Life Cycle Assessment for Concrete and Asphalt Pavement at the Network Scale

Ronald Collette[1]

Abstract

In 2001 the Québec Ministry of Transportation (MTQ), Canada, has adopted a policy subdividing the existing pavement network into dedicated concrete and asphalt networks. Pavement designs for 16 Functional Class were compared for asphalt and concrete for a 50 years analysis period using a Life Cycle Cost Analysis (LCCA). In addition to LCCA, a multiple criteria analysis was performed to account for input factors not amenable to quantification in monetary terms. The 2010 policy was updated for cost and traffic demand. Environment issues were also addressed through a life cycle assessment (LCA) performed on 32 pavements designs. This paper presents the application of conventional LCA methodology to roads, salient inventory data and main comparative results with respect to midpoint and endpoint environmental impacts. Results are clearly in favour of asphalt pavements for three out of four endpoint impact, namely human health, climate change and ecosystem quality, whereas impacts on resource consumption is favorable to concrete pavement.

Introduction

The Québec Ministry of Transport relies primarily on a Life Cycle Cost Analysis (LCCA) for the selection the pavement type providing the best value for the network (MTQ 2001). In addition to the LCCA however, a multi-criteria grid is used to account for a number of non-monetary parameters. As part of the Policy update, MTQ has innovated by introducing energy and environmental parameters through a life cycle assessment (LCA) in a sustainable development perspective. The study discussed here is a rare example of comprehensive and fully independent LCA used to compare asphalt and concrete pavements designs (Kicak and al 2009). Industries involved in concrete production (Canadian Cement Association) and asphaltic mix production (Bitume Québec), as well as road construction and maintenance[2] participated directly to the data collection and review process. The study was conducted by CIRAIG[3], an internationally recognized life cycle research and development centre. The independent critical review process was performed according to ISO 14 040 and 14 044 standards (ISO 2006a, b).

LCA methodology

Life cycle assessment (LCA) is an environmental accounting method that integrates all the processes involved in manufacturing a product or delivering a service. The methodology includes raw material extraction and processing, manufacturing, transportation, distribution and final use of the products or services, as well as end-of-life management. LCA is an approach that supports decision making processes seeking to minimize the potential environmental impacts of industrial activities. The method is based on 1) the definition of a functional unit as a reference for

---

[1] Author contact: ronald.collette@mtq.gouv.qc.ca
[2] Québec road builders and heavy construction association ACRGTQ
[3] Interuniversity Research Centre for the Life Cycle of Products, Processes and Services, CIRAIG stands for Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et services.

comparative assessment and the establishment of clear boundaries for the systems under study; 2) a quantitative and comparative life cycle inventory (LCI) of inputs (materials and energy) and outputs (emissions to air, water and soil) generated by the systems; 3) a life cycle impact assessment (LCIA); and 4) a critical evaluation of results[4].

Using the LCA method to evaluate pavement types

A. Baseline unit and the boundaries of the systems under study The LCA was used to evaluate and compare the environmental impacts generated by a new road with either cement concrete (CC) or asphaltic mixture (AM) pavement. The functional unit is defined as new a road that allows vehicles to travel a 5 km distance over a 50 years reference period. The processes involved in the product system, encompasses all activities necessary to establish and maintain the function: initial construction, maintenance and partial reconstruction of the pavement when necessary.

All processes obviously common to both types of pavement were excluded from the analysis (deforestation, initial excavation, snow removal, maintenance of vegetated rights of way, fences, railings and signage). Some potentiely different parameters which could not be differentiated were also excluded (ex: lighting and fuel consumption from traffic). Other items, not accounted for due to lack of data include various material losses, dust emissions during operations, tire wear caused by traffic, together with post demolition site and machinery cleaning.

Given the relative importance of certain parameters or assumptions, a sensitivity analysis (SA) was performed to confirm findings relative to transportation distance, environmental profile of bitumen productionand cement production, bitumen fume emissions (polycyclic aromatic hydrocarbons), concrete pavement technology (continuously reinforced concrete instead of jointed concrete slabs) and the carbonation process of cement concrete. IMPACT2002+ (Joliet and al 2003), the method used as a basis for assessing the potential impacts (LCIA), was also compared with Eco-indicator99 (Goedkoop 2001a, b) and LUCAS (Toffoletto 2007) two other widely recognized methods.

B. Applying the LCA method at the network scale The Ministry of Transportation operates nearly 30,000 km of roads. Each section of the whole network corresponds to one of 16 Functional Classes defined in the LCCA framework, according to the intensity of traffic, trucking, and the number of lanes (see Table 1).

