and rigid designs.

Based on these assumptions, the ESALs calculated for design purposes are summarized in Table 1.

Table 1. ESAL Calculation Summary.

Roadway Classification	Collector Roads/ Minor Highways	Arterial Roads/ Major Highways	High Volume Highways
AADT	**5,000**	15,000	50,000
% Commercial	10	10	10
Directional split	50/50	50/50	50/50
Average truck factor	2.0	2.0	2.0
ESALs (million)	4	12	40

For the 2002 Guide trial designs, the program default traffic class and axle load distributions were used for the traffic input.

4.0 Flexible Pavement Design

<u>AASHTO 1993 Flexible Designs</u>

The output of the 1993 AASHTO flexible model is a structural number that characterizes the structural capacity of the pavement layers required for the given set of inputs. This structural number (SN) is then distributed in terms of thickness among the various pavement layers (e.g., HMA surface, binder, aggregate base, and so on) according to coefficients characterizing the relative structural support of each material. The inputs chosen for calculation of the required structural number for flexible pavements in the AASHTO method are summarized in Table 2.

Table 2. Structural Number Calculation.

ESALs (million)	4		12		40	
Initial Serviceability	4.5		4.5		4.5	
Terminal Serviceability	2.5		2.5		2.5	
Reliability Level, (%)	90					
Standard Deviation	0.45					
Resilient Modulus, M_r (MPa)	30	80	30	80	30	80
Structural Number, SN (mm)	125	91	145	107	169	127

Flexible pavement designs were developed using untreated granular base and subbase. The granular base thickness was selected to be 150 mm, which is considered a common design practice for many municipalities/agencies across Canada. Using the AASHTO layer elastic principals, the thickness of the hot mix asphalt (HMA) layer is selected to limit stress and strains in the underlying base layer. The thickness of subbase is then selected to achieve the design structural number. The flexible pavement designs developed using the AASHTO 1993 design procedure are presented in Table 3.

Table 3. AASHTO 1993 Flexible Pavement Designs.

	Collector Roads/ Minor Highways		Arterial Roads/ Major Highways		High Volume Highways	
ESALs (M)	4.0 (low)		12.0 (med)		40.0 (high)	
M_r (MPa)	30	80	30	80	30	80
HMA (mm)	140	140	170	170	205	205
Base (mm)	150	150	150	150	150	150
Subbase (mm)	500	115	585	165	700	225
Thickness (mm)	*790*	*405*	*905*	*485*	*1055*	*580*
SN (mm)	*125*	*91*	*145*	*107*	*169*	*127*

<u>AASHTO 2002 Flexible Design</u>

For the 2002 Guide flexible mechanistic-empirical analysis, the following limiting distress criteria were used:

- Top down cracking – 200 m/km (1000 ft/mile)
- Fatigue cracking – 25 percent of pavement area
- Thermal cracking – 200 m/km (1000 ft/mile)
- Rutting – 10 mm (0.4 inches)
- IRI – 3.2 mm/m (200 inches/mile)

The results of the AASHTO 2002 flexible pavement design for a traffic level of 40 millions ESALs and 30 MPa subgrade resilient modulus as shown in Table 3 above are as follows:

