COMPARISON OF NEW PAVEMENT CONSTRUCTION GHG AND ENERGY IMPACTS IN DIFFERENT REGIONS

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ABSTRACT

This paper presents a summary of the results of a comparison of asphalt pavement designs for the same traffic between four regions of the world (California, France, South Africa and China), and the environmental impact of their materials production and transportation to the site using two life cycle inventories (LCI, namely *ECORCE* from France and UCPRC from California). Two of the regions have similar pavement designs (flexible), while one region uses a thin asphalt structure with cemented and granular layers and the other uses a semi-rigid structure. The environmental impacts of the three types of designs are different for different indicators. The two inventories produce similar rankings of the designs but different results because of various assumptions included in them. Adjustment for electrical power mix and mixing plant fuel source produce some differences in results among pavement designs, but quite different results between the two LCI because of differences in process modeling.

INTRODUCTION

The environmental impact of pavement materials production and construction depends on the context of the pavement construction, including regional differences in design, production and construction practices in addition to the specifics of the individual project *(1-3).*

Pavement design practice is normally based on local availability of road construction materials and cost, either initial cost or life cycle cost. Design practice also depends on the history of research and development of relationships between pavement performance and design of the pavement system (materials types and layer thicknesses), traffic loading and climate. For highways, the damage caused to the pavement by traffic depends on the numbers of trucks, axle configurations, tire pressures, axle loads and the speed at which the trucks operate, which vary between locations. Similarly, the performance relationships on which design methods are based either explicitly or implicitly account for local climate variables affecting pavement performance, most importantly temperature and rainfall regimes. Construction quality and drainage design are also a part of the design, usually implicitly embedded in the performance data through the construction of the test sections used in the development of the design to performance relationships. The result can be very different approaches around the world to solve the same problem of designing a pavement to maintain functionality while carrying a given amount of traffic within a design period. Consideration of alternative pavement designs from outside the traditional approach used in one region may or may not result in a change in practice, but it can definitely cause a questioning of assumptions and review of what is best practice.

As the introduction of life cycle assessment (LCA) into pavement decision making proceeds, the authors believe that benchmarking of LCA practice is important. Benchmarking that includes comparisons of assumptions, life cycle inventory (LCI) process models, and the differences in inventory results for individual materials and energy flows should lead to better understanding of ones' own practice and improved results. Benchmarking should also help increase the transparency of LCA because having to understand someone else's data and assumptions and compare it to your own helps reduce the tendency to treat LCI results from any source as "golden black boxes". This is important because information in many inventories has been used extensively and is widely accepted, but has not been subjected to recent critical review.

The purpose of this paper is to provide an illustration of regional differences in pavement design in four very different parts of the world, and estimates of the cradle to roadway (cradle to gate plus transport to the construction site) energy consumption and global warming potential (GWP) for a simple medium volume traffic asphalt highway. The second purpose of the paper is to consider the effects of two independently developed LCI databases and their application to the four pavement designs. Among the many possible regional adjustments that could be made within each LCI database, the study investigated the effects of differences in energy and GWP caused by adjustments to the average electrical power production inventory using data for each region and the fuel type used for the asphalt mixing plant. These were selected in large part because they are the only variables for which data are available.

There have been many studies comparing different types of pavement with the same LCI and one pavement design method, particularly for particular designs using asphalt and concrete. A number of other studies have investigated differences in materials selection and design, such as use of recycled materials, and other variables within a given design and using one LCI. Somewhat similar studies to the study presented in this paper have been performed previously, including a study of different assumptions for LCA by Ventura and Jullien *(4)*, comparison of use of different LCI on the same pavement treatments *(5)*, and a review of LCA practice for pavement by Santero et al *(1)*.

GOAL, SCOPE AND FUNCTIONAL UNIT

Goal and Scope

The goal of this study is to compare GWP and energy use from materials production and transport to the construction site for pavements intended to carry the same traffic, but designed and built in different regions; and to compare (as much as possible) each national pavement design using LCI from, or adjusted to the extent possible, each region. The four regions are California, France, South Africa and eastern China. Although there can be extreme ranges in climate and other factors within these regions, they have each historically made use of fairly standard pavement design approaches within their jurisdictions.