Table 1 – Pavement Functional Classes specified by the MTQ

	TYPE OF TRAFFIC	URBAN		RURAL	
	% TRUCKS	5	10	10	25
Number of lanes	Traffic (000)[1]	Functional Class Number			
2	20	# 1	# 2	# 3	# 4
	40	# 5	# 6	# 7	# 8
3	50	# 9	# 10	# 11	# 12
	90	# 13	# 14	# 15	# 16

[1]: Daily highway traffic (total number of vehicles both ways). For design purposes the number shown is divided by two and by the number of lanes. It is then adjusted by a factor reflecting the traffic on the most solicited lane)

[4] Readers not familiar with LCA basic concepts are invited to consult the relevant literature cited in reference and to visit United Nations life cycle initiative at http://lcinitiative.unep.fr/

With the help of the Functional Class framework, the type of pavement that provides the best value for investment is determined for each section of the total network. At the end of the analysis, each section is identified as belonging to a concrete or asphalt corridor for future investment purposes. LCA contributes to this comparative analysis between cement concrete (jointed concrete slabs) and asphaltic mixture designs, by implementing a rigorous quantitative environmental assessment for each 16 Functional Classes, yealding a total of 32 separate assessments. Functional Classes designs set by MTQ reflects different traffic volume and aggressiveness, which span from light traffic conditions in the upper left hand corner of Table 1, to the heaviest and most aggressive traffic conditions in the lower right hand corner. Figures 1 to 4 illustrate the overall maintenance schedule shared by different Functional Classes with respect to pavement type over the 50-year analysis period. In addition to maintenance requirements, pavement and other road material thickness also varies from one Functional Class design to the next. Functional Classes roads corresponding to lighter traffic conditions are shown in Figure 1. The concrete maintenance schedule for these classes is as follows: repairs at year 10, 19 and 29. At year 39 the concrete pavement is covered with a layer of asphalt. The schedule ends with the complete replacement of the pavement at year 50. The maintenance schedule for the equivalent asphalt pavements includes repairs at year 14, 27 and 39, and full pavement replacement at year 49.

As shown in Figure 2, more severe driving conditions accelerate repair schedule as is the case with roads of the second group of *Functional Classes*. As a result, concrete pavement is replaced a year earlier. Asphalt pavement is also repaired earlier and is completely replaced at year 42 instead of year 49. Concrete roads of the third group of *Functional Classes* (Figure 3) have to be replaced at year 47, and asphalt roads require an additional maintenance operation and replacement at year 40. For the heaviest traffic conditions (Figure 4) concrete pavement is replaced at year 46 and asphalt pavement at year 38 and also require two additional maintenances operations.

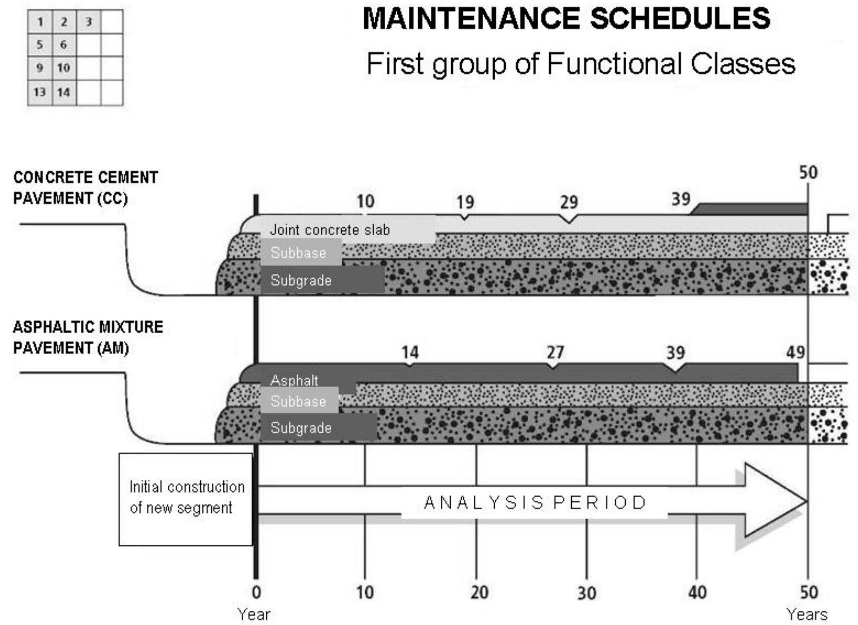

Figure 1 – Maintenance schedule for the first group of *Functional Classes*.

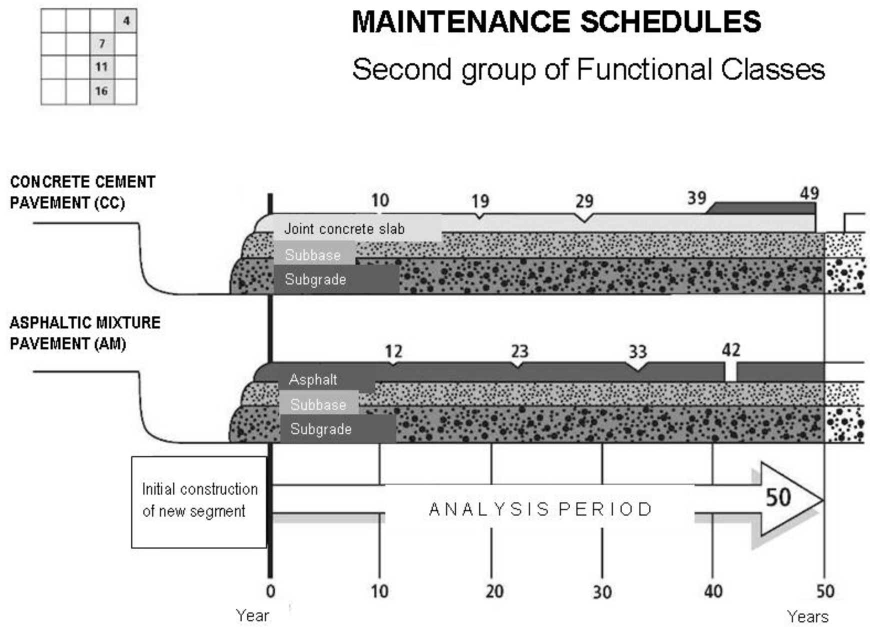

Figure 2 – Maintenance schedule for the second group of *Functional Classes*.