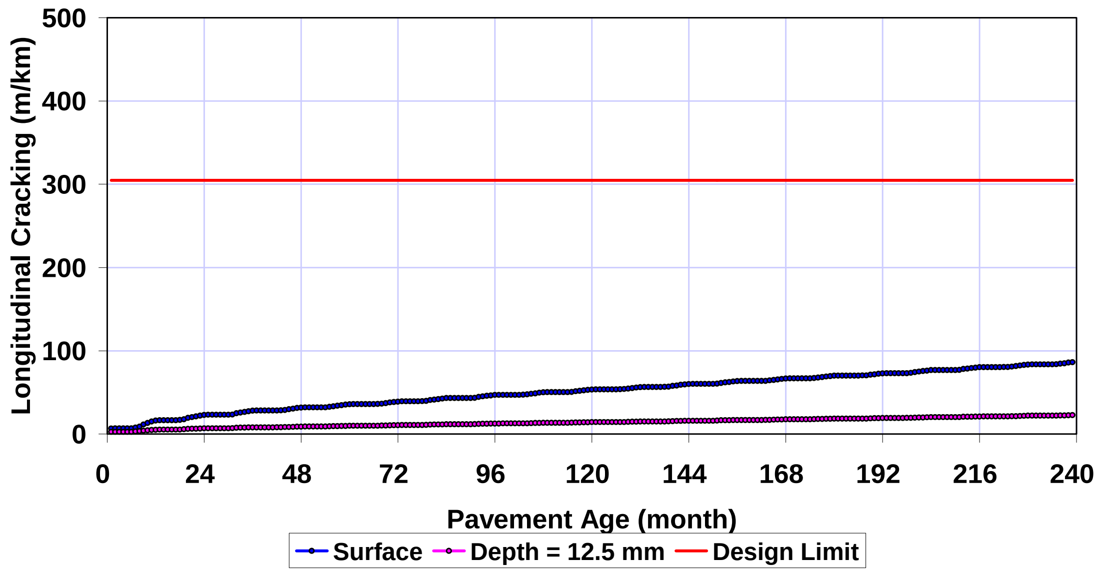

Figure 1. Predicted Top Down Cracking

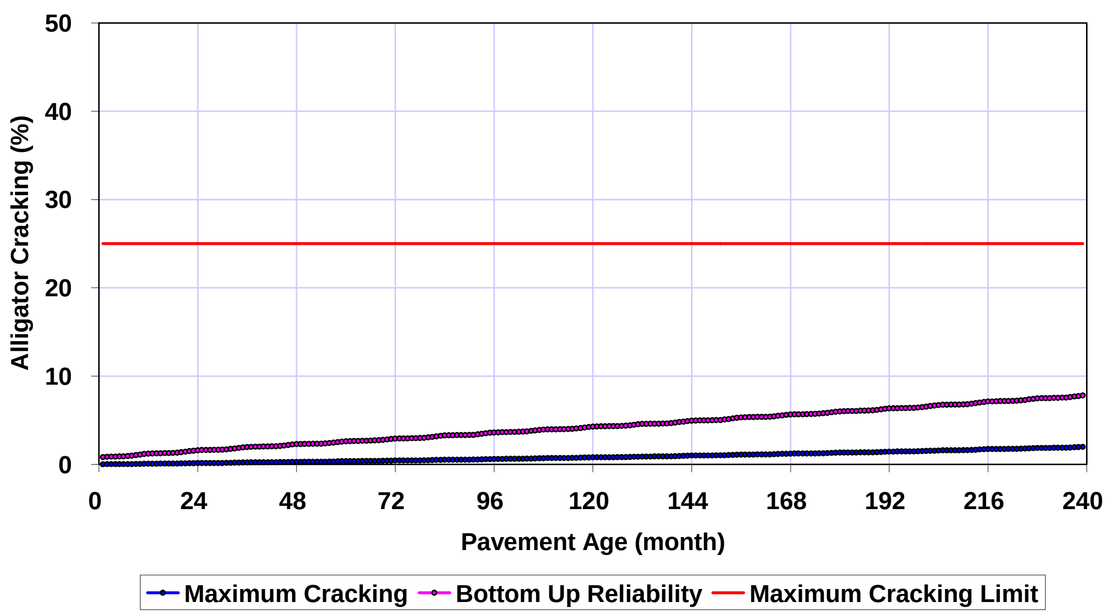

Figure 2. Predicted Damage for Alligator Cracking

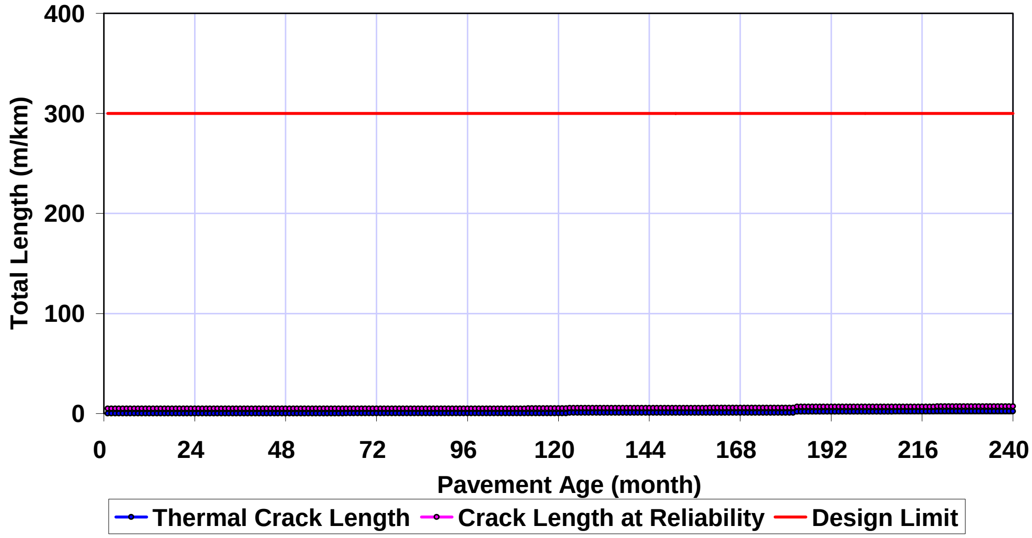

Figure 3. Predicted Thermal Cracking

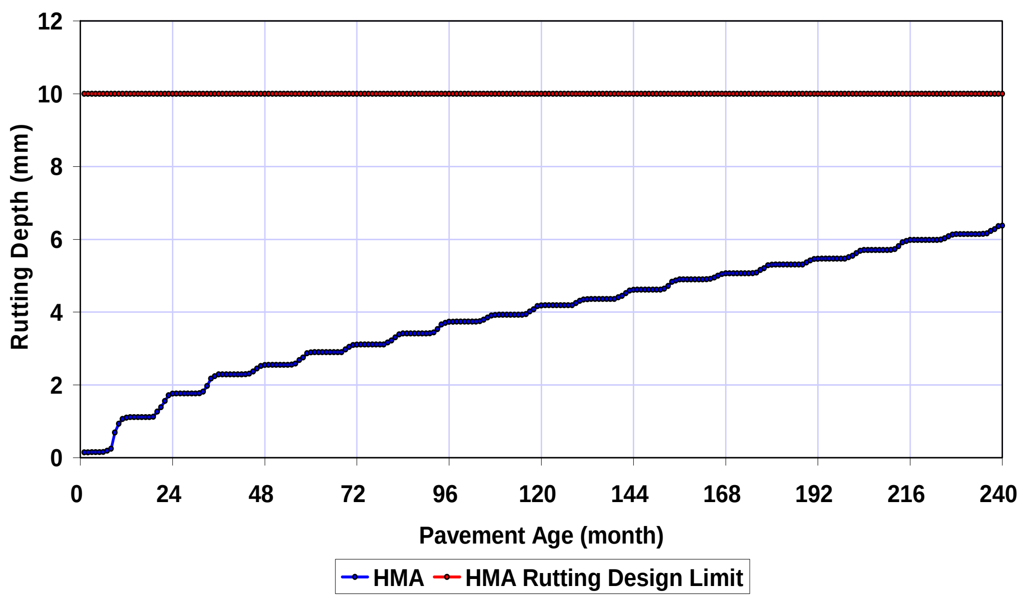

Figure 4. Predicted HMA Rutting

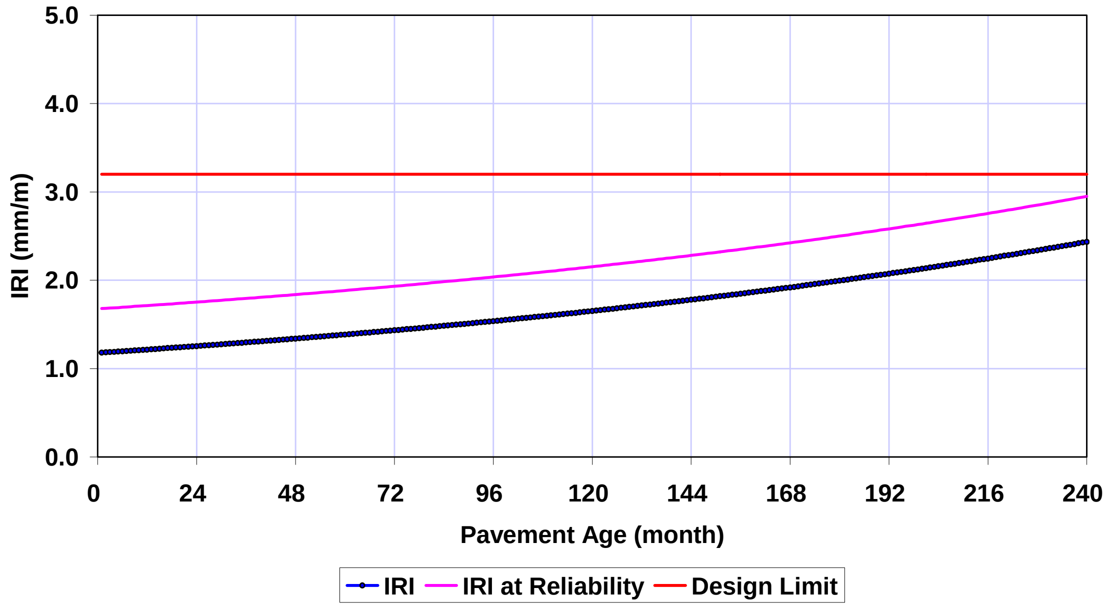

Figure 5. Predicted IRI

5.0 Rigid Pavement Design

AASHTO 1993 Rigid Design

The inputs chosen for calculation of the required pavement thickness using the AASHTO 1993 rigid design procedure are summarized in Table 4.

Table 4. AASHTO 1993 Design Thickness Calculation.

ESALs (million)	4.0		12.0		40.0	
Initial Serviceability	4.5					
Terminal Serviceability	2.5					
Overall Standard Deviation	0.35					
Reliability	90					
Load Transfer Coefficient	2.7					
Modulus of Rupture, (MPa)	5.0					
Subgrade Modulus, k (kPa/mm)	25	49	25	49	25	49
Calculated Thickness, (mm)	195	185	230	225	280	270

The AASHTO 1993 designs have assumed that the PCC would be constructed over 150 mm of granular base and that load transfer devices would be used at all transverse joints. The design has assumed HMA shoulders beyond the PCC pavement.

CAC Simplified Rigid Design

The CAC design method (PACPAV) is a mechanistic-empirical procedure that considers the flexural strength of concrete, the modulus of subgrade reaction, and the commercial vehicle axle-load spectra in conjunction with the past performance of experimental pavements and test roads. The simplified procedure was used.

The inputs chosen for calculation of the required pavement thickness using the CAC method are summarized in Table 5. All pavement designs include dowel bars and a widened outside lane.

Table 5. CAC Design Thickness Calculation.

ESALs (million)	4.0		12.0		40.0	
Axle Load Category	1		2		4	
ADTT Two Directions	550		1650		5500	
Modulus of Rupture, (MPa)	5.0					
Subgrade Modulus, k (kPa/mm)	25	49	25	49	25	49
Calculated Thickness, (mm)	180	175	200	190	225	215

AASHTO 2002 Rigid Design

For the 2002 Guide rigid mechanistic-empirical analysis, the following limiting distress criteria were used:

- Transverse cracking – 20 percent of slabs
- Transverse joint faulting– 3 mm (0.12 inches)
- IRI – 3.2 mm/m (200 inches/mile)

The results of the AASHTO 2002 rigid design for a trial concrete thickness of 200 mm, traffic equivalent to 40 millions ESALs and subgrade resilient modulus of 30 MPa is given in Figures 6 to 10.