The two LCIs used for this study are *ECORCE (76, 7)*, developed by IFSTTAR for use in France and downloadable at http://ecorcem.ifsttar.fr, and an inventory developed for California by the UCPRC *(5)*. The matrix of pavement design and LCI cases evaluated is shown in Table 1.

Functional Unit

One asphalt surfaced pavement was designed for each region for traffic of one million 80 kN equivalent single axle loads (E80) in California, France and South Africa and the equivalent number of 100kN single axle loads for China over 20 years, using the regional standard design method. The subgrade is assumed to be medium plasticity clay, with a CBR value of 5. The pavement section is 5 km of two lane highway, with lanes that are 3.6 m wide, and the functional unit does not consider the shoulders, imported embankment materials, drainage or other features besides pavement.

Table 1: Scope of Comparisons of Pavement Design and LCI

Inventory/Design	California R-Value Design	France LCPC Catalog Design	South Africa Standard Design	China National Catalog Design
ECORCE	X	X	X	X
UCPRC[1]	X	X	X	X
ECORCE adjusted to local country conditions[2]	X	-	X	X
UCPRC adjusted to local country conditions[2]	-	X	X	X

Notes: 1. UCPRC LCI from commercial and open source inventories and adjusted to California conditions. 2. Locally adjusted LCI means that the *ECORCE* or UCPRC LCI has been adjusted to account for the a) local electrical energy production mix, and b) typical asphalt plant burner fuel source (natural gas or fuel oil).

Analysis Boundaries

The system boundaries for the analysis are the materials production and transport to the construction site. It was assumed that aggregate sources are 20 km away from the construction site and the mixing plant is at the aggregate source. It was assumed that cement and asphalt binder must be hauled 100 km to the mixing plant or site.

PAVEMENT DESIGNS

For the California design, the current R-value (Hveem) pavement design equations were used, converting the E80s into a Traffic Index of 9, and converting the subgrade CBR value to an R-value of 15. For the French design, the Aziz software was used corresponding to the LCPRC SETRA Routes method 1998 catalog. The subgrade CBR value was converted to an average modulus of 55 kPa. The 20 year traffic was linearly converted from a 30 year equivalent (standard French design life) and an assumption of 0.82 E80s per heavy truck, resulting in a traffic class of $TC3_{30}$ for entry into the software or catalog.

For the South African design, use of the standard design method was straightforward using the CBR and E80 given values. For the Chinese design, the E80s in the 20 year design life were converted into E100 repetitions in a standard 15 year design life using an axle load damage ratio exponent of 4.2. In sum, the resultant pavement designs shown in Table 2 are based on approximations of equivalent subgrade stiffness and shear strength and approximations of the same number of E80 repetitions. Each design method may offer options in terms of compensating thicknesses of materials in different layers, and in some cases the use of different materials. The designs were selected as being fairly "typical" for each region by the authors for the purposes of comparison for this study, recognizing that this is a gross simplification. Also shown in the table is the expected first maintenance or rehabilitation (M&R) expected for the new pavement, although that treatment was not considered in the analysis.

Table 2: Typical Pavement Designs for California, France, South Africa and China

Region	Type of layer	Name of Material	Thickness (mm)	Type of Material (% coarse aggregate >4.75mm; % fine aggregate <4.75 mm)	Source of Material (alluvial, hard rock or other); if alluvial % of crushed particles	Binder Types (cement, asphalt, polymer modified, rubberized, etc)	% by Mass of Total Mix of each Binder Type; if Modified Binder, % of Modifier by Mass of Binder
USA (California)	Surface	Dense graded asphalt concrete	150	50% coarse, 50% fine	Crushed alluvial (100% crushed)	Conventional PG 64-10	5%
	Base	Class 2 aggregate base (38 mm max)	460	60% coarse, 40% fine	Crushed alluvial (50% building waste, no inventory)	NA	NA
	Expected M&R: Seal coat at 8 to 12 years; Thin overlay at Year 20; Thick overlay with 20 year design life at Year 25						
South Africa	Surface	AC	30	40% course, 60% fine	Crushed aggregate	Asphalt	5%
	Base	Graded crushed stone	125	40% course, 60% fine	Natural gravel	Cement	4%
	Subbase	Cemented natural gravel	150	40% course, 60% fine	Natural gravel	Cement	3%
	Selected	Gravel soil	150	No specification	Gravel soil	NA	NA
	Imported Subgrade Cap	Gravel soil	150	No specification	Gravel soil	NA	NA
	Expected M&R: Reseal or new surfacing every 5 to 8 years (ideally); At the end of 20th year, rework the base by adding cement (1%) and some bitumen emulsion (1.5%) to form emulsion treated base and resurface.						