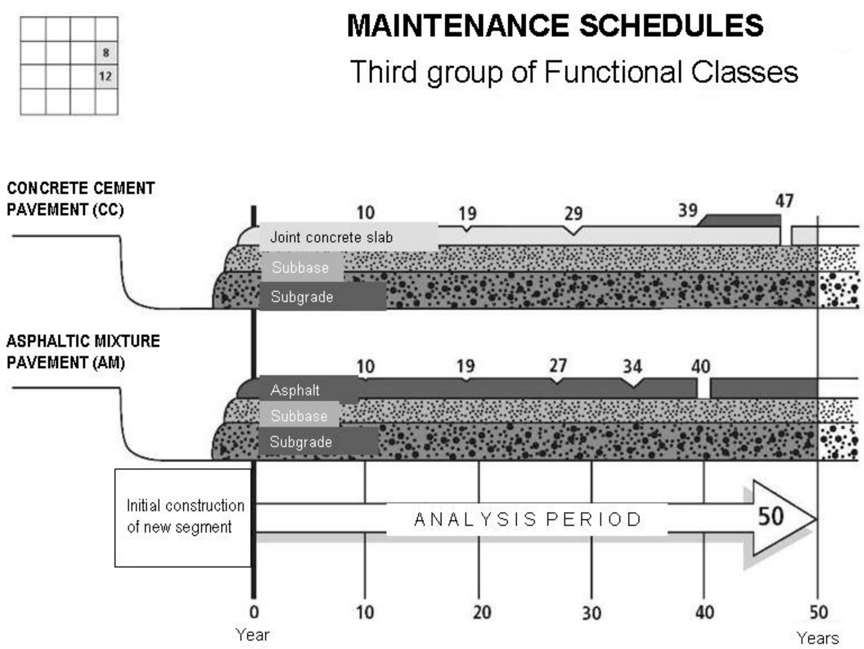

Figure 3 – Maintenance schedule for the third group of *Functional Classes*.

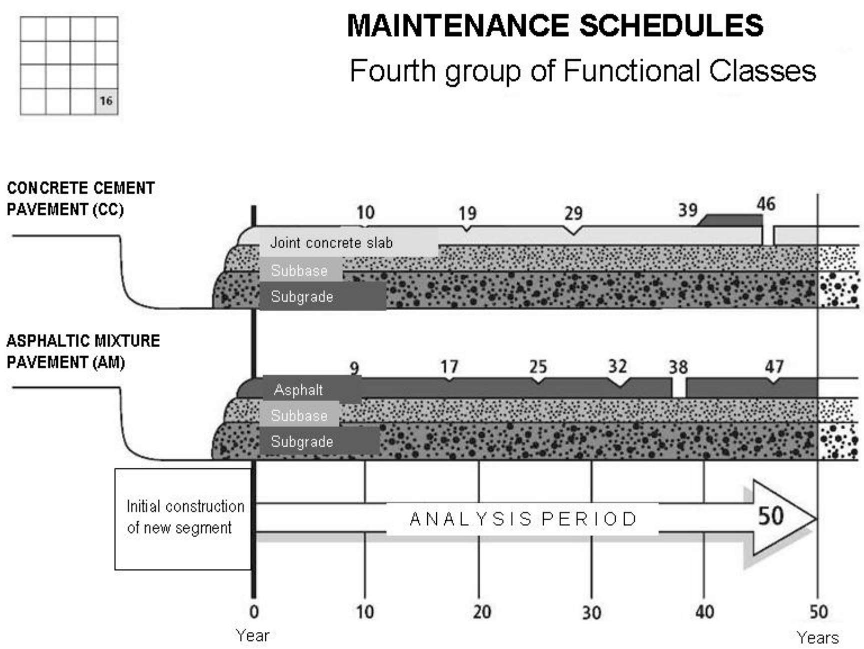

Figure 4 – Maintenance schedule for the fourth group of *Functional Classes*.

C. Inventory data sources Québec Ministry of Transportation established the *Functional Classes* and determined pavement designs. CIRAIG analysts had access to primary data directly from the industry, namely: the Cement Association of Canada, Bitume Québec and Petro-Canada refinery. When required the primary data was supplemented by referring to the Swiss generic databank *Ecoinvent*[5]. Adaptation to Quebec and North America context was performed where possible. The construction sites were documented by the Association des constructeurs de routes et grands travaux du Québec (ACRGTQ) and supplemented by using the California PaLATE[6] (Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects) database.

