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# Life Cycle Assessment applied to road pavements: an analysis of method and results relevancy

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**ABSTRACT:** In Europe, the use of Life Cycle Assessment for evaluating environmental performances of products is becoming usual. In that context, many studies have been published aiming at comparing different technologies for construction and maintenance of pavements. The purpose of this paper is to examine and compare studies performing LCA of pavements, with the aim of pulling out important parameters that can explain different results. The first step of this paper consists of selecting some of the available studies on different criteria. In a second part, the paper examines the main hypothesis of selected studies highlighting differences and similarities. In the last part, the paper compares results in link with chosen hypothesis.

Apart from possible differences between environmental data sources, several tendencies can be highlighted on selected studies. The use of steel inside CRCC materials conducts to an important increase in both energy consumption and greenhouse gas emissions. Then, considering road shoulders would lead to a 30% increase of both indicators as well, and considering road dismantling would lead to a comparable increase. Finally, the influence of materials on traffic could lead to drastic differences. However, this assumption is still controversial and should be the subject of further researches.

## 1 INTRODUCTION

In Europe, the use of Life Cycle Assessment (LCA) for evaluating environmental performances of products is becoming usual, especially through the intercession of the Integrated Product Policy (IPP), and results can conduct to political decisions. In Québec province (Canada), the LCA and Life Cycle Cost Analysis (LCCA) methods have been recognized by the Ministry of Transports as the basics (Cormier & Thébeau 2003) for choosing types of pavement. In that context, many studies have been published on various supports, aiming at comparing different technologies for construction and maintenance of pavements. LCPC has performed several studies based on LCA, with the aim of developing a method suitable for the environmental evaluation of roads pavements. The first LCA study was devoted to the assessment of aggregates recycling in an asphalt layer on a given road site and taking into account measurements for data collection (Jullien et al., 2006). The other study concentrated on the LCI assessment at the step of the road pavement design, comparing technologies and using literature data, revealing some discrepancies between the data (Hoang, 2005). Finally in the last study the impacts indicators choice was explained (Ventura et al., 2008). This research has finally led to create a software tool for pavement construction and maintenance environmental assessment. This tool called ECORCE that has been developed by LCPC in 2008 and is available since 2009. However, key issues of environmental assumptions still need to be highlighted in order to contribute to future improvements of the method. The purpose of this paper is to examine and compare various studies performing LCA of pavements, with the aim of pulling out important parameters that can explain different results.

The first step of this paper consists of selecting some of the available studies on different criteria. In a second part, the paper examines the main hypothesis of selected studies highlighting differences and similarities. In the last part, the paper compares results in link with chosen hypothesis.

## 2 SELECTION OF STUDIES TO BE COMPARED

Several studies have been gathered (see Table 1), each author has investigated different parameters expected to influence the pavement structure and thus final LCA results. The criteria to select comparable studies are as follows:

- C1. their objectives and studied cases must be similar: as any LCA study is performed according to a defined objective, comparing studies with different ones is hazardous.
- C2. their level of quality must be sufficient to perform the comparison: studies must provide enough information on technical choices and hypothesis, to be exploitable.
- C3. it also appeared relevant to select studies using similar pavement design methods in order to avoid very different road structures.

Table 1. List of LCA studies, their objectives and their content.