Note: NA = not applicable

The French and Californian pavements are classical “flexible pavements” with load bearing capacity in both the asphalt and granular layers. The South African pavement uses the asphalt only as a thin wearing surface and relies on cemented and granular layers for most of the structural capacity. The Chinese design is a “semi-rigid” pavement, with both thick asphalt and thick cement layers. This design is intended to withstand the very heavy axle loads typical of China, which may or may not be well accounted for with the axle load conversion used for this paper. Reliability levels in the three designs are not explicitly accounted for in the design procedures and may also differ.

INVENTORIES AND ADJUSTMENTS

The *ECORCE* inventories are based on research conducted by IFSTTAR in Nantes and additional information developed in collaboration with regional laboratories across France, Sétra, Polytech'Orléan and interaction with the Ministère des Transports du Québec. The inventories used in this study also include information from the Eurobitume European LCI for asphalt *(*8*)* to which an indirect upstream nuclear energy LCI has been added from AFNOR.

Table 2: Typical Pavement Designs for California, France, South Africa and China *(Continued)*

Region	Type of layer	Name of Material	Thickness (mm)	Type of Material (% coarse aggregate >4.75 mm; % fine aggregate <4.75 mm)	Source of Material (alluvial, hard rock or other); if alluvial % of crushed particles	Binder Types (cement, asphalt, polymer modified, rubberized, etc)	% by Mass of Total Mix of each Binder Type; if Modified Binder, % of Modifier by Mass of Binder
France	Surface	AC	60	60% coarse, 40% fine	Crushed rocks	Asphalt	5.4%
	Base	Gravel bitumen	100	65% coarse, 35% fine	Crushed rocks	Asphalt	4.4%
	Subbase	natural gravel	350	75% coarse, 25% fine	Crushed rocks	NA	NA
	Expected M&R: A surface treatment or a layer of asphalt every 8 to 10 years.						
China (eastern)	Surface	Dense graded asphalt concrete	150 mm (40 mm, 50 mm, 60 mm)	55% coarse, 45% Fine 60% coarse, 40% Fine 65%Coarse, 35% Fine	crushed basalt, limestone, granite or diabase	SBS modified asphalt SBS modified asphalt A-70 unmodified asphalt	5%, with 3% SBS; 4.5% with 2.5% SBS; 4%
	Base	Cement treated base	200 mm	65% coarse, 35% fine	crushed limestone, granite or diabase	Cement	4.5%
	Subbase	Aggregate subbase	150 mm	65% coarse, 35% fine	crushed limestone, granite or diabase	NA	NA
	Expected M&R schedule: Based on condition assessment.						

Note: NA = not applicable

The UCPRC inventory data used in this study were assembled from an LCI database that is based on various LCI sources *(5)*. Three of these sources are mainly used: *Ecoinvent* (9), Athena *(10)*, and the Portland Cement Association in the U.S. *(11, 12)*. Additional information was used from Eurobitume *(8)* and USLCI *(13)*. The California regional electricity LCI is assembled from data from California Energy Almanac by California Energy Commission and *GaBi (14)*.

A larger number of indicators were calculated using both inventories. However, energy use and GWP are primarily shown in this paper in the interest of length. No adjustments were made for cement production or the composition of the cementitious materials. For example, South Africa would use 6 to 35 percent fly ash as a supplementary cementious material included in the total cement percentage shown in Table 2, which would reduce the GWP for the cemented layers in the South African and Chinese pavement designs.

The South African electricity mix data shown in Table 3 are from Eskom *(15)* and the Chinese National Power Planning Research Center *(16)*. The electrical power generation in California is primarily natural gas, with some diversification, primarily nuclear energy and hydro in France, mostly coal in South Africa, and primarily coal with significant hydro in China. Feedstock energy for bitumen (asphalt) was calculated but is not shown in the interest of space.