D. Development of the pavement life cycle inventory (LCI) Regardless of its complexity, an industrial system undergoing an LCA is defined within single conceptual boundary and broken down into basic processes whose individual inputs and outputs are known. The inventory of every basic processes involved is used to calculate the sum of exchanges between the industrial system as a whole and the environment. Flows of material or energy between an industrial process and the natural environment are called *elementary flows*. They can be either *inputs* or *outputs*. *Input* flows are resources taken from the environment to drive the industrial systems. *Output* flows are generated by industrial systems and directed towards the environment, including all emissions of undesirable or non-economic substances or by-products.

Whenever inventoried components are identical in cement and asphalt systems, only differential quantities are taken into account. Such is the case for common subbase materials and construction operations. Subsequent impact calculations are based on these differential quantities. Emissions to the environment are accounted for in tems of mass (kg) or volume (m^3) of released substances, land area (m^2) occupied for that purpose, or by units of emitted radiation (Bq). Emissions are gases discharged into the atmosphere, effluent loads generated by processes (organic or inorganic solids and dissolved or suspended materials), or liquid and solid substances left in the soil. The amount of natural resources taken from the environment are expressed as mass (kg) or volume (m^3) of material, area of occupied land (m^2), or energy (MJ) as in the case of petroleum.

Results: cement – asphalt comparative Life Cycle Inventory (LCI)

For inventory purposes the environment is divided into air, water and soil "compartments" receiving emission flows. A fourth compartment is added for resource consumption further divided into natural resources, water and energy. All comparisons are arbitrarily based on values obtained for the cement pavement system taken as a reference. Consequently, as shown in the following equation, the difference (Δ delta) is negative when the inventory results for asphalt design are higher (shown in pink) than those for cement design. To be noted, Δ is a relative value computed by dividing the overall difference (cement minus asphalt) by the value for asphalt.

$$\Delta_{inventory}(\%) = \frac{\left(inventory_{CCsystem} - inventory_{AMsystem}\right)}{inventory_{AMsystem}}$$

[5] http://www.ecoinvent.ch/

[6] http://www.ce.berkeley.edu/~horvath/palate.html

Table 2: LCI Relative difference between the elementary flows (CC system - AM system / AM system)

Functional Class	Relative Difference (%) for Each Compartment of the Ecosystem					
	Natural Resources Used	Water Consumption	Energy Consumption	Total Emissions to Air	Total Emissions to Water	Total Emissions to Soil
1	-8.4	65.2	66.5	100.9	25.8	86.4
2	-8.6	69.6	70.9	105.8	24.5	89.8
3	-8.8	71.8	73.1	107.0	21.3	92.5
4	-11.9	68.0	69.4	97.4	8.8	88.2
5	-8.6	68.9	70.2	105.0	24.5	89.0
6	-9.0	71.5	72.9	107.1	21.8	92.4
7	-11.2	66.2	67.5	96.9	12.0	86.1
8	-16.9	57.2	58.4	82.7	-3.6	77.7
9	-8.6	69.0	70.4	106.3	27.6	89.3
10	-9.4	71.2	72.6	103.0	16.5	90.9
11	-12.5	67.0	68.4	94.2	5.8	86.2
12	-17.9	65.2	66.5	89.7	-4.4	85.6
13	-9.3	67.9	69.3	100.2	17.6	87.5
14	-9.6	73.0	74.4	104.9	15.8	93.2
15	-12.5	69.3	70.7	96.2	5.3	88.4
16	-19.7	63.2	64.5	86.6	-7.6	83.6
(pink)	Negative difference or decrease in flows (inputs or outputs) by replacing an asphalt road with a concrete road. **Favours the concrete road.**					
(green)	Positive difference or increase in flows (inputs or outputs) by replacing an asphalt road with a concrete road **Favours the asphalt road.**					

Table 2 presents the global inventory results for the full life cycle of pavements. Main findings about the elementary flows are the following. Releases: the cement system discharges more waste into the air, water and soil (shown in green) than the asphalt system. The only exception are emissions to water for 3 out of 16 Functional Classes[7] (shown in pink). Resource extraction: the cement system uses more water and energy than the asphalt system but less natural resources.

Each inventory compartment can be examined to indentify main substances responsibles for the gap between systems and eventually the processes involved. The gap varies widely among substances and can favour one type of pavement system or the other. With respect to natural resource consumption, substances making the asphalt system less attractive include granular material for subbases and new asphalt, as well as petroleum extracted to produce the bitumen. Not surprisingly, emissions to air that put the cement system at a disadvantage are dominated by CO_2. This gas is essentially generated during cement production[8]. The most significant emissions to water generated by the cement system (for most Functional classes) is silicone and is linked to steel and road salt production. However, the results are split since dissolved solids are also generated by production bitumen and asphalt production which contributes to reverse the results for three *Functional Classes*.

[7] As seen above Functional Classes 8, 12, 16 are the most robust and Asphalt designs require a larger quantity of materials for the complete reconstruction and involve supplementary repair requirements within the 50-year period.

[8] The inventory distinguished between CO_2 production during the calcination of calcite and CO_2 released during fossil fuel combustion. Fossil CO_2 is of the same order of magnitude for both types of pavement consequently the difference is essentially attributable to calcination.

