LIFE CYCLE ASSESSMENT FOR MEASURING THE ENVIRONMENTAL EFFECTS OF THE MANUFACTURE AND CONSTRUCTION OF BITUMINOUS MIX PAVING

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ABSTRACT

A method to evaluate and quantify environmental impacts due to the production processes of component materials, manufacturing and construction of mix asphalt pavements is presented in this paper. The Kyoto Protocol has introduced new variables in the sustainability analysis of any construction activity as greenhouse-gas emissions. Nevertheless, production of a bituminous mix causes very different environmental consequences depending upon the materials used, typology of the plant and fuel, on-site pouring technique, transport distances and even its possible recycling.

The proposed methodology for the environmental analysis and valuation of this construction activity is based on the *Life Cycle Assessment (LCA)* taking into account all the non-renewable resource consumption, from the extraction and treatment of the primary raw materials, manufacture and transport of the product, to reworking or extinction as a waste, and the potential environment and public health effects during all the lifespan of the product. In addition, the *LCA* enables us to compare alternative roadbed designs and construction techniques in terms of their environmental impact. All the life cycle phases, inputs (energy and fuel consumption) and outputs (manufactured products, emissions and waste materials) generated are exhaustive compiled and calculated by means of a specifically-developed simple software.

The results related to hot asphalt mixes show that the use of mixing plants equipped with co-generating systems makes possible to reduce atmospheric emissions by 25%, and by 85% if making use of natural gas as fuel. Moreover, the filler can multiply by 1000 the CO_2-eq emissions. Using *Warm Mix Asphalt* technologies and *Low-Energy Coating* techniques, the emissions could be reduced above 50% in comparison with conventional bituminous mixes at high temperatures.

Keywords: Life Cycle Assessment (LCA), sustainable engineering, environmental impacts, hot mix asphalt

1. INTRODUCTION

Environment must neither be consider as a specialized field of civil engineering, nor a limitation for its development, but an essential component of this activity. Our engineering should be focused on the principles of efficiency, equity and sustainability. This means a challenge to a greater search in providing sustainable solutions for the environmental problems. The Kyoto Protocol has introduced new variables in the environmental analysis of any human activity that are not suitably considered in road engineering as yet. *Greenhouse-gas* emissions are an additional factor easy to evaluate both in the construction phase and in the operation stage. In Spain, the *2nd National Plan for the Greenhouse-Gas Emission Rights Distribution (2008-2012)*, to apply the *European Union Directive 2003/87/CE*, has the aim of meeting the European Union agreements with the Kyoto Protocol. At present, Spain has an important deficit in Emission Rights. The production of bituminous materials is one of the industrial sectors directly controlled by the European Directive aforementioned. The current *1st National Plan for Emission Rights Distribution, 2005-2007* has allocated to this construction sector up to 15250 tonnes of CO_2-eq during this period of time.

Environmentally-friendly roadbed technologies and paving construction procedures are being more and more important, such as pavement recycling techniques or soil treatments and stabilizations, allowing the use of the on-site and local materials, and besides, has made possible to employ waste of industrial processes and building demolition in road construction. However, the comparison of different kinds of processes, operating management and control systems from the environmental point of view demands analysis procedures to assess the sustainability. Therefore, the environmental interest of these material-reclaiming techniques obtained from existing aged asphalt pavements or on-site soils, depends closely on the transportation distances involved in the different processes, the type of admixture and rates and the laying procedures. The same considerations could be taken into account to compare pavement sections constructed with different materials but with similar structural behaviour, which could mean, nevertheless, very different environment effects.

The environmental impacts to be considered are not only the ones produced during the highway or airport pavement construction, but also those resulting from the extraction and treatment of the raw materials, manufacturing and transport of the product, or the ones generated by the supply industries, take part in the global environmental computation. Moreover, the environmental assessments should consider the construction procedures.

Currently, some different models to measure the environmental impacts of the construction processes are available for engineers such as the *"ecological footprint"* analysis, that allows technicians to compare its global sustainability; or the *"Life Cycle Assessment" (LCA)*, which offers very precise values of the potential environment results during all the lifespan of a product or process. The *LCA* takes into account all the non-renewable natural resource consumption, from the extraction, manufacture and transportation, to reworking or extinction as a waste, and the potential environment and public health effects. Therefore, this analysis enables us to compare alternative pavement designs and construction techniques in terms of their environmental impacts. It is a methodology promoted by the *United Nations Programme for the Environment* and the *World Summit Conference for Sustainable Development* of Johannesburg in 2002. This method has been standardized with the *ISO 14040*(1).

However, the *LCA* of construction processes or products has an important degree of difficulty. Thus, most of the studies often only consider some phases of its life cycle or are focused on a few construction materials or services(2). Relating to paving materials and processes, some works even suggest a new index to assess the sustainability of different solutions *("Index of Pavement Sustainability")*(3), but the consumptions (energy, fuel, lubricants, raw materials), emissions (to atmosphere and to water) and waste, are not often clearly assessed and quantified.

In an attempt to propose an analytical method considering all the mentioned inputs and outputs, the object of this work has been to study the effects of the manufacturing procedure of hot-mixed asphalt *(HMA)* on the environment, and the influence of the materials utilized, typology of the coating plant, fuel employed, on-site pouring technique, transportation distances, and its possible recycling. Within this aim, a specifically simple software has been developed which allows us a really objective comparison in terms of environmental impact.

2. LIFE CYCLE ASSESSMENT METHODOLOGY

To complete all the life cycle of a hot bituminous mix, each associated process from the aggregate extraction to its laying on the pavement has been estimated. According to the *ISO 14040*, the production of one metric ton of hot mix asphalt has been defined as the system production unit, and as associated subsystems: aggregate extraction from the quarry or gravel pit, manufacturing and transport, *HMA* production, transportation to roadworks and spreading. The possibility of shutting down the system with the aged bituminous mix reuse by means of recycling has also been studied *(whole life cycle)*. Once all of the subsystems have been established, the system inputs and outputs are properly identified, even the ones to and from the elementary subsystems (Figure 1). It can be noted that the main inputs into the general system are the basic raw materials and the global energy consumption. Main outputs are usual waste materials and emissions to the environment; and the final product, the *HMA*.

For the purpose of quantifying the above-mentioned system inputs and outputs, the considered parameters are shown on Table 1. They have been grouped by consumed resources, emissions and generated waste. Total greenhouse-gas emissions have been defined as only one value expressed in terms of kg CO_2-eq, which determines the global warming.