Reference	Objectives of the study	Studied parameters
(Lundström 1998)	Compare environmental impacts of cement and asphalt concretes materials used into roads	- Materials and structure - Cement content - Thickness of pavement layer
(Stripple 2000)	- create a better environmental understanding of asphalt in a life cycle perspective - increase knowledge - produce valid LCI data available for the asphalt industry and optimize future processes - communicate with external bodies interested in environmental matters	None
(Mroueh et al. 2000), (Mroueh et al. 2001)	comparison of industrial by-products and conventional materials in the sphere of road construction	- Materials and structure - Recycled materials
(Stripple, 2001)	- analyze the road construction process - increase knowledge base concerning technical mechanisms - come up with a methodology and design a model for LCA of road processes	- Materials and structure - Asphalt manufacturing method (hot or cold)
(Athena 1999), (Pontarollo et al. 2001)	better understanding of environmental impacts associated with asphalt and (cement) concrete pavements	- Materials and structure - Traffic
(Rouwette & Schuurmans 2001)	- provide verifiable, reliable and peer reviewed environmental information on cement concrete - prepare an LCA tool applicable to a broader range of (cement) concrete products - derive arguments to positively position (cement) concrete in the context of sustainable development	None
(Chappat & Bilal 2003)	- Assess environmental impacts in order to decrease them - Help choosing ecological pavements	- Materials and structure - Traffic - Security fences
(Hoang 2005)	develop a methodology for environmental assessment of road processes	- Materials and structure
(Peuportier 2005)	Inform on environmental quality of products	- Materials and structure - Security fences
(Ventura et al. 2008)	comparison of different recycling rates of reclaimed asphalt pavement used into a binder course	Recycling rate in binding layer

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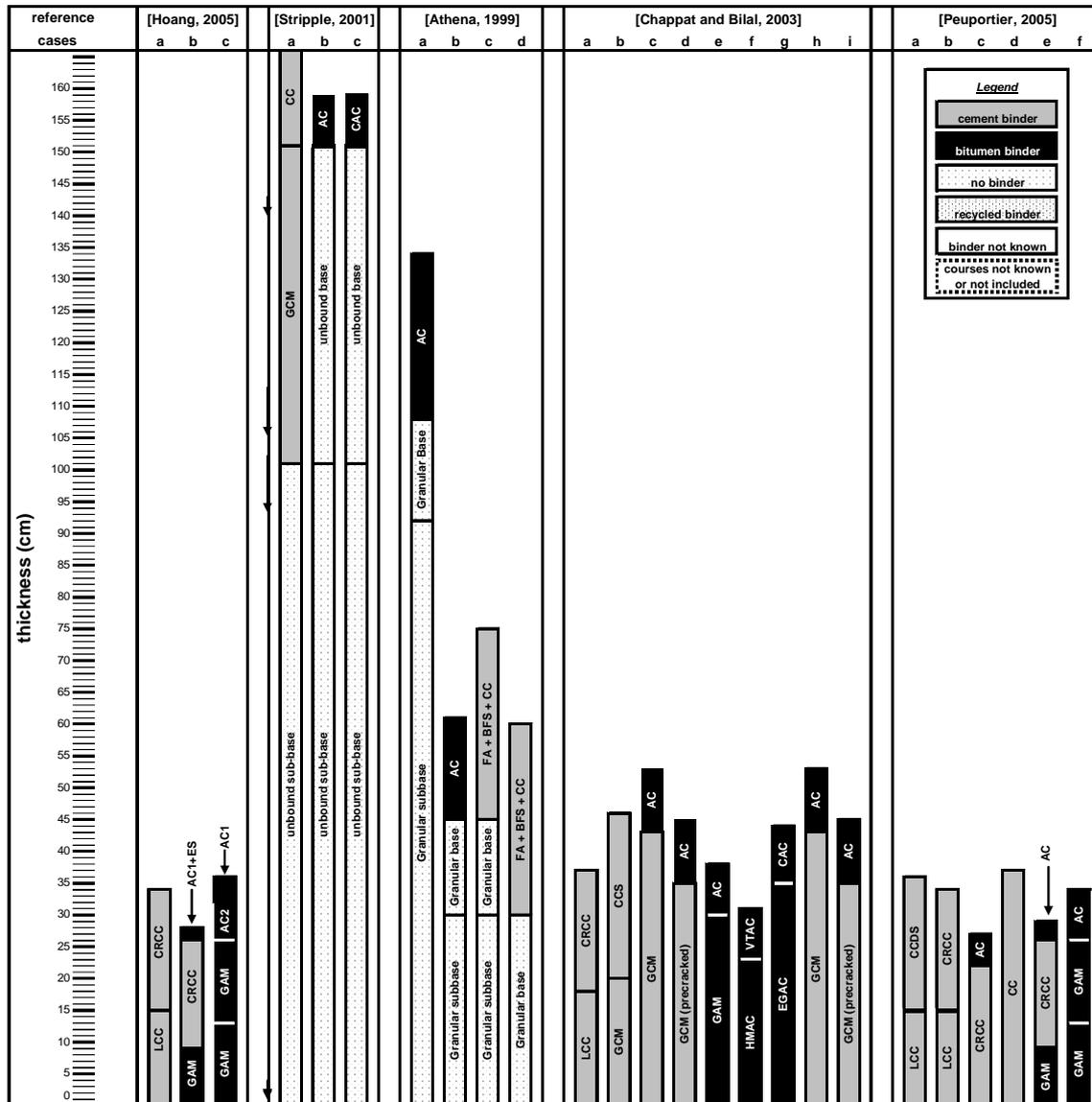
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**C1:** Among possible parameters, the studies focusing on use of recycled materials (Mroueh et al. 2000), (Mroueh et al. 2001) and (Ventura et al. 2008), have been discarded from the comparison; because it appears important to first analyze classical pavement solutions before being able to discuss on alternative techniques.