Limitations of the LCI

Limitations of the inventory analysis are chiefly related to the relative incompleteness and limited accuracy of some data. But in all cases, this shortcoming is not critical to results as shown by the sensitivity analysis. Due to inventory gap, concrete cement and asphalt plants are implicitely considered equivalent. The same goes for the overall dust emissions and emissions to water associated with the use of road salt. Also, substitute data was used to cover manufacturing of road marking products.

Life cycle impact assessment (LCIA) indicators

The inventory of elementary flows includes hundreds of substances. At such a level of detail results are difficult to read and to interpret. LCIA methodology has been developed to synthesize this material based on a limited number of important environmental issues known as *impact categories*. Each impact category is defined as the effect of a typical substance on the environment and this substance is used as a measurement standard. For example, ethylene gas is the standard substance used to assess the impact of smog. CO_2, the well-known standard for assessing climate warming, is another example. A LCA process known as *classification* enables to compile a very large number of elementary flows into a limited number of impact categories through their common effect on the environment.

Thousands of classified flows are *characterised* i.e. assigned a factor that quantifies its potency relative to a standard. For example, methane is classified as a greenhouse gas with a potency characterized as 23 times greater than CO_2. Characterization of substances is based on models and observations about effects on people and the environment. There are characterization factors for a great number of flows and each one is established on the basis of demonstrated environmental mechanisms or empirical data. Obviously, due to the large number of industrial processes, some elementary flows (pesticides, radioactive materials, but also crushed stone etc.), have not yet been assigned characterization factors. As knowledge increases in this field, limitations are removed and new substances are gradually included in LCA's. For now the lack of characterization factors contributes to a residual uncertainty of the LCA results.

LCA methodology uses the inventory data in a simple, consistent manner so as to yield a unique indicator for each impact category. For a whole industrial system, impact indicators are the sum of the characterization factors of all the flows of the system having a relevant impact. Indicators are expressed as equivalent quantities of a reference substance, and reported as mass, energy or radioactive decay per functional unit.

This study is based on the European IMPACT2002+, one of the few widely used impact estimation method.[9] This internationally recognized method defines 15 impact categories and enables the aggregation of most impact categories (*midpoint*) into four final damage categories (*endpoint*)[10]: human health, ecosystem quality, climate change and resource consumption. Up to now, science does not provide any mean for aggregating results any further into a single score. Table 3 identifies impact categories aggregated into damage categories.

---

[9] The method itself was tested for bias as part of the sensitivity analysis.
[10] The exclusion are water eutrophication and acidification remaining as impacts..

Results: The pavement comparative life cycle impact assessment (LCIA)
Comparative LCIA values are computed as differences between indicators and expressed as percentages. The differences between cement and asphalt pavement indicators are also calculated the same way as for inventories. The same convention applies so the difference (Δ) is negative when asphalt results are worse than for cement and positive otherwise.

$$\Delta_{impact}(\%) = \frac{\left(impact_{CCsystem} - impact_{AMsystem}\right)}{impact_{AMsystem}}$$

$$\Delta_{damage}(\%) = \frac{\left(damage_{CCsystem} - damage_{AMsystem}\right)}{damage_{AMsystem}}$$

Table 3: IMPACT 2002+ method damage and impact category indicators

IMPACT 2002+	
***Endpoint* Damage Category**	***Midpoint* Impact Category**
Human health (HH)	Carcinogenic effects
	Non-carcinogenic effects
	Respiratory effects caused by inorganic substances
	Ionizing radiation
	Ozone layer deterioration
	Respiratory effects caused by organic substances
Ecosystem quality (EQ)	Aquatic eco-toxicity
	Terrestrial eco-toxicity
	Terrestrial acidification / eutrophication
	Land occupancy
Climate change (CC)	Global warming
Resources consumption (R)	Non-renewable energy
	Mining
Non aggregated impact categories due to lack of accurate conversion model	Aquatic acidification
	Aquatic eutrophication

A. Comparative cement – asphalt damage indicators The comparative LCIA results are summarized in Tables 4 and 5. As can be seen, results are remarkably consistent throughout the 16 Functional Classes. The first four columns of Table 4 show the damage indicators and the last two columns show the remaining non-aggregated impact indicators. Human health, ecosystem quality and global warming indicators all show a difference in favour of the asphalt system (green). However, resource consumption damage as well as aquatic eutrophication impact indicators (for Functional Classes 8, 12 and 16) favour the cement system (pink).

It should be recalled that Functional Classes 8, 12 and 16, asphalt designs require earlier reconstruction and more repairs (see Figures 3 and 4). As a consequence a larger amount of asphalt and bitumen is allocated to the system, increasing emissions to water and eutrophication. Tables 5 also show that:

- The damage to human health favours the AM system overall, despite a human “cancer” toxicity indicator favouring the CC system.

- For the sake of clarity, the non-renewable energy indicator was broken down into two components, drawing a line between nonrenewable primary energy (consumed in the process) and the significant amount of inherent energy in the mass of bitumen used to build the roads.
- The damage to resource generally favours the CC system, due to the weight of the inherent energy of bitumen used in the AM system.