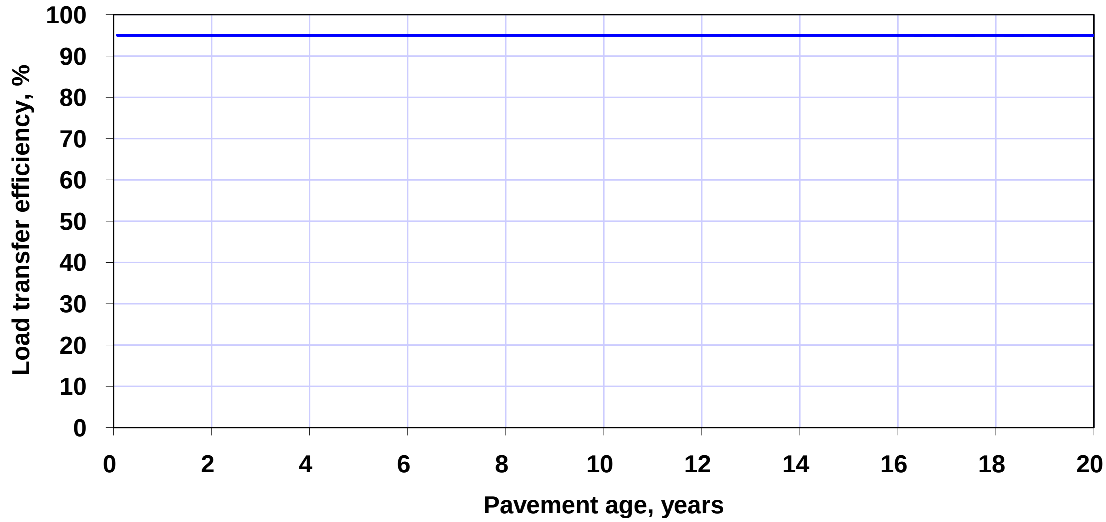

Figure 6. Predicted Load Transfer Efficiency

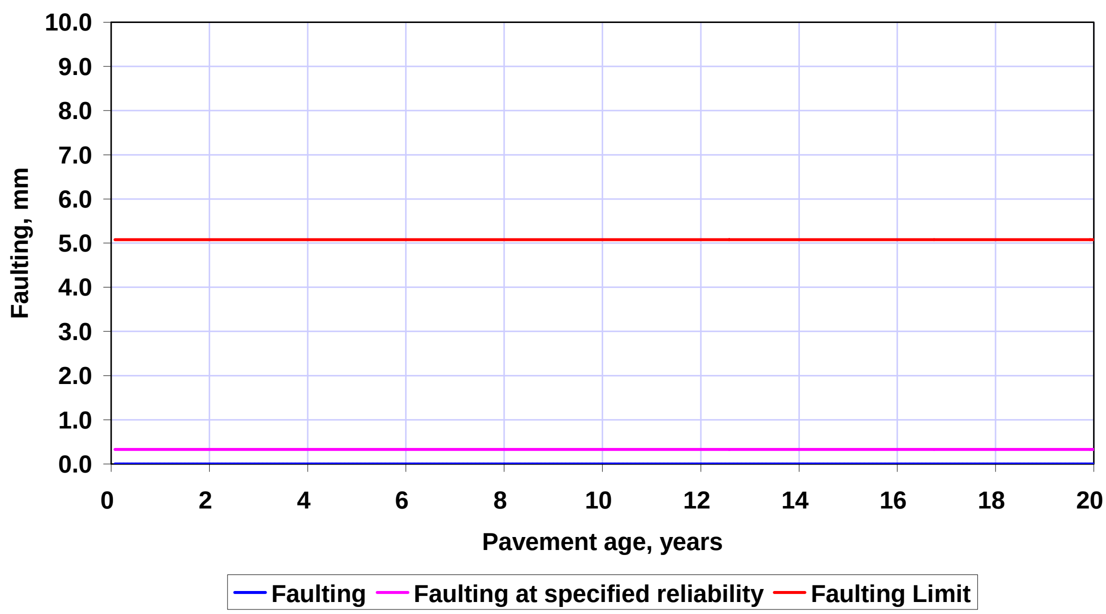

Figure 7. Predicted Joint Faulting

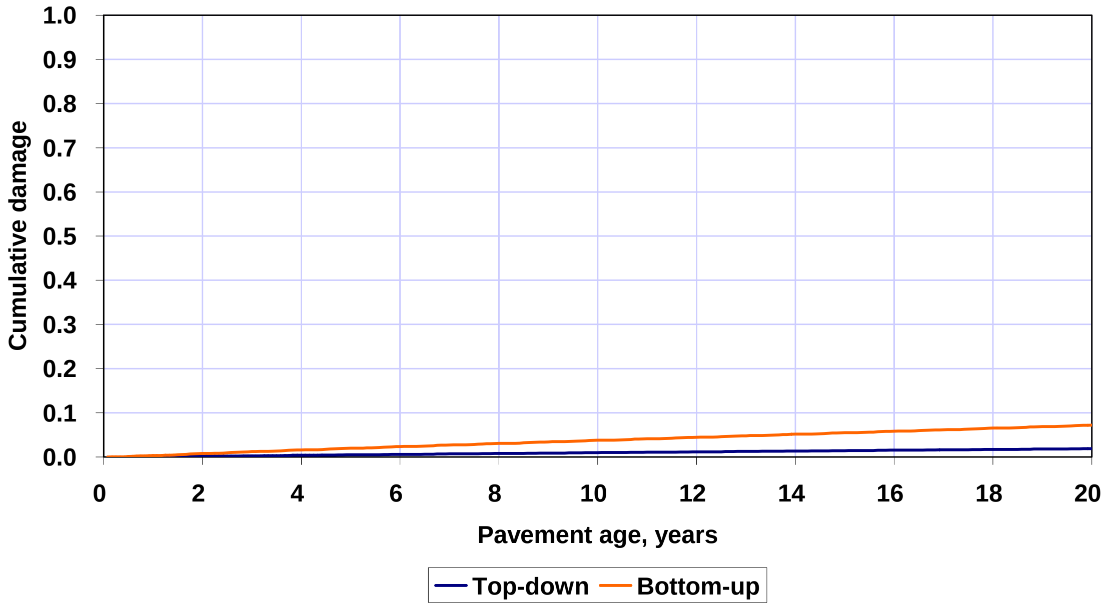

Figure 8. Predicted Cumulative Fatigue Damage

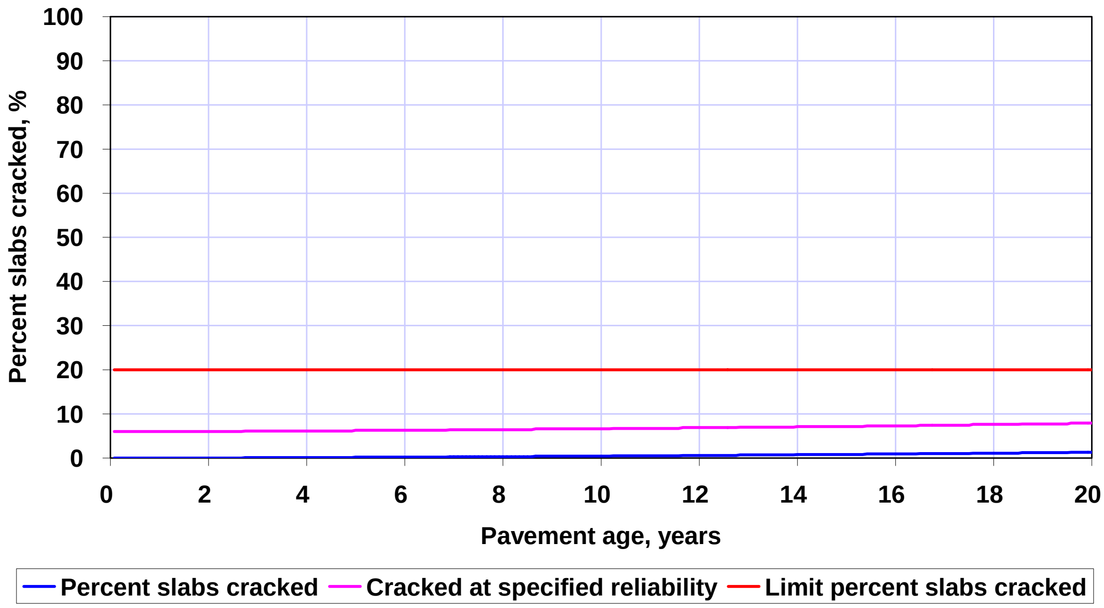

Figure 9. Predicted Percent of Cracked Slabs

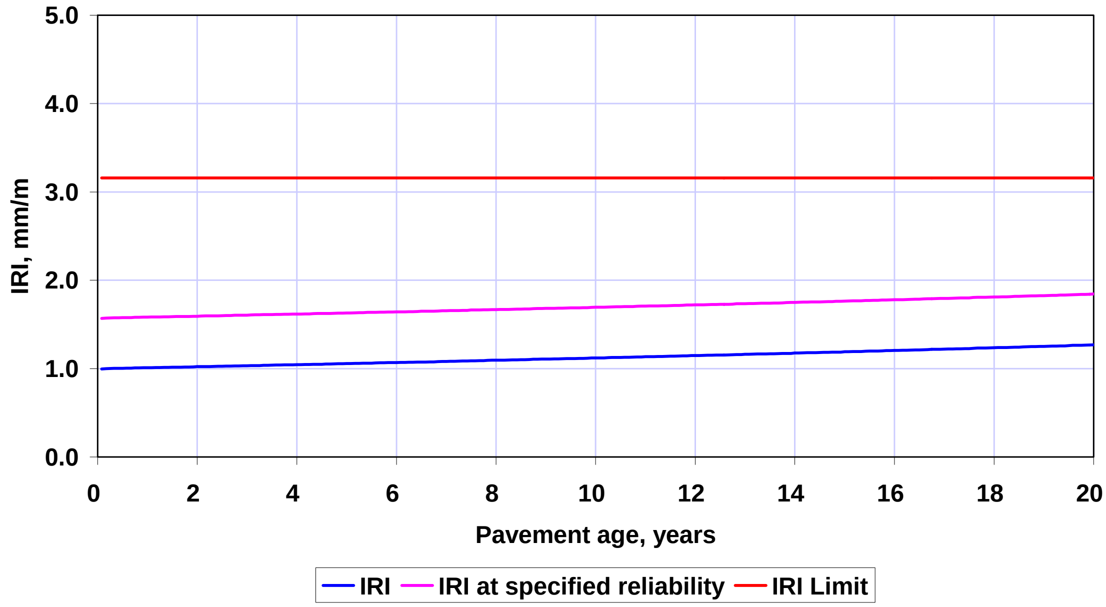

Figure 10. Predicted IRI

Trial designs with a PCC thickness of less than 200 mm resulted in fatigue damage that exceeded the maximum specified limits.