**C2:** Studies that do not examine influence of various parameters (Stripple 2000) and (Rouwette & Schuurmans 2001), have also been discarded because they do not bring enough elements for results comparison. The studies from (Lundström 1998) and (Pontarollo et al. 2001) do not provide sufficient basic information to be compared to others and has thus been discarded.

**C3:** Finally, studies from (Stripple 2001) and (Athena 1999) have also been discarded because pavements structures are respectively typical from Sweden and Canada. Apart from traffic and constitutive materials, structure design also depends on climate and on desired duration of service time. Sweden and Canada design their structures for 40 years of service time, and for adaptation to tough winter conditions (frequent ice and snow). Therefore, layers are much thicker in those countries than in Southern Europe (see Figure 1). Such differences in structure design and in maintenance policies, would complicate the comparison and should be considered in further step.

Figure 1. Pavement structures selected after C1 and C2 criteria (for abbreviations, see lexica)



Finally, on the previous basis, three studies are compared: (Chappat & Bilal 2003), (Hoang 2005) and (Peuportier 2005). Results presented by (Peuportier 2005) detail an additional case named “g case”, compared to pavement structures cases presented in Figure 1. The “g case” is totally equal to the “f case” except for the choice of data source concerning the bitumen production process. For the “f case” data come from (Eurobitume, 1999) whereas for the “g case” they come from the Oekoinventare database.

### 3 PRESENTATION OF COMPARED STUDIES

#### 3.1 Functional unit and environmental system

Functional Units (FU) are chosen by authors. (Hoang 2005) and (Peuportier 2005) presents their FU as a road section (1 km length and a given width), whereas (Chappat & Bilal 2003) consider a road surface area. The pavement service time is 30 years for all studies. Traffic is set at  $25 \cdot 10^6$  trucks/yr/lane for (Hoang 2005) and (Peuportier 2005), whereas it varies from  $66 \cdot 10^4$  to  $57 \cdot 10^6$  for (Chappat & Bilal 2003).