Table 4: Relative difference between the damage/impact indicators of the comparative life cycle of pavements (CC system - AM system / AM system)

Functional Class	Relative Difference (%) for Each Damage/Impact Category					
	Human Health	Ecosystem Quality	Global Warming	Resource Consumption	Aquatic Acidification	Aquatic Eutrophication
1	43	104	101	-33	76	30
2	46	109	106	-35	81	28
3	46	111	107	-38	82	24
4	40	104	97	-47	76	7
5	45	108	105	-34	80	28
6	46	111	107	-37	82	25
7	40	103	97	-44	75	11
8	30	92	82	-55	64	-6
9	46	109	106	-35	81	27
10	44	108	103	-43	80	14
11	38	102	94	-50	74	2
12	33	99	89	-57	71	-8
13	42	105	100	-42	77	15
14	45	110	105	-44	82	13
15	39	104	96	-50	76	2
16	31	96	86	-59	69	-11
(purple)	Negative numbers occur when a decrease in the damage/impact indicator is obtained by replacing asphalt by concrete pavement. **Favours the concrete road (CC).**					
(green)	Positive number occurs when a increase in the damage/impact indicator is obtained by replacing asphalt with concrete pavement. **Favours the asphalt road (AM).**					

The inclusion of the inherent energy of the bitumen as part of the total primary energy contributes significantly to the resource consumption impact of the *asphalt* system and favours the *concrete* system. The inherent energy of the bitumen actually accounts for 76% of the *asphalt* system's total primary energy (averaged over the 16 Functional Classes), but only 30% of the *concrete* system's total primary energy.

The results for the four aggregated indicators can be standardized for the sake of illustration. Such a standard scoring format helps visualize representation as shown in Figure 5. In order to achieve this, damage indicators are *normalised* through weighing over a reference population. The reader must take note that this type of processing is not to be taken as an endorsement of any comparative weighting between indicators since this would require an arbitrary judgement on the relative value of the damage. For the same reason, the assignment of a single overall score is officially proscribed in the case of publicly disclosed comparative statements according to ISO standards.

Table 5: System with the least impact in each category

Damage Category	Impact Category	CC System	AM System
Human health	Human "cancer" toxicity	√	
	Human "non-cancer" toxicity		√
	Respiratory effects (inorganic)		√
	Ionizing radiation		√
	Thinning of the ozone layer		√
	Respiratory effects (organic)		√
	Human health		√
Ecosystem Quality	Aquatic eco-toxicity		√
	Terrestrial eco-toxicity		√
	Terrestrial acidification		√
	Land use		√
	Ecosystem quality		√
--	**Aquatic acidification**		√
--	**Aquatic eutrophication**	√ (Functional Classes 8, 12 and 16)	√
Global warming	Global warming		√
	Climate warming		√
Resource consumption	Mineral mining		√
	Non-renewable energy		√
	Inherent energy of bitumen	√	
	Resources	√	

(purple)	Negative difference or decrease in the damage/impact indicator by replacing an asphalt road with a concrete road. **Favours the concrete road.**
(green)	Positive difference or increase in the damage/impact indicator by replacing an asphalt road with a concrete road. **Favours the asphalt road.**

Contribution analysis

Specific industrial processes contributing most significantly to the overall difference between life cycle impacts of cement and asphalt systems include: 1) cement production for initial construction and reconstruction; 2) cement concrete and steel production for initial construction; 3) bitumen production for initial construction and maintenance; and 4) asphalt production during construction and maintenance. Other processes such as the use of machinery and road marking did not make any significant difference since the overall parameters are of the same order of magnitude for both systems. It should be noted that findings relative to impacts and findings relative to inventory flows tend to be narrowly consistent. Exceptions are processes that involve significant flows with no known or very low potential impact (i.e. non-characterized substances). This is the case for the production of granular material, crushed stone, sand and the production of epoxy paint. The lack of characterization factors for some inventory flows is an inherent limitation of the LCA method.