6.0 Recommended Pavement Designs

The pavement designs recommended for use are the AASHTO 1993 designs for the flexible pavements and the CAC designs for the rigid pavements. ERES recommends the CAC designs for the rigid pavements as it is well know that the AASHTO 1993 procedure tends to recommend fairly conservative rigid pavement thicknesses particularly for the higher traffic levels and higher levels of reliability. This fact is confirmed by the AASHTO 2002 analysis which indicted that a PCC slab thickness of 200 mm was sufficient to accommodate the 40 million ESALs for a subgrade resilient modulus of reaction of 30 MPa. The results of several trial pavement designs for moderate and high traffic levels comparing the AASHTO 1993 and AASHTO 2002 design procedures are shown in Figures 11 and 12.

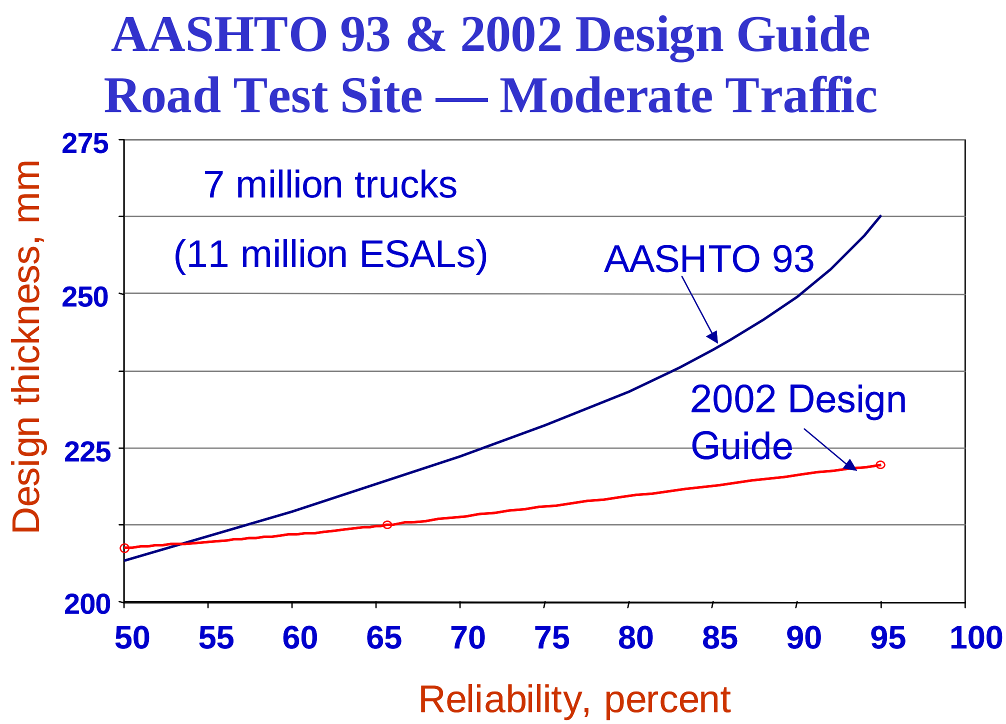

Figure 11. Comparison between AASHTO 1993 and AASHTO 2002 Procedures – Moderate Traffic.

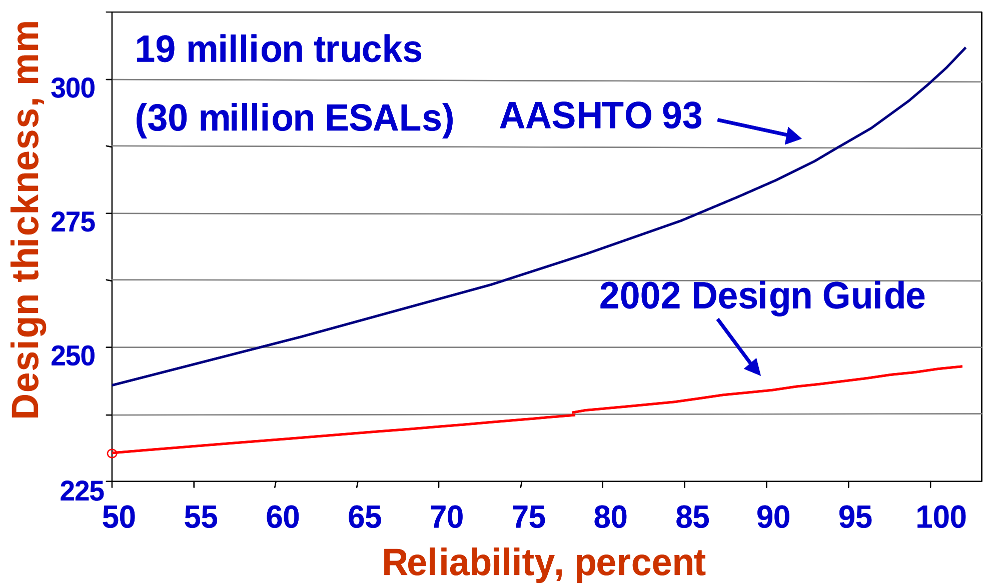

Figure 12. Comparison between AASHTO 1993 and AASHTO 2002 Procedures – Heavy Traffic.

7.0 Estimated Quantities and Unit Costs

Quantity estimates have been calculated for each of the recommended pavement designs. All estimates are based on 2 lane-km of pavement with a 3.0 m outside shoulder (2.5 m beyond the widened lane for the PCC pavement) and 1.0 m inside shoulder. The units of measure for each major material are based on the traditional units of purchase; square metre for PCC and tonne for HMA and unbound granular materials. The estimated quantities and assumed unit costs are summarized in Table 6.

8.0 Closure

The purpose of this study was to develop typical pavement designs for roadway/highway sections along with their associated initial construction cost per two lane-kilometre. The selected flexible pavement sections were developed using the 1993 AASHTO Guide for the Design of Pavement Structures. The selected rigid pavement sections were developed using the Cement Association of Canada pavement design procedure (PCAPAV). It should be noted that this exercise is intended to compare only initial costs and is not a life-cycle cost analysis. A true comparison of the total life-cycle costs would need to include both initial and future maintenance and rehabilitation costs, user delay costs, etc.

Applied Research Associates, Inc.
ERES Consultants Division

David K. Hein, P.Eng.
Principal Engineer

Table 6. Estimated Quantities and Costs (2 lane-km plus shoulders both sides).

	Collector Roads/Minor Highways								Arterial Roads/Major Highways								High Volume Highways							
Subgrade Support	Low				Medium				Low				Medium				Low				Medium			
Pavement Type	Rigid		Flexible		Rigid		Flexible		Rigid		Flexible		Rigid		Flexible		Rigid		Flexible		Rigid		Flexible	
Concrete	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**
Thickness (mm)	180				175				200				190				225				215			
Quantity (m^3)	1440	201600			1400	196000			1600	224000			1520	212800			1800	252000			1720	240800		
Dowel Bars		30000				30000				30000				30000				30000				30000		
Shoulders																								
HMA Surface (mm)	40		40		40		40		40		40		40		40		40		40		40		40	
HMA Binder (mm)	50		50		50		50		50		50		50		50		50		50		50		50	
Gran A Shoulder (tonnes)	725	8694	460	5520	684	8211	460	5520	886	10626	1564	18768	805	9660	1564	18768	1087	13041	1886	22632	1006	12075	1886	22632
HMA Surface (tonnes)	343	17150	392	19600	343	17150	392	19600	343	17150	392	19600	343	17150	392	19600	343	17150	392	19600	343	17150	392	19600
HMA Binder (tonnes)	429	17150	490	19600	429	17150	490	19600	429	17150	490	19600	429	17150	490	19600	429	17150	490	19600	429	17150	490	19600
HMA																								
HMA Surface (mm)			50				50				50				50				50				50	
HMA Binder (mm)			90				90				120				120				155				155	
HMA Surface (tonnes)			919	45938			919	45938			919	45938			919	45938			919	45938			919	45938
HMA Binder (tonnes)			1654	66150			1654	66150			2205	88200			2205	88200			2848	113925			2848	113925
Granular Base																								
Base (mm)	150		150		150		150		150		150		150		150		150		150		150		150	
Base (tonnes)	3967.5	$47,610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610	3967.5	47610
Granular Subbase																								
Subbase (mm)	150		500				115		150		585				165		150		700				225	
Subbase (tonnes)	3300	$29,700	11000	$99,000			2530	22770	3300	$29,700	12870	115830			3630	32670	3300	$29,700	15400	138600			4950	44550
Total Cost/2 lane-km		**$ 351,904**		**$ 303,418**		**$ 316,121**		**$ 227,188**		**$ 376,236**		**$ 355,546**		**$ 334,370**		**$ 272,386**		**$ 406,651**		**$ 407,905**		**$ 364,785**		**$ 313,855**
Rigid % of Flexible		116				139				106				123				100				116		

APPENDIX B

PRIMARY ENERGY AND GLOBAL WARMING POTENTIAL FOR PRODUCTION OF ONE CUBIC METER OF PORTLAND CEMENT-BASED ROAD CONCRETE IN CANADA, QUEBEC AND ONTARIO

Originally Prepared by:
Venta, Glaser & Associates (1999)

Updated by:
Athena Sustainable Materials Institute (2006)

Primary Energy and Global Warming Potential for Production of One Cubic Meter of Portland Cement-Based Road Concrete for Canada, Quebec and Ontario

Introduction:
Detailed calculation factors are shown in Tables 1 through 6, following the text and references. Summary tables of the final results are presented at the end of the Appendix.