Table 3: Electricity Mix in California, US, France, South Africa and China

Type	California	France	South Africa	China
Coal	7.7%	4.5%	85.6%	66.0%
Natural Gas	41.9%	4.1%	5.5%	3.3%
Hydro	10.8%	12.5%	1.4%	21.7%
Nuclear	13.9%	78.0%	4.3%	1.1%
Oil (Pumped Storage)	0.02%	-	3.2%	-
Wind (Renewable)	13.7%	Included in the Hydro	0.01%	5.3%
Solar (Renewable)	-	Included in the Hydro	-	0.3%
Other	12.0%	0.9%	-	< 2%

The asphalt mixing plant fuel type for each region is shown in Table 4. It can be seen that natural gas are primarily used in California and France, while fuel oil is primarily used in South Africa and China.

Table 4: Asphalt Mixing Plant Fuel Type

Type	California	France	South Africa	China
Fuel Type	Natural Gas	Natural Gas	Heavy Fuel Oil	Fuel oil

RESULTS

Comparison with Same LCI without Local Adjustment

Table 5 shows energy use for the processes considered in *ECORCE* for each pavement structure, calculated assuming the French electrical energy production and natural gas as the HMA mixing plant fuel. The results indicate that the French and Californian pavement structures use similar amounts of energy, which is not surprising considering that they have almost identical pavement designs. The California energy is slightly higher, most likely because of a slightly higher average binder content in the asphalt layers. The South African pavement has the next highest energy use. It has much less asphalt as a surfacing than to the French and Californian pavements, but it has 250 mm of cemented materials. The Chinese pavement has the highest overall energy use because it has the same asphalt thickness as the Californian and French pavements, and 200 mm of cemented base.

Table 5: Energy Results in MJ (*ECORCE*) with French Electrical Energy and HMA Plant Fuel

Parameter	French Case	Californian Case	South African Case	China Case
Bitumen	1.93E+06	1,898, 689	3.68E+05	1.66E+06
Stabilization plant	-	-	8.41E+05	6.12E+05
Hot-mix asphalt plant using gas	3.85E+06	3.56E+06	-	-
Hot-mix asphalt plant using fuel oil	-	-	7.71E+05	3.86E+06
EN 197-1 Portland slag cement CEM/II A-S 81	-	-	4.00E+6	3.79E+06
Gravel soil extraction	-	-	8.32E+04	-
SBS Elastomer	-	-	-	6.95E+05
Emulsion plant	4.97E+03	9.93E+03	-	9.93E+03
Aggregates	1.98E+06	2.36E+06	1,068 625	1.84E+03
Road transport	9.83E+05	1.15E+06	6.30E+05	1.03E+06
Gravel soil transport by dumper	-	-	1.66E+05	-
Total	8.74E+06	8.98E+06	7.93E+06	1.35E+07

Similar results are shown for the UCPRC LCI in Table 6. The processes are similar but have some differences. The rankings of the pavement structures are the same, with the Californian, South African and Chinese pavements using 1.03, 0.91 and 1.54 times more energy than the French pavement according to the *ECORCE* inventory, and the same comparison showing ratios of 1.28, 0.90 and 2.83 for the UCPRC inventory. Differences between structures are likely due to differences in the electrical energy requirements of the different materials used in each structure, which are influenced by the two power generation mixes, different cement types, as well as other differences in the inventories.

Table 6: Energy Results in MJ (UCPRC) with California Energy and HMA Plant Fuel

Parameter	France	California	South Africa	China
Hot Mix asphalt surface	6.32E+06	1.52E+07	3.16E+06	3.38E+07
Coarse Aggregate	1.82E+06	1.57E+06	2.28E+06	1.24E+06
Fine Aggregate	4.89E+05	7.60E+05	6.48E+05	4.84E+05
Asphalt (not in HMA)	4.90E+06	-	-	-
Cement (Type I/II portland cement)	-	-	5.70E+06	5.32E+06
Transportation (Asphalt+Cement)	8.52E+04	8.41E+04	1.28E+05	1.79E+05
Transportation (Aggregate)	1.17E+06	1.41E+06	1.38E+06	8.59E+05
Total Material Production	1.35E+07	1.75E+07	1.18E+07	4.09E+07
Total Transportation	1.25E+06	1.49E+06	1.51E+06	1.04E+06
Total	1.48E+07	1.90E+07	1.33E+07	4.19E+07

Figures 1 and 2 show GWP for each of the structures for the French and Californian inventory and assumptions, respectively. The rankings are the same as for energy use. However, the French inventory shows a smaller ratio between the Chinese and South African pavements versus the two flexible pavements, likely due primarily to the difference in the assumed cement (slag cement in France, ordinary portland cement in California). Overall GWP is much lower with the French assumptions, by a factor of about 3.5 for the Chinese pavement, most likely due to the French inventory having electrical energy production primarily based on nuclear power generation.