Mairepav 6 : the Sixth International Conference on maintenance and rehabilitation of pavements and technological control, At Torino, Italy, July 8-10, 2009

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Table 2. Environmental system of compared studies. *ng*: not given

Reference	From “cradle to pavement”																			
	Processes of natural resources extraction					Processes of materials production					Processes of recycled materials production			Other connected processes						
	Crude oil	Limestone	Clay	Aggregates	Cuts and fills	Iron ore	Bitumen	Lime	Cement	Chemical	Asphalt	Cement	Steel	Recycled binders	Recycled aggregates	Recycled steel	Energy	Equipment	Waste water	Solid wastes
(Hoang 2005)	+	+	+	+		+		+		+	+	+								
(Chappat & Bilal 2003)	+	+	+	+		+		+		+	+	+						+		
(Peuportier 2005)	+	+	+	+		+		+		+	+	+						+		

Reference	From “pavement to grave”																			
	Initial construction				Exploitation						Other connected activities									
	Road	Other equipment			Structural maintenance	General maintenance			General installations		Traffic	Users and employees	Road end of life							
(Hoang 2005)	+				+	+	+													
(Chappat & Bilal 2003)	+		+		<i>ng</i>	+								+			+			
(Peuportier 2005)	+		+		+	+												+		+

Table 2 presents the list of processes involved in the production of pavement layers, and, for each reference, each process is dotted when included in the environmental system.

The three studies show very similar environmental systems. The only difference is the inclusion of energy production systems inside the environmental system of (Peuportier 2005), whereas it is not for other studies.

The main differences of environmental system boundaries between references, can be seen for the pavement life cycle, in Table 2. (Chappat & Bilal 2003) and (Peuportier 2005) both include some equipments such as fences, and traffic, whereas (Hoang 2005) does not. On the contrary, (Hoang 2005) includes traffic congestion induced by road works, whereas the two other studies do not. Furthermore, (Peuportier 2005) is the only study to consider the pavement’s end of life.

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### 3.2 Pavements materials composition and service time

Mixtures compositions differ between studies. Compositions of materials are detailed in Table 3 for asphalt concrete mixtures, and in and Table 4 for cement concrete mixtures.

For asphalt concretes (Table 3) bitumen ratio range from 3.8% up to 4.5% for gravel asphalt mixtures, and from 5.2% up to 9% for upper layers asphalt concrete. The composition of bitumen itself can vary, i.e. bitumen grade, chemical additives... However, bitumen grade, and chemical nature and quantity of additives are not given, whereas they could be of environmental concern.

Table 3. Composition of asphalt concrete mixtures. (for abbreviations, see lexica)

Reference	Nomination from Figure 1	Natural aggregates		Bitumen	Other information
		Type	Mass (%w)	Mass (%w)	
(Hoang 2005)	AC1	0/10	94.4	5.62	
	HSD		10 L/m <sup>2</sup>	1.6 kg/m <sup>2</sup>	
	AC2	0/14	94.8	5.2	
	GAM	0/20	95.7	4.35	
(Chappat & Bilal 2003)	AC	crushed	94.3	5.7	
	GAM	crushed and rounded	95.8	4	crushed 70% rounded 25.8%
	HMAC	crushed	94	5.8	
	VTAC				Not given
	EGAC	crushed	93.5	6.5 <sup>(c)</sup>	
	CAC	crushed	91	9	
(Peuportier 2005)	AC		94.7	5.3	
	GAM		96.2	3.8	

For cement concretes (Table 4), the cement content varies from 7.7% to 9% for lower and middle layers (or shoulders), and from 12 to 14.1 for upper layers. The type of cement is only given for (Hoang 2005). Cement can also contain chemical additives as well as recycled industrial wastes such as blast furnace slags or fly ashes, but given compositions do not reach such accuracy, although it is interesting from the environmental point of view.

Duration of pavement service time is set at 30 years for the three references. Study from (Peuportier 2005) considers two maintenance operations for each studied case, (Hoang 2005) between three and four, whereas (Chappat & Bilal 2003) do not detail the maintenance scenario. Maintenance scenarios from (Hoang 2005) come from (Laurent, 2004), and those from (Peuportier 2005) probably come out from the feedback from experiences of road works companies. Most of maintenance scenarios considers the addition of 2.5 cm or 4 cm of asphalt concrete (+2.5 AC and + 4 AC on Figure 2), with previous milling (Mil on Figure 2) from time to time. Scenarios from (Peuportier 2005) consider a dismantling operation after 30 years.