Background:
Cement-based road concrete has a typical compressive strength of 30 to 40 MPa and a total cementing material input of 350kg/m^3. Supplementary cementing materials (SCMs) are commonly used to displace a portion of the Portland cement in road design mixes. Generally, when specifying Type 10 Portland cement in concrete road design mixes, SCM usage does not exceed a certain mass of the total cementing materials; i.e., the maximum amount of fly ash should not be more than 25%, for blast furnace slag 50%, and for silica fume 10% by mass of cementing materials (Reference 1). The previous 1999 study's mix design used for Canada falls within these SCM use guidelines and remains unchanged. It includes replacement of 10% of the cement by fly ash and, where available (Central and West Coast regions), blast furnace slag (BFS) is used to replace an additional 25% of the remaining cement. The Canadian overall weighted average design mix is defined in Table 1. According to the Ministry of Transportation in Quebec, the SCM percentage usually used in Quebec concrete road mix designs is provided via a ternary blend comprised of 22% slag, 5% silica fume and the remainder Type 10 Portland cement (Ref. 1). The typical concrete road mix design for Ontario incorporates 25% blast furnace slag, with Portland cement making up the remainder of the mix. Both the Quebec and Ontario road concrete mix designs are also provided in Table 1.

Assumptions:

1. **Functional unit:** The functional unit used for analysis is 1 m^3 of Portland cement-based road mix concrete having the composition for Canada, Quebec and Ontario as specified above.

2. **System boundary:** The system boundary for Portland cement-based road concrete includes the following:
   - extraction and processing of aggregates;
   - processing of BFS;
   - production of Portland cement;
   - transportation of aggregates, BFS, fly ash, silica fume and cement to the concrete plant; and
   - concrete processing.

   The boundary ends at material ready for shipment at the concrete plant gate.

3. **Transportation distances:**
   Aggregates: quarry to concrete plant: 30 km round trip by truck (35 tonne capacity, 6-axle tractor-trailer combination). (Ref. 5)
   Fly ash, BFS, cement: weighted average of actual distances, as per the Athena Institute (Ref. 2)

4. **Aggregate production:**
   It is assumed that both coarse and fine aggregates require the same extraction energy input; the processing (crushing, grinding) energy of the fine aggregate is higher than that of coarse aggregates (Athena Institute, Ref. 2, based on Ref. 5,6).

5. **Upstream pre-combustion and greenhouse gas profiles:**
   The energy and greenhouse gas emissions associated with the extraction, production and delivery of various energy sources (e.g., diesel fuel and electricity) to the point of combustion are referred to as upstream pre-combustion. These are included in the LCI results presented herein. The primary energy and related greenhouse gas emissions associated with purchased electricity are tabulated for both Canada as a whole and Quebec and Ontario separately. The pre-combustion effects associated with other common fuels (e.g., natural gas, coal and transportation energy) are assumed to be the same for Canada as well as the provinces of Ontario and Quebec.

Methodology:
The method of calculating the material and energy consumption and emissions per m^3 of Portland cement-based road concrete mirrors the approach used by the Athena Institute for development of raw material balances, energy profiles and environmental unit factor estimates for cement and structural concrete products. (Ref. 2) The same approach was used for asphalt concrete.

The Portland cement-based concrete manufacturing process is viewed as consisting of four steps:

1. cement production;
2. raw materials (aggregate, BFS) extraction and processing;
3. raw materials (aggregate, BFS, fly ash, silica fume) transportation from source to concrete plant; and
4. concrete plant processing.

The energy consumption and emissions associated with each step are calculated and added to give energy consumption and emissions per m^3 of concrete.

All the material and energy inputs and emission outputs were, as in the case of other Athena Institute projects, developed on a regional basis for six major metropolitan areas. The Canadian weighted averages were than calculated, based on cement production in the four regions under consideration (West Coast, Prairie, Central and East). For the Prairie and East regions, where more than one metro area was included, the populations of Alberta vs. Manitoba and of Quebec vs. New Brunswick, Nova Scotia, P.E.I. and Newfoundland were used as a proxy for concrete production levels to develop relative weights. This resulted in the weights/distribution shown in Table 2 for the six metro areas.

The separate material and energy inputs and emission outputs developed specifically for Quebec and Ontario rely on unique values calculated from CAC data for cement plants located in the two provinces with transportation values for SCMs based on a notional Montreal and Toronto location, respectively.

All results are based on the most recent information about the Canadian cement plants' production capacities and equipment used, provided by the CAC (2004/05 data). Energy inputs and emission outputs for both cement production, and ultimately for concrete production, using the defined mix designs, are estimated using the model developed by the Athena Institute for all cement and structural concrete products.

Information sources and references

Information	*Ref. No.*	*Reference*
SCM usage in Portland cement-based concrete	1	McLeod, N. F. 2005. A Synthesis of Data on the Use of Supplementary Cementing Materials (SCMs) in Concrete Pavement Applications Exposed to Freeze/Thaw and Deicing Chemicals.
Composition of Portland cement-based Concrete – Canada weighted average	2	Life Cycle Embodied Energy and Global Warming Emissions for Concrete and Asphalt Roadways. Athena Institute et al. May 1999
Energy used and emissions generated in cement production	3	Cement and Structural Concrete Products - Raw Material Balances, Energy Profiles and Environmental Estimates, Athena Sustainable Materials Institute, Ottawa, ON, October, 1993 & May, 1999. Updated, based on most recent CAC information re Canadian cement plants (Jan, 2006)
Aggregate extraction emissions	4	same as Ref. 2, based on Canadian Industry Program for Energy Conservation (CIPEC), EMR Canada, 1989
Aggregate and BFS processing emissions	5	same as Ref. 2, based on An INDEPTH Model of Ontario Cement Industry, Ontario Hydro, December 1989
Transportation distances aggregates	6	J.G. Emery and Associates, Toronto, ON, Dec. 4, 1998 in Ref. 2 above
BFS, fly ash, silica fume	7	calculated, based on Ref. 2
Energy inputs and greenhouse gas emissions outputs due to aggregates, BFS, fly ash and silica fume transport	8	calculated, based on Ref. 2
Energy/fuel emissions	9	Primary Energy and Pre-combustion energy and emission estimates from Franklin and Associates (SimaPro Database 1998). Direct Greenhouse Gas Emission Factors by Fuel Type from: Canada's Greenhouse Gas Inventory 1990-02 (August 2004) Environment Canada
Concrete plant processing	10	Same as Ref. 2, based on Present and Future Use of Energy in the Cement and Concrete Industries in Canada, Holderbank Consulting Ltd. report prepared for EMR Canada, March, 1993
Composition of granular base and sub-base	11	J.G. Emery and Associates, Toronto, ON, Sept. 18, 1998, Table 4 in Ref. 2 above

Table 1: Composition of Portland cement-based road concrete [t/m3]

	Ref. 2	Ref. 1	Ref.1
Material	**Canada Average**	**Quebec Average**	**Ontario Average**
Cement	0.26686	0.25500	0.26250
Blast furnace slag	0.04814	0.07700	0.08750
Fly ash	0.03500	0.00000	0.00000
Silica fume	0.00000	0.01750	0.00000
Coarse aggregate	1.10000	1.10000	1.10000
Fine aggregate	0.70000	0.70000	0.70000
Water	0.15000	0.15000	0.15000
TOTAL	2.30000	2.30000	2.30000

Table 2: Factors used to estimate weighted averages as applied to Canada

West Coast	Vancouver	12.9
Prairie	Calgary	9.1
	Winnipeg	4.1
Central	Toronto	48.3
East	Montreal	19.1
	Halifax	6.6
		100.0