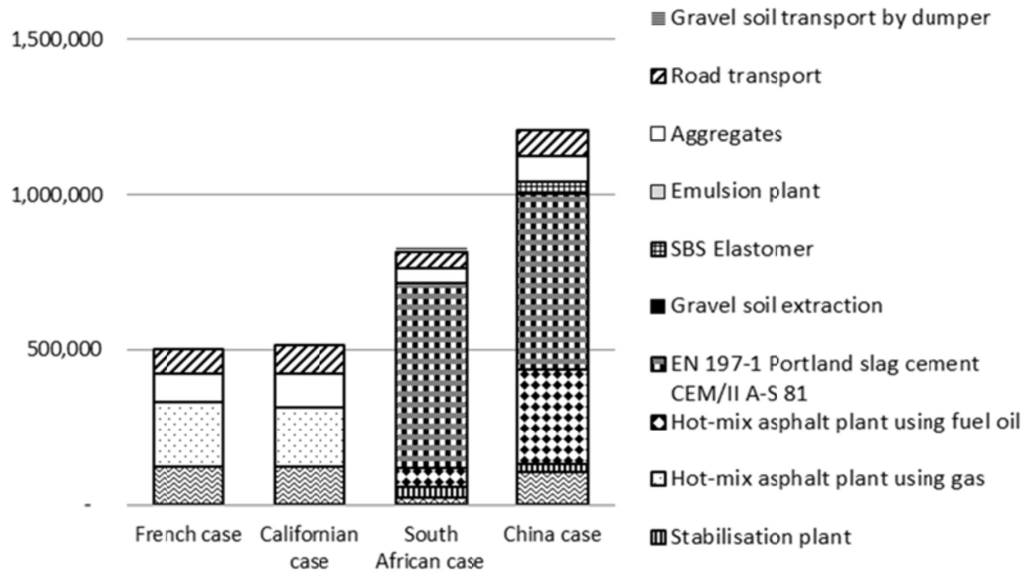

Figure 1: Global Warming Potential in kg eq CO_2 (*ECORCE*) with French Energy and HMA Plant Fuel.

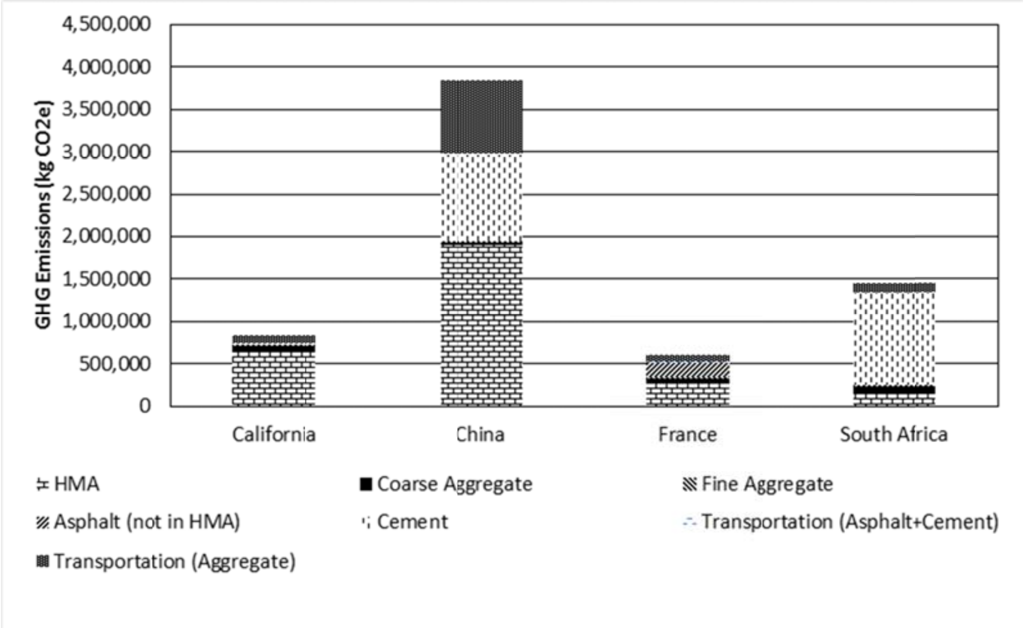

Figure 2: Global warming potential (*ECORCE*) with California energy and HMA plant fuel.