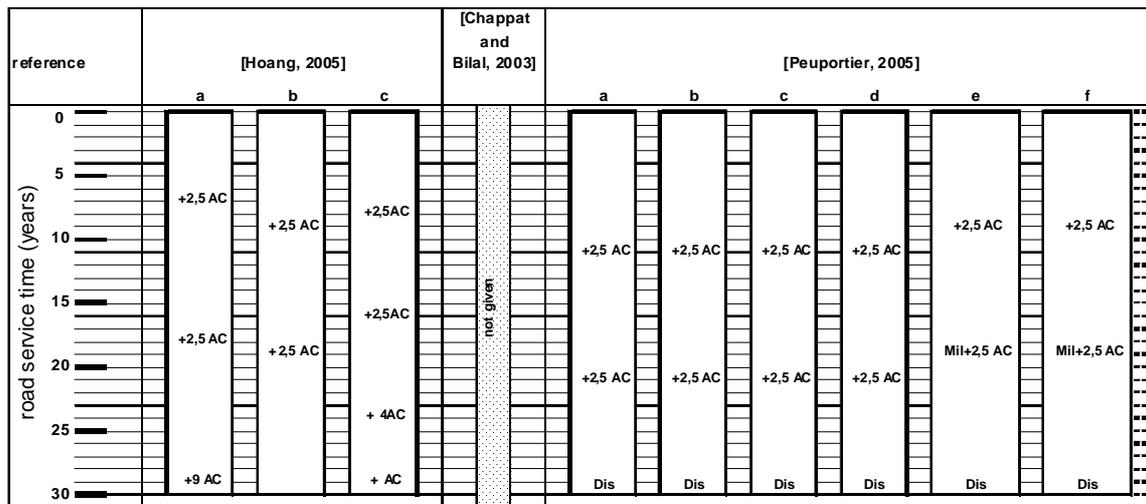
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Table 4. Composition of cement concrete mixtures. (for abbreviations, see lexica)

Reference	Nomination from Figure 1	Natural Aggregates		Water		Cement		Other information
		Type	Mass (%w)	Mass (%w)	Type	Mass (%w)		
(Hoang 2005)	CRCC	sand 0/5, ryolithe 5/10, limestone 10/20	79.4	6	CEM II/A	14.1	sand 34.8% ryolithe 19.1% limestone 25.5%	
	LCC	sand 0/5, sand-lime 5/25	78.3			7.7	sand 36.1% sand-lime 42.2%	
(Chappat & Bilal 2003)	CCS	crushed and rounded	82	6	12	crushed 41% - rounded 41%		
	CRCC	crushed and rounded	82	6	12	crushed 41% rounded 41% steel 2%		
	LCC	Not given						
(Peuportier 2005)	CC		81.7	6.1	12.2			
	CCS		81.7	6.1	12.2			
	CRCC		81.7	6.1	12.2			
	LCC		84.9	6.1	9			

Figure 2. Maintenance of pavements during service time. (for abbreviations, see lexica)



### 3.3 Analysis of transports scenarios

Transports scenarios of each study are presented in Table 5. All studies consider road transport. Given distances are very comparable between references. Some distances are not detailed by all references. Scenarios of crude oil transport are not detailed by authors, although they may involve long distances and particular means of transport (i.e. ships for iron ore or crude oil). In that case, it is noticeable that environmental data are all taken from a single reference (Blomberg et al. 1999), where the details of crude oil ship transport is fully described.