Source: Calculated from Ref. 2

Table 3: Energy inputs for aggregate extraction, processing and transportation

Material/Process step	**Energy source**	**GJ/t**
Coarse aggregate extraction	diesel	0.02700
Coarse aggregate processing	electricity	0.01080
Fine aggregate extraction	diesel	0.02700
Fine aggregate processing	electricity	0.03240
Coarse aggregate transportation	diesel road	0.03540
Fine aggregate transportation	diesel road	0.03540

Source: Ref.4-6

Table 4: Energy inputs for BFS processing, BFS and fly ash transportation

Material/Process step	**Energy source**	**GJ/t**
BFS processing	electricity	0.17877
BFS transportation	diesel road	0.09301
	electricity	0.17877
TOTAL BFS transportation		0.27179
Fly ash transportation	diesel road	0.45526
	diesel rail	0.11040
	HFO marine	0.05715
TOTAL fly ash transportation		0.62281

Source: Ref. 5,7

Table 5: Cement production primary energy use by energy form [GJ/t]

	Canada	Quebec	Ontario
Diesel road	0.2840	0.2214	0.3116
Diesel rail	0.0912	0.0021	0.0050
HFO marine	0.0317	0.0101	0.3278
Natural gas	0.7528	0.5357	0.8100
Coal	2.0726	1.5019	1.8022
Oil	0.1533	0.0892	0.2319
Coke	0.8672	1.3854	1.0899
Waste	0.3798	1.4066	0.1865
Electricity	0.5992	0.0171	1.3694
TOTAL	5.2317	5.1695	5.8393

Source: Ref. 2

Table 6: Primary energy & GHG emission factors by fuel type

Fuel type, unit	**Primary energy MJ/unit**	**CO2**	**CH4**	**N2O**
		[kg/GJ of fuel]		
Natural gas, m^3	44.30	57.61	0.16000	0.0000051
Coal, kg	28.86	89.28	0.19500	0.0008330
Diesel fuel, L	42.63	90.03	0.01300	0.0003487
Fuel Oil	45.70	70.70000	0.00780	0.057000
LPG, L	28.85	74.00000	0.00082	0.014400
Gasoline, L	35.80	73.10000	0.00016	0.015500
Coke, kg	31.36	93.74	0.00055	0.088000
Waste, kg	23.98	67.50000	0.00110	0.000000
Electricity, MJ delivered				
Canada	0.9712	71.83	0.15158	0.000525
Quebec	0.0285	2.02	0.00157	0.000006
Ontario	1.2084	86.70	0.19622	0.000645

Source: Ref. 9

Summary Table 1: Canada (Weighted Average)

Material and Energy Inputs and Greenhouse Emissions per m^3
of Portland Cement-Based Road Concrete

	Cement manufacture		**Raw materials extraction and processing**		**Raw materials transportation**		**Concrete plant processing**		**TOTAL**
	input	output	input	output	input	output	input	output	
Materials [t/m³]									
Cement		0.26686					0.26686		
Slag				0.04814			0.04814		
Fly ash							0.03500		
Coarse aggregate				1.10000			1.10000		
Fine aggregate				0.70000			0.70000		
Water							0.15000		
Concrete								2.30000	2.30000
GHG emissions [kg/m3 of concrete]									
CO2		242.35		7.32		6.30		17.77	273.75
CH4		0.0284		0.0090		0.0027		0.0224	.0626
N2O		0.00012		0.00002		0.0000007		0.000009	.0001567
Embodied primary energy [GJ/m3 of concrete]									
Embodied primary energy	1.3961		0.1002		0.0998		0.2619		1.8580

Summary Table 2: Quebec

Material and Energy Inputs and Greenhouse Emissions per m^3
of Portland Cement-Based Road Concrete

	Cement manufacture		**Raw materials extraction and processing**		**Raw materials transportation**		**Concrete plant processing**		**TOTAL**
	input	output	input	output	input	output	input	output	
Materials [t/m3]									
Cement		0.2550					0.2550		
Slag				0.077			0.077		
Silica fume							.0175		
Coarse aggregate				1.10000			1.10000		
Fne aggregate				0.70000			0.70000		
Water							0.15000		
Concrete								2.30000	2.30000
GHG emissions [kg/m3 of concrete]									
CO2		231.93		3.95		7.42		16.81	260.11
CH4		0.0328		0.0018		0.0032		0.0203	0.0581
N2O		0.00003		0.0000008		0.0000008		0.000002	0.000031
Embodied primary energy [GJ/m3 of concrete]									
Embodied primary energy	1.3208		0.0546		0.1026		0.2489		1.7269

Summary Table 3: Ontario

Material and Energy Inputs and Greenhouse Emissions per m^3
of Portland Cement-Based Road Concrete

	Cement manufacture		Raw materials extraction and processing		Raw materials transportation		Concrete plant processing		TOTAL
	input	output	input	output	input	output	input	output	
Materials [t/m3]									
Cement		0.2625					0.2625		
Slag				0.0875			0.0875		
Coarse aggregate				1.10000			1.10000		
Fine aggregate				0.70000			0.70000		
Water							0.15000		
Concrete								2.30000	2.30000
GHG emissions [kg/m3 of concrete]									
CO2		238.37		9.05		6.81		17.98	272.21
CH4		0.0037		0.0135		0.0030		0.0230	0.4253
N2O		0.00014		0.00003		0.0000008		0.00001	0.00017
Embodied primary energy [GJ/m3 of concrete]									
Embodied primary energy	1.5328		0.1256		0.0942		0.2652		2.0178

APPENDIX C

PRIMARY ENERGY AND GLOBAL WARMING POTENTIAL RESULTS FOR PRODUCTION OF ONE CUBIC METER OF ASPHALT CONCRETE

Originally Prepared by:

JAN Consultants (1999)

Updated by:

Athena Sustainable Materials Institute (2006)

Primary Energy and Global Warming Potential Results for Production of One Cubic Meter of Asphalt Concrete

Introduction:
Detailed calculation factors are shown in Tables 1 through 11, following the text and references. Summary tables of the final results are presented at the end of the Appendix.

Definitions:

Asphalt or bitumen	The binder used in asphalt concrete.
Asphalt concrete	The mixture of asphalt and aggregate (hot mix).
Feedstock or inherent energy	The calorific value of a substance. For example, the energy value of bitumen if it were used as a fuel.
Recycled asphalt pavement (RAP)	Asphalt concrete that is removed from the road surface and is used as a component of new asphalt concrete.

Assumptions:

1) **Functional unit.** Functional unit is one cubic meter of asphalt concrete having the composition provided by JEGEL (Reference 1).

2) **System boundary.** The system boundary includes the following:
   • production of crude oil;
   • transportation of crude oil to the refinery;
   • production of asphalt;
   • transportation of asphalt to the asphalt plant;
   • aggregate production and RAP removal;
   • aggregate and RAP transportation to the asphalt plant; and
   • production of asphalt concrete.

The boundary ends at material ready for shipment at the asphalt plant gate.

3) **Transportation distances.**
   a) Crude to refinery transportation as determined by Franklin Associates (Ref.2):

Mode	Percent of Total	Average Distance km
Boat	70%	6,400
Pipeline	30%	1,500
Rail	0%	
Truck	0%	

   b) Aggregates: quarry to asphalt plant — 30 km round trip, truck capacity 35 tonnes. The CCA publication (Ref.5) indicates that portable hot mix asphalt plants are often located adjacent to the aggregate source to limit transportation. However, permanent plants typically haul aggregates over a distance of 60 km round trip. The 30 km round trip distance used in this study represents an approximate or typical hauling distance.

c) Asphalt: refinery to asphalt plant — 200 km round trip, truck capacity 32 tonnes. Asphalt or bitumen is produced at numerous refinery operations across the country. Again, the CCA publication reports a transportation distance of 200 km for asphalt to portable plants; we have used that value in this report.

4) Recycled asphalt pavement (RAP). There is no RAP in the initial Canada-wide mix. Further communication indicated that 20% RAP would typically be included in the initial binder course construction of arterial and high volume highways, but not in construction or overlays of major freeways. When RAP is used in the binder course, the energy required to mill the road surface and transport RAP is included in the LCI. This study describes both a basic or virgin asphalt design mix and a 20% RAP mix for the three regions considered in this study.

RAP is assumed to be recycled through the asphalt plant. In the LCI calculations, RAP is presumed to consist of the same components in the same proportions as the asphalt concrete that it is replacing. It is also assumed that no additional energy or greenhouse gas emissions are associated with processing RAP at the asphalt plant, which is a conservative assumption as it is common to use additional energy to heat the RAP to expedite its break-up and mixing.