Table 7 presents a summary of all of the eco-indicators considered by *ECORCE*, and Figure 3 shows the same information in the form of a spider graph for the five indicators. The flexible pavements (France, California) rank best for energy use and GWP, followed by the South African thin asphalt pavement and the Chinese semi-rigid pavement. For acidification the flexible and thin asphalt pavements show better than the semi-rigid pavement. For eutrophication and ozone formation the thin asphalt pavement has the best results. Overall, the semi-rigid pavement ranks worst for all categories. However, it must be remembered that this pavement is expected to carry heavier axle loads than the pavements in the other regions, and the conversion of the axle load may have caused a comparison of unequal pavements. On the other hand, a wetter climate or construction climate may be an issue, or the thicker structure used in China may be failing due to shrinkage cracking of the cement reflecting up into the asphalt (as reported by Chinese experts this is the main failure mechanism), and the pavement may be overdesigned for the axle loads.

Table 7: Summary of all Indicators (*ECORCE*) with French Energy and HMA Plant Fuel

Case	Energy (MJ/t)	Greenhouse effect (kg eq CO_2)	Acidification (kg eq. SO_2)	Eutrophication (kg eq. PO_4)	Tropospheric Ozone Formation (kg eq. C_2H_4)
French	8,736,701	501,969	940	202	642
Californian	8,980,149	515,902	1,036	231	681
South African	7,929,917	837,204	1,078	188	467
China	13,495,527	1,208,807	2,131	300	1,127

Comparison with *ECORCE* and UCPRC LCI with Local Adjustment

Table 8 shows the processes in the *ECORCE* LCI that can be changed to reflect regional differences in electrical power generation. Figure 4 shows the effect of changing the electrical power generation mix in *ECORCE* for the South African pavement. It can be seen that there is a large change in GWP, mostly due to the heavy reliance on coal in the South African power mix, and somewhat influenced by the change from fuel oil to natural gas for heating asphalt and aggregate in the mixing plant. There is also a large increase in acidification for the same reason.

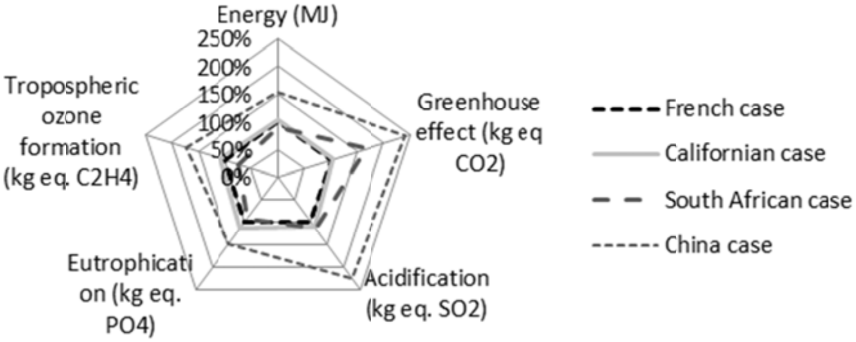

Figure 3: Spider diagram of all indicators (*ECORCE*) with French energy and HMA plant fuel.