Mairepav 6 : the Sixth International Conference on maintenance and rehabilitation of pavements and technological control, At Torino, Italy, July 8-10, 2009

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Table 5. Transport scenarios

Material	Trip description		Distances (km)		
	Departure	Destination	(Hoang 2005)	(Chappat & Bilal 2003)	(Peuportier 2005)
Crude oil	Well	Refinery			
	Quarry	CC mix plant	39	75	100
Aggregates		AC mix plant	39	75	100
Steel	Steelwork	Roadworks	500	500	500
Bitumen	Refinery	AC mix plant	333	300	300
		Roadworks	354		
Asphalt concrete	AC mix plant	Roadworks	21		20
Cement	Cement plant	CC mix plant	152	150	150
Cement Concrete	CC mix plant	Roadworks	21		
Solid wastes	Roadworks	Stockpile or treatment plant	18		20
Equipment	Parking	Roadworks	20		

### 3.4 Environmental data and indicators

(Chappat & Bilal 2003) calculate energy consumption and a greenhouse effect indicator, using GWP100 (IPCC 2001). Sources of environmental data are taken from (Stripple 2001), (Athena 1999), (USIRF 2002).

(Peuportier 2005) calculate energy consumption, GWP100, water consumption, natural resources consumption, wastes production, radioactive wastes, GWP, AP, EI, POCP, ecotoxicity, toxicity, and odors. Data are taken from the Oekoinventare Swiss database (Ecole Polytechnique Fédérale de Zürich), and from the German database (Oekoinstitut von Weimar, Karlsruhe University).

(Hoang 2005) calculates energy and CO<sub>2</sub> emissions. This last value can be compared to GWP100 because this indicator is expressed in kg eq. CO<sub>2</sub>. Data come from multiple sources; it is not possible to cite them all. Nevertheless, many environmental data come from (Stripple 2001).

## 4 RESULTS AND DISCUSSION

The analysis of studies principles lead to set a basis of comparison between them. For the FU, results from (Hoang 2005) and (Peuportier 2005) will be converted in a 1 m<sup>2</sup> surface area in order to remove influences due to differences in pavement width. Thus, the FU will correspond to the one chosen by (Chappat & Bilal 2003). Furthermore, comparison will be restricted to cases corresponding to the 25 x 10<sup>6</sup> trucks/yr/lane traffic value that is common to the three studies.

Finally, the 3 studies can be compared on the basis of energy consumption and GWP100, knowing that results of (Hoang 2005) concern CO<sub>2</sub> emissions, and that this value is probably slightly inferior to the one that would be for GWP100.

Cumulated energy consumption is presented in Figure 3a and GWP100 results are presented in Figure 3b. Significant differences are shown between pavement structures. If only regarding

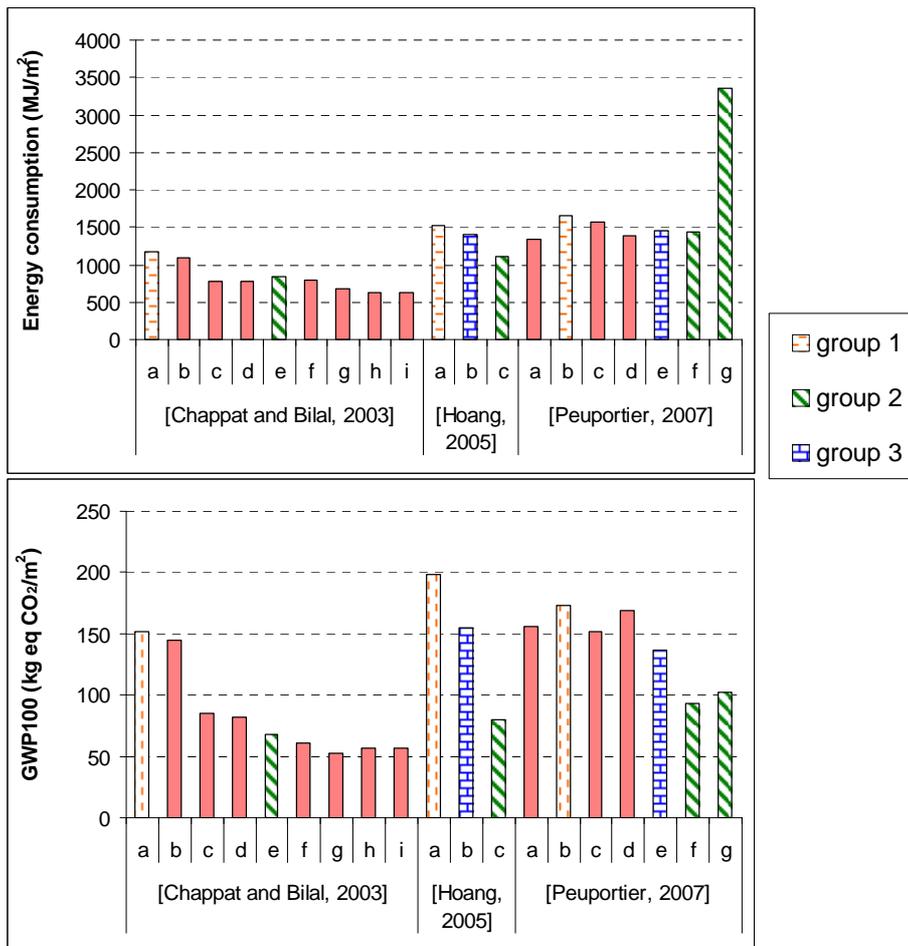
Mairepav 6 : the Sixth International Conference on maintenance and rehabilitation of pavements and technological control, At Torino, Italy, July 8-10, 2009