5) Aggregate production. Coarse and fine aggregates have been assumed to require the same transportation energy as was used to construct the Portland cement-based concrete profile. The actual processing (crushing) of fine and coarse aggregates differs according to their relative energy intensity. Again, we have used the same processing energy values as were used to construct the Portland cement-based concrete LCI profile.

6) Feedstock energy value of asphalt. A well accepted LCA guideline is to include the inherent energy value of a material if that material is derived from a generally used energy source. For example, the inherent energy value of petrochemicals (e.g., bitumen) should be included in an LCI, because they are derived from petroleum based products (e.g., crude oil). In fact, Alberta's oil (tar) sands are made up of bitumen (10% to 12%), mineral matter (80% to 85%) and the remainder water (4%). These bitumen deposits through rigorous treatment become gasoline and other fuels.

7) Upstream profiles. The energy and greenhouse emissions associated with the extraction, production and transportation of fossil fuels and electricity are examples of upstream profiles included in this LCI. In the Franklin data (Ref. 2), the upstream emissions associated with pre-combustion energy used in the refining process were included with the emissions from production of bitumen. The other upstream values used for the other process steps are the same as those used in the Portland cement-based concrete profile.

Methodology:
The method of calculating the energy and emissions per cubic meter of asphalt involved four steps: basic asphalt production at the refinery, aggregate production, transportation, and asphalt concrete production at the asphalt plant. Energy and emissions from transportation of crude oil from the source to the refinery are included in the data for basic asphalt production in each study region. The transportation step deals with the transport of aggregates from the source to the asphalt plant, and of asphalt from the refinery to the asphalt concrete plant. For each of the four steps, the upstream or pre-combustion energy and greenhouse gases are also calculated and included. The raw data for each of the process step inputs were then converted to units of energy and greenhouse emissions per cubic meter of asphalt concrete and added, to give regional totals per cubic meter.

The data required to calculate the energy and greenhouse gas emissions per cubic meter of asphalt concrete is provided in the tables listed below. As noted in the Introduction, these tables follow the references.

Table	*Title*	*Reference*
1	Composition of virgin and RAP Asphalt Concrete mix design	1
2	Primary Energy Used to Manufacture Asphalt Binder and Its Contribution to Asphalt Concrete	2
3	Primary Energy Used to Quarry Coarse and Fine Aggregates	3
4	Primary Energy used to Mill Asphalt Concrete Road surface	5
5	Primary Energy Used to Manufacture Asphalt Concrete	5
6	Primary Energy Used in Transportation of Materials to the Asphalt Plant	3, 5
7	Asphalt Binder Production GHG Emissions	2
8	Aggregate Extraction and Processing GHG emissions	calculated
9	RAP Processing GHG Emissions	calculated
10	Material Transportation GHG Emissions	calculated
11	Asphalt Plant GHG Emissions	calculated

Calculations of energy consumption and greenhouse gas emissions are based on the composition of the asphalt concrete and the relevant energy use data by fuel type and associated emission factor.

Purchased electricity consumption for each of the process steps is reported separately.

Feedstock energy calculation:
The results are presented with the feedstock energy value of the asphalt (bitumen) reported separately.

Franklin Associates (Ref. 2) reports the energy value of the petroleum resources needed to produce 1000 lbs. of asphalt to be 20.1 mmBtu. This is equivalent to the inherent energy in the asphalt. Therefore 1 tonne of asphalt binder will have an embodied energy of —

$$20.1 \times 1.0551 \times 2.2046 = 46.75 \text{ GJ/t of asphalt}$$

One cubic meter of virgin asphalt concrete contains 120 kg of asphalt and will have an inherent or feedstock energy value of —

$$46.75 \times 0.120 = 5.61 \text{ GJ/t}$$

Asphalt concrete design mixes:
The asphalt concrete design mixes are displayed below for 0% and 20% RAP. The summary tables at the end of this appendix show the primary energy and greenhouse gas emissions for these two mix designs for Canadian roads, and the 0% RAP design cases for Ontario and Quebec.

	RAP 0%	**RAP 2 0%**
	kg/m^3	
Asphalt	120	96
Coarse aggregate	1100	880
Fine aggregate	1200	960
RAP	0	484
Total	2420	2420

References:

Information	***Ref. No.***	***Reference***
Asphalt Concrete Mix	1	J. G. Emery and Associates, Toronto, Ontario, Appendix B, Table 5, in Life Cycle Embodied Energy and Global Warming Emissions for Concrete and Asphalt Roadways. May, 1999.
Energy and emissions from asphalt production	2	Franklin Associates, Prairie Village, Kansas, March, 2001.
Transportation energy and emissions to air from transportation	3	Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates: Cement and Structural Concrete Products, Athena Sustainable Materials Institute, 2006.
Calorific value of energy sources	4	Annual Energy Outlook 1996, Energy Information Administration, U.S. Dept of Energy, DOE/EIA-0383 (96) Appendix I, Table I1, 1996.
Energy use in asphalt concrete plant operations	5	Road Rehabilitation Energy Reduction Guide for Canadian Road Builders. Natural Resources Canada in collaboration with the Canadian Construction Association, 2005.

Table 1: Composition of asphalt concrete

	RAP 0%	RAP 20%
Composition	**kg/M3**	
Asphalt	120	96
Coarse aggregate	1100	880
Fine aggregate	1200	960
RAP	0	484
TOTAL	2420	2420

Source: Calculated from Ref. 1

Table 2: Primary energy used to manufacture asphalt binder (bitumen)

Fuel type	Primary energy		
	Canada	**Quebec**	**Ontario**
Natural gas	4098	4098	4098
LPG	65	65	65
Middle distillates	97	97	97
Residual oil	1249	1249	1249
Gasoline	28	28	28
Feedstock	46750	46750	46750
Electricity	275	8	343
TOTAL (including feedstock)	52562	52295	52629
TOTAL (excluding feedstock)	5812	5545	5879

Source: Ref. 2 Includes transportation of crude oil (cradle-to-gate LCI)

Table 3: Primary energy used to extract and process coarse and fine aggregates

Fuel type	Primary energy input MJ/tonne		
Coarse	**Canada**	**Quebec**	**Ontario**
Diesel fuel	29.4	29.4	29.4
Electricity	10.5	0.3	13.1
Fine			
Diesel fuel	29.4	29.4	29.4
Electricity	31.5	0.9	39.2
TOTAL	100.8	60.1	111.1

Source: Calculated from Ref. 3

Table 4: Primary energy use to lift (recover) RAP (MJ/tonne)

Fuel Type	Canada	Quebec	Ontario
Diesel Fuel	65.4	65.4	65.4

Table 5: Primary energy used in the asphalt plant

Fuel Type	Primary Energy Input MJ/m^3 of Asphalt Concrete		
	Canada	**Quebec**	**Ontario**
LPG	36	36	36
Fuel oil	80	80	80
Diesel fuel	128	128	128
Waste oil	308	308	308
Natural gas	500	500	500
Electricity	18	1	22
TOTAL	1069	1052	1073

Source: Calculated from Ref. 5

Table 6: Primary energy used in transportation of materials to asphalt plant

Material	kg/m^3 asphalt concrete	Kilometers shipped (round trip)	Tonne-km shipped/m^3 asphalt concrete	MJ/m^3 asphalt concrete
Base Mix (0% RAP)				
Asphalt binder (bitumen)	120	200	24	30.9
Coarse aggregate	1100	30	33	42.4
Fine aggregate	1200	30	36	46.3
TOTAL	2420	260	93	119.6
20% RAP Mix				
Asphalt binder (bitumen)	96	200	19	24.7
Coarse aggregate	880	30	33	34.0
Fine aggregate	960	30	36	37.0
RAP	484	120	58	74.7
TOTAL	2420	380	93	170

Sources: Fuel consumption Ref. 3, transportation distances Ref. 1,5

Table 7: GHG emissions from production of asphalt binder (kg/tonne)

	Canada	**Quebec**	**Ontario**
CO_2	373.7800	354.0200	383.7000
CH_4	1.0700	1.0300	1.1000
N_2O	0.0002	0.0001	0.0003

Source: Ref. 2   NB: includes transportation of crude oil

Table 8: GHG emissions from aggregate extraction and processing (kg/tonne)

	Canada	**Quebec**	**Ontario**
CO_2	7.96465	4.94870	8.60713
CH_4	0.00727	0.00079	0.00920
N_2O	0.00004	0.00002	0.00005

Source: Ref. 5

Table 9: GHG emissions for RAP processing (kg/tonne)

	Canada	Quebec	Ontario
CO_2	5.4018	5.4018	5.4018
CH_4	0.0008	0.0008	0.0008
N_2O	0.0000	0.0000	0.0000

Table 10: GHG emissions for material transportation (kg/m3)