Table 8: Summary of Possible LCI Processes in *ECORCE* for Electrical Power

Process	Comments about Mix Change
Bitumen	Not possible to change LCI used
Stabilization plant	Possible
Hot mix plant	Possible
Cement	Not possible to change LCI used
SBS Elastomers	Not possible to change LCI used
Emulsion plant	Possible but negligible
Aggregates	Possible
Road transport	No effect or negligible

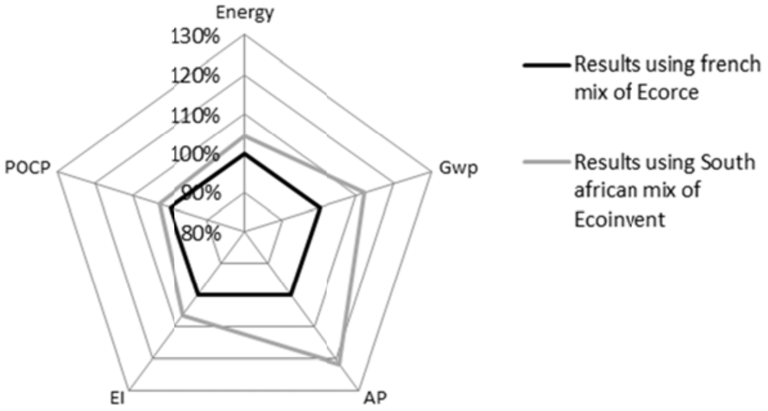

Figure 4: Spider diagram for South Africa case with change of electrical power and mixing plant fuel.

Figure 5 shows the GWP for the four pavements with regional adjustment of the electrical power generation mix and the mixing plant fuel source. The results show small increases for the South African and Chinese designs, and a small reduction for the French design, primarily based on extend of coal use compared to California for the first two, and nuclear use for the latter. Processes affected by electrical power mix in the UCPRC inventory were production of fine and coarse aggregate, bitumen, cement, and HMA.

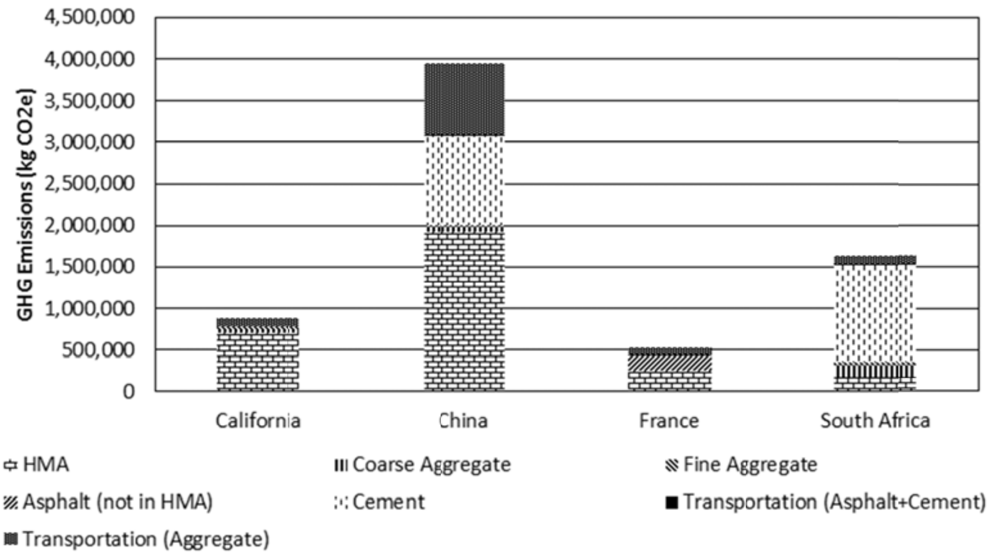

Figure 5: Global warming potential in kg eq CO_2 (UCPRC) with regional energy and HMA plant fuel.

SUMMARY AND CONCLUSIONS

This paper showed some of the results of a study that compared pavement designs, and benchmarked LCI calculations for those structures, including comparison of the effects of LCI database and sensitivity to electrical power generation mix and asphalt mixing plant fuel type.

The results showed that there are large differences in the approaches taken for pavement design, and it is likely that each of these pavements can provide satisfactory performance. The two LCIs produced results that showed similar rankings for energy use and GWP for the different pavements, but had important differences in actual values reflecting primarily differences in electrical power mix and assumed cement type. This suggests that they can produce similar results if these differences are accounted for. Future work by the authors, and others doing similar work, should evaluated reasons for differences. Comparison of GWP results between pavement types showed important differences based on electric power generation mix. In general, the thin asphalt pavement had somewhat lower energy use because it used less asphalt, but much greater GWP because of its use of cement. The semi-rigid pavement had the highest environmental footprint, however, the Chinese example evaluated here may be overdesigned for traffic loading compared to the other pavements.

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