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pavements structures, it appears from Figure 1, that 3 groups of structures can be compared between studies:

- group 1 gathers cases (a) from (Hoang 2005) and (Chappat & Bilal 2003) and case (b) from (Peuportier 2005);
- group 2 gathers cases (c) from (Hoang 2005), case (e) from (Chappat & Bilal 2003) and cases (f) and (g) from (Peuportier 2005);
- group 3 gathers case (b) from (Hoang 2005) and case (e) from (Peuportier 2005).

Figure 3. Cumulated indicators for 30 years (traffic not included) **a)** Energy consumption in MJ/m<sup>2</sup> of pavement surface area, **b)** GWP100 in kg eq CO<sub>2</sub>/m<sup>2</sup> of pavement surface area



Results values will first be compared inside these 3 groups in order to examine influence differences in author's hypotheses.

The group 1 structures are found the most important energy consumers inside each study. These materials contain steel, of which contribution to energy consumption appears important, although its mass is weak (< 5%) compared to total mass. The result from (Chappat & Bilal 2003) is found much lower than the two others. Apart from possible differences in sources of environmental data, this may be explained by the probable absence of the road shoulders inside the system for (Chappat & Bilal 2003) as it is not explicitly mentioned in the reference (see Table 2). The structure from (Peuportier 2005) consumed around 9% more energy than the one from (Hoang 2005). This may be explained by the inclusion of the road's end of life with a dismantling in the (Peuportier 2005) study. The group 1 structures are also found the most important greenhouse gas emitters inside each study. GWP100 (Figure 3b) varies from around

Mairepav 6 : the Sixth International Conference on maintenance and rehabilitation of pavements and technological control, At Torino, Italy, July 8-10, 2009

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150 up to 200 kg eq CO<sub>2</sub>/m<sup>2</sup>, but compared to energy consumption (Figure 3a), the order between cases is not the same. GWP100 can often be found to evolve in the same manner as energy consumption, when energy source majorly comes from fossil fuels, and when no other processes than combustion ones emits CO<sub>2</sub>. In the case of CRCC structures, the cement plant emits CO<sub>2</sub> from combustion processes, but also from chemical reactions. Thus, observed differences are probably due to differences between cement plants environmental data, instead of differences between environmental systems.