	Canada	Quebec	Ontario
Base mix (0%RAP)			
CO_2	9.87989	9.87989	9.87989
CH_4	0.01467	0.01467	0.01467
N_2O	0.00004	0.00004	0.00004
20% RAP mix			
CO_2	14.07407	14.07407	14.07407
CH_4	.00209	.00209	.00209
N_2O	0.00005	0.00005	0.00005

Table 11: GHG emissions from asphalt mixing plant (kg/m3)

	Canada	Quebec	Ontario
CO_2	69.5458	68.2564	69.8205
CH_4	0.1844	0.1816	0.1852
N_2O	0.0001	0.0000	0.0001

Source: Calculated from Ref. 2

Summary Table 1: Canada Average (per m^3)

Primary Energy Inputs and Greenhouse Gas Emissions for Asphalt Concrete, RAP 0%

	Asphalt manufacture		**Extraction and processing**		**Materials transportation**		**Asphalt plant**		**TOTAL**
Materials (kg/m^3 asphalt concrete)	input	output	input	output	input	output	input	output	
Asphalt		120					120		
Coarse aggregate				1100			1100		
Fine aggregate				1200			1200		
RAP									
Asphalt concrete								2420	2420
Greenhouse gas emissions (kg/m3)									
CO_2		44.853		9.237		9.880		69.546	133.516
CH_4		0.129		0.009		0.001		0.184	0.323
N_2O		0.000		0.000		0.000		0.000	0.0002
Primary energy (GJ/m3)									
Primary energy	0.697		0.1170		0.1200		1.069		2.003
Inherent energy	5.610								5.610
TOTAL	6.307		0.1170		0.1200		1.069		7.613

Summary Table 2: Quebec (per m^3)

Primary Energy Inputs and Greenhouse Gas Emissions for Asphalt Concrete, RAP 0%

	Asphalt manufacture		**Extraction and processing**		**Materials transportation**		**Asphalt plant**		**TOTAL**
Materials (kg/m^3 asphalt concrete)	input	output	input	output	input	output	input	output	
Asphalt		120					120		
Coarse aggregate				1100			1100		
Fine aggregate				1200			1200		
RAP									
Asphalt concrete								2420	2420
Greenhouse gas emissions (kg/m3)									
CO_2		42.483		5.693		9.880		69.546	127.602
CH_4		0.124		0.001		0.001		0.184	0.310
N_2O		0.000		0.000		0.000		0.000	0.0001
Primary energy (GJ/m3)									
Primary energy	0.665		0.069		0.1200		1.052		1.906
Inherent energy	5.610								5.610
TOTAL	6.275		0.069		0.1200		1.052		7.516

Summary Table 3: Ontario (per m^3)

Primary Energy Inputs and Greenhouse Gas Emissions for Asphalt Concrete, RAP 0%

	Asphalt manufacture		Extraction and processing		Materials transportation		Asphalt plant		TOTAL
Materials (kg/m^3 asphalt concrete)	input	output	input	output	input	output	input	output	
Asphalt		120					120		
Coarse aggregate				1100			1100		
Fine aggregate				1200			1200		
RAP									
Asphalt concrete								2420	2420
Greenhouse gas emissions (kg/m3)									
CO_2		46.044		9.992		9.880		69.546	135.462
CH_4		0.132		0.011		0.001		0.184	0.3280
N_2O		0.000		0.000		0.000		0.000	0.0002
Primary energy (GJ/m3)									
Primary energy	0.705		0.129		0.1200		1.073		2.027
Inherent energy	5.610								5.610
TOTAL	6.315		0.129		0.1200		1.073		7.637

Summary Table 4: Canada Average (per m^3)

Primary Energy Inputs and Greenhouse Gas Emissions for Asphalt Concrete, RAP 20%

	Asphalt manufacture		Extraction and processing		Materials transportation		Asphalt plant		TOTAL
Materials (kg/m^3 asphalt concrete)	input	output	input	output	input	output	input	output	
Asphalt		96					96		
Coarse aggregate				880			880		
Fine aggregate				960			960		
RAP				484			484		
Asphalt concrete								2420	2420
Greenhouse gas emissions (kg/m3)									
CO_2		35.882		10.239		14.074		69.546	129.74
CH_4		0.103		0.007		0.002		0.184	0.296
N_2O		0.000		0.000		0.000		0.000	0.0002
Primary energy (GJ/m3)									
Primary energy	0.558		0.1252		0.1700		1.069		1.922
Inherent energy	4.488								4.488
TOTAL	5.046		0.1252		0.1700		1.069		6.410

APPENDIX D

PRIMARY ENERGY AND GLOBAL WARMING POTENTIAL RESULTS FOR PRODUCTION OF ONE TONNE OR CUBIC METER OF GRANULAR BASE AND SUB-BASE

Originally Prepared by:
Venta, Glaser & Associates (1999)

Updated by:
Athena Sustainable Materials Institute (2006)

Primary Energy and Global Warming Potential Results for Production of One Tonne or Cubic Meter of Granular Base and Sub-Base

Assumptions:

1. **Functional unit.** Functional unit is one tonne or 1 m^3 of granular base or sub-base having the same composition as the original report (see aggregate production below)

2. **System boundary.** The system boundary includes the following:
   - extraction and processing of aggregates, and
   - transportation of aggregates to the road building site.

3. **Transportation distances.** Transportation distances are the same as for Portland concrete and asphalt concrete aggregates; i.e., from quarry to road building site: 30 km round trip by truck (35 tonne capacity, 6-axle tractor-trailer combination).

4. **Aggregate production.** Material for granular base is composed equally of 50% coarse and 50% fine aggregate — crushed stone or crushed gravel. Material for granular sub-base can be of a wider variety: sand, gravel, or crushed stone with a maximum size of about 100 mm (versus 20 mm for coarse aggregate for granular base).

   It is assumed that both coarse and fine aggregates for granular base, as for Portland concrete and asphalt concrete aggregates, require the same extraction energy input. The processing (crushing, grinding) energy of the fine aggregate is higher than that of coarse aggregates.

   As the aggregates for the granular sub-base require less processing, we have assumed that the electricity energy required is only 25% of the electricity used to process granular base, i.e., 0.0054 GJ/t as opposed to 0.0216 GJ/t.

5. **Upstream profiles.** Both the reported primary energy and greenhouse gas emissions reflect pre-combustion requirements on a regional basis.

6. **Results / Tables**. Energy inputs and emission outputs for both the granular base and sub-base are shown in the following tables.

Table 1: Granular Base

Energy and Greenhouse Gas Emissions by Region

2.2 t/m^3; 50/50 fine and coarse aggregate

Per tonne			**Primary Energy**	**Greenhouse Gas Emissions in kg**		
Fuel type	**Qty**	**Units**	**MJ**	**CO_2**	**CH_4**	**N_2O**
Canada						
diesel	1.6	L	68.6	5.6	0.0008	2.2E-05
electricity	21.6	MJ	21.0	1.6	0.0033	1.1E-05
TOTAL			89.6	7.2	0.0041	3.3E-05
per m^3			197.1	15.8	0.0090	7.3E-05
Quebec						
diesel	1.6	L	68.6	5.6	0.0008	2.2E-05
electricity	21.6	MJ	0.6	0.0	0.0000	1.3E-07
TOTAL			69.2	5.7	0.0008	2.2E-05
per m^3			152.3	12.5	0.0019	4.8E-05
Ontario						
diesel	1.6	L	68.6	5.6	0.0008	2.2E-05
electricity	21.6	MJ	26.1	1.9	0.0042	1.4E-05
TOTAL			94.7	7.5	0.0050	3.6E-05
per m^3			208.4	16.5	0.0111	7.9E-05

Table 2: Granular Sub-base

Energy and Greenhouse Gas Emissions by Region

2.2 t/m^3; sand, gravel or coarse aggregate

Per tonne			**Primary Energy**	**Greenhouse Gas Emissions in kg**		
Fuel type	**Qty**	**Units**	**MJ**	**CO_2**	**CH_4**	**N_2O**
Canada						
diesel	1.6	L	68.6	5.6	0.0008	2.2E-05
electricity	5.4	MJ	5.2	0.4	0.0008	2.8E-06
TOTAL			73.9	6.0	0.0016	2.5E-05
per m^3			162.5	13.2	0.0036	5.4E-05
Quebec						
diesel	1.6	L	68.6	5.6	0.0008	2.2E-05
electricity	5.4	MJ	0.2	0.0	0.0000	3.2E-08
TOTAL			68.8	5.6	0.0008	2.2E-05
per m^3			151.3	12.4	0.0018	4.8E-05
Ontario						
diesel	1.6	L	68.6	5.6	0.0008	2.2E-05
electricity	5.4	MJ	6.5	0.5	0.0011	3.5E-06
TOTAL			75.1	6.1	0.0019	2.5E-05
per m^3			165.3	13.4	0.0041	5.6E-05