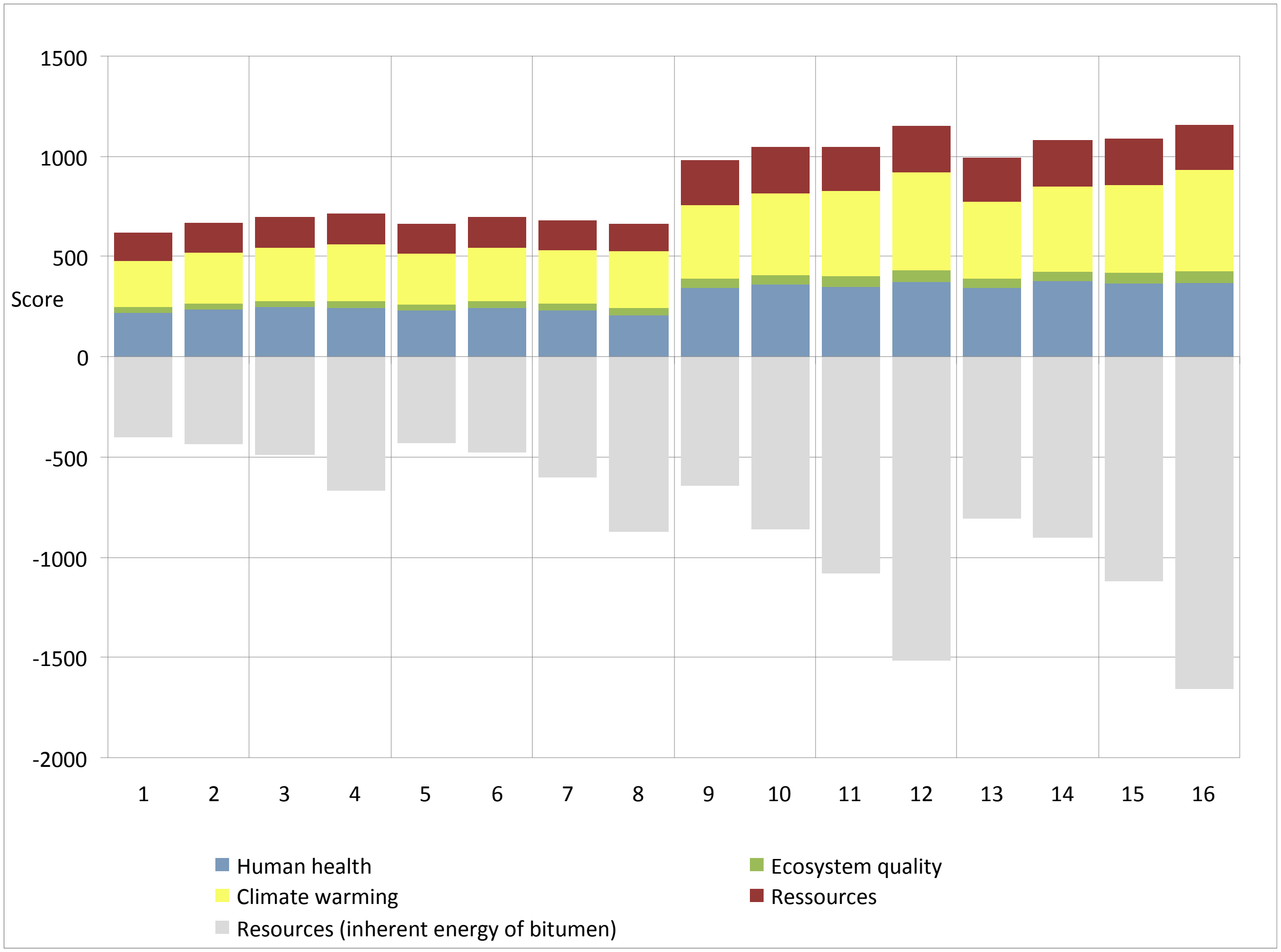

Figure 5: Comparative life cycle of pavements (CC system - AM system) damage category scores for the 16 Functional Classes

Uncertainty analysis

A few thousand elementary flows were identified based on industrial data for this study only. In most cases, the *Ecoinvent* generic database has been used to help complete the data. The variability of generic data depends on data origin, collection method and representativeness and is typically expressed as a “lognormal” distribution around a central value and a standard deviation. Variability associated with most primary data collected directly from the industriesis also expressed as a “lognormal” distribution. The degree of uncertainty reflected onthe overall results is established with a Monte-Carlo analysis.

The 1,000 iterations Monte Carlo simulation confirmed all previous results in more than 95% of cases. Namely, that the *concrete* system has clearly the highest indicators for most *midpoint* impacts except for the following: a) “cancer” human health; b) aquatic eutrophication (for Functional Classes 8, 12 and 16); and c) non-renewable energy, all of these indicators maintains higher scores than the *asphalt* system. The only results that are not clear because of data variability concern the “cancer” (human health) indicator with a 50% probability that the results would be overturned for Functional Class 1. This overturn would only favour the asphalt system with respect to the overall *endpoint* damage to human health indicator. The probability of reversing results for aquatic eutrophication is between 46% (*Functional Class* 16) ansd 18% (*Functional Class* 1). However, it must be noted that none of these inversions would affect the overall findings on damage indicators. Finally, the probability that the non-renewable energy results would be inverted is less than 2% for all Functional Classes.

Confirmation of results by sensitivity analysis

Apart from data itself, uncertainties in LCIA mainly come from the choice of assumptions and from impact and damage assessment modeling. For that reason, a series of Sensitivity analysis (SA) was run in order to test the robustness of the most critical assumptions with respect to results and findings. For SA purposes, starting values are changed within a sufficiently broad spectrum to cover all possible cases. The consequent variation of results indicates the importance of the modified parameters and the range within which most valid results are most likely to occur.

SA were conducted to outline the sensitivity of the findings to variations in assumptions concerning: 1) transportation distance for construction material; 2) environmental profile of bitumen production; 3) PAH emissions in bitumen fumes generated by bitumen production; 4) environmental profile of the construction of continuously reinforced concrete (CRC) pavements as a replacement to jointed concrete slab (JCS) pavements (Functional Class 16); 5) impact assessment method; 6) environmental profile of cement production; 7) fuel consumption by vehicles depending on the type of pavement; and 8) concrete carbonation process throughout the life cycle of the cement concrete. The findings of the SA are the follow.

1) Only improbable transportation distances between material suppliers and construction site would change any conclusion of the study.

2) No change in the results was likely to arise from a variation in the bitumen production data.

3) Increased PAH emissions from bitumen fumes reduces the difference between the AM and CC systems with respect to the human health indicator. However, the *asphalt* system is still favoured for this damage category overall (as other indicators remained unchanged).