The group 2 structures show important differences in energy consumption results (Figure 3a): from around 850 MJ/m<sup>2</sup> for (Chappat & Bilal 2003) up to around 3350 MJ/m<sup>2</sup> for (Peuportier 2005). The inclusion of shoulders by (Hoang 2005) compared to (Chappat & Bilal 2003) may result in a 30% increase of total energy consumption. And the dismantling process from (Peuportier 2005) case (f), compared to (Hoang 2005) may result in a 29% increase. Finally, the “g case” from (Peuportier, 2005) is twice more important than its “f case”. This shows that the total energy is extremely sensitive to the chosen database: all other cases uses the same (Eurobitume, 1999) source of data for bitumen production. The author mentions that in the “g case” the bitumen feedstock energy is included in the consumed energy, whereas it is not for the “f case”. For GWP100 of group 2 structures (Figure 3b), the order between cases is found the same for energy consumption. The inclusion of shoulders by (Hoang 2005) compared to (Chappat & Bilal 2003) may result in a 18% increase of total greenhouse gas emissions. And the dismantling process from (Peuportier 2005) case (f), compared to (Hoang 2005) may result in a 16% increase. The difference between cases (f) and (g) from (Peuportier 2005) is around 9% and is directly attributable to differences between data sources.

The group 3 structures show almost identical results with a slight 3% increase of (Peuportier 2005) compared to (Hoang 2005), maybe attributable to road dismantling. For GWP100 inside group 3, order between cases is again reversed compared to the order found for energy consumption. This again shows differences between sources of data concerning the cement plant process.

Finally, influence of traffic can be observed in the (Chappat & Bilal 2003) and (Peuportier 2005) studies. Both studies consider that traffic is responsible for the consumption of  $1.3 \times 10^9$  MJ/km and for the emission of around  $10^8$  kg eq CO<sub>2</sub>/km. The (Peuportier 2005) study considers the hypothesis that vehicles consume less energy when driving on rigid pavement surfaces. This hypothesis conducts to a decrease of around  $6 \times 10^6$  kg eq CO<sub>2</sub>/km for cases (a) to (d) compared to cases (e) to (g).

## 5 CONCLUSION

A comparison of energy consumption and greenhouse gas emissions has been performed between results from 3 different studies applying the LCA methodology to comparable road pavements structures, in order to highlight their sensitivity to author's hypotheses. The influence of data sources may be important but could not be deeply examined because initial environmental data are not always given by authors. Thus influences of other hypotheses should be examined accounting for that uncertainty. Important differences are in environmental data sources between studies, are especially suspected for the cement plant processes. Apart from environmental data sources, several sensitive hypotheses can be highlighted and discussed.

Firstly, very important differences are found if considering or not the bitumen feedstock energy. The feedstock energy definition is the energy contained inside the material (SETAC, 1194): it is not a consumed energy, as it is considered as an energy resource. Therefore, it should not be added to the consumed energy. Secondly, the use of steel inside CRCC materials conducts to an important increase in both energy consumption and greenhouse gas emissions. Then, considering road shoulders inside the system would lead to a 30% increase of both energy consumption and greenhouse gas emissions, as well as considering road dismantling would lead to a comparable increase. This last hypothesis is however almost never occurring in European countries, where pavements are maintained not to be dismantled. Finally, the influence of

Mairepav 6 : the Sixth International Conference on maintenance and rehabilitation of pavements and technological control, At Torino, Italy, July 8-10, 2009

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materials on traffic could lead to drastic differences. However, this assumption is still controversial and should be the subject of further researches.

**Lexica** : AC : Asphalt Concrete; BFS: Blast Furnace Slag; CAC: Cold Asphalt Concrete; CC: Cement Concrete; CCS: Cement Concrete Slab; CRCC : Continuous Reinforced Cement Concrete; EGAC: Emulsion of Gravel Asphalt Concrete; FA: Fly Ashes; GAM: Gravel Asphalt Mixture; GCM: Gravel Cement Mixture; HMAC: High Module Asphalt Concrete; HSD: Hydrocarbon Surface Dressing; LCC: Lean Cement Concrete; VTAC: Very Thin Asphalt Concrete

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