4) Using *continuously reinforced concrete* technology increases the four damage indicators for concrete pavement as compared to the reference *jointed concrete slab* system. This is partly due to the greater amounts of cement and steel required, and the composite material added. Not surprisingly findings were unchanged for damage indicators already exceeding those of the *asphalt* system. But interestingly resource consumption indicator remained lower than for the *asphalt* system.

5) Human health and ecosystem quality comparative indicators were still positive, and therefore favourable to the *asphalt* system, regardless of the impact assessment method chosen. Climate change however is not taken in consideration in the other methods. However, according to EcoIndicator (Individualist sub model) resource consumption would also favor asphaltic mixture design.

6) An inversion with respect to the human health damage indicator would occur if using generic data instead of local and specific data. However, it is clear that the former is less accurate as it underestimates air emission from cement production.

7) Energy consumed by vehicles is outside the scope of this study. It was nonetheless examined to explore the relative importance of this parameter in the full life cycle of a road. Keeping in mind that the assumption of a difference between the two types of roads is not definitely established, analysis shows that a 1% difference would reverse the findings of the study.

8) Re-absorption of CO_2 by carbonation was proven not to be a sensitive parameter and did not alter any findings of the study.

Limitations of the LCIA

Life cycle impacts presented here are calculated using a recognised software and method. Damages and potential impacts are assessed through a simplified model of the environment. Results are relative expressions that do not predict final impacts by category, non attainment of criteria or safety margins, nor risks. Results should not be taken as the sole basis for comparative statements for public disclosed LCA, to the extent that additional information would be needed to address some of the LCIA's inherent limitations. These results could possibly be refined either by the use of other tools, such as risk analysis, or pursuant to future methodological developments.

More importantly, characterization and its interpretation is limited to elementaty flows of substances and energy for which there are actual characterization factors that make it possible to assess impacts and damage indicators. In this study 448 elementary flows could not be converted into indicators and consequently could not be considered for impact and damage assessments. However uncharacterized elementary flows were the same for both types of pavements and the bare mass differences for these flows put the cement system at a disadvantage in 340 cases out of 448. If characterization factors had been available for these flows, the impacts associated with them would probably have been detrimental to the CC system, a situation that would support the present study's findings.

Critical review

This LCA was subject to a peer review by an independent expert who consulted the industries in accordance with ISO 14044 standards. The review confirmed the validity of CIRAIG's data, calculations and assumptions[11].

Conclusions/recommendations

The results are very consistent for all 16 Functional Classes but require a nuanced overall conclusion. Three out of four damage indicators favour the *asphalt* system: human health, climate change and ecosystem quality. However, the resource consumption indicator favours the *cement* system. The non-integrated impact indicators also provided mixed results: aquatic acidification favours the *asphalt* system while uncertainty prevented us from reaching any conclusion regarding eutrophication. The sensitivity and uncertainty analysis has demonstrated the robustness of these findings.

It was not possible to quantify and to model some potentially non negligible factors for both pavement types like noise, tire wear, urban heat effect. Differential fuel consumption, lacked peer reviewed unequivocal results applicable to a network scale. Moreover, it must be kept in mind that production technology and pavement performance will evolve over time Regular updates will be required to keep comparative pavement types LCA's up to date.

Use made of the results

The four aggregated LCA damage indicators were ultimately weighted against 16 other non cost comparative parameters in the contexte of a multi-criteria analysis. The other parameters related to matters such as planning flexibility, on use reliability and impact to users. The overall comparative multicriteria score cement vs asphalt score was then used as a modulator to LCCA for the purpose of selecting pavement type at the network scale.

[11] Critical review is included in the original report (Kicak and al 2009).

References

Journals

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G. and Rosenbaum, R. (2003). “IMPACT2002+: A New Life Cycle Impact Assessment Methodology.” *International Journal of Life Cycle Assessment*, 8(6) p.324–330

Toffoletto, L., Bulle, C., Godin, J., Reid, C. and Deschênes, L. (2007). “LUCAS - A New LCIA Method Used for a Canadian-Specific Context”. International Journal of Life Cycle Assessment 12(2) p.93-102.

Books and Reports

ISO 14040, ISO (2006). Management environnemental — Analyse du cycle de vie — Principes et cadre, 24 p.

ISO 14044, ISO (2006). Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices, 56 p.

Kicak, K., Ménard, J.-F., Michaud, R, Clément, E. and Samson, R. (2009). *Analyse comparative du cycle de vie des chaussées en béton de ciment et en béton bitumineux à des fins d’intégration de paramètres énergétiques et environnementaux au choix des types de chaussées*, CIRAIG, École Polytechnique de Montréal.

Goedkoop, M. and Spriensma, R. (2001a). *The Eco-indicator 99, A Damage Oriented Method for LCA.* Amersfoort, PRé Consultants, 144 p.

Goedkoop, M. ans Spriensma, R. (2001b). *The Eco-indicator 99, a damage oriented method for Life Cycle Assessment - Methodology Report*. Amersfoort, PRé Consultants, 132 p.

Ministère des Transports du Québec (2001), *Orientation ministérielle sur le choix des types de chaussées*, Québec <http://www.mtq.gouv.qc.ca/portal/page/portal/Librairie/bpm/orientation.pdf> (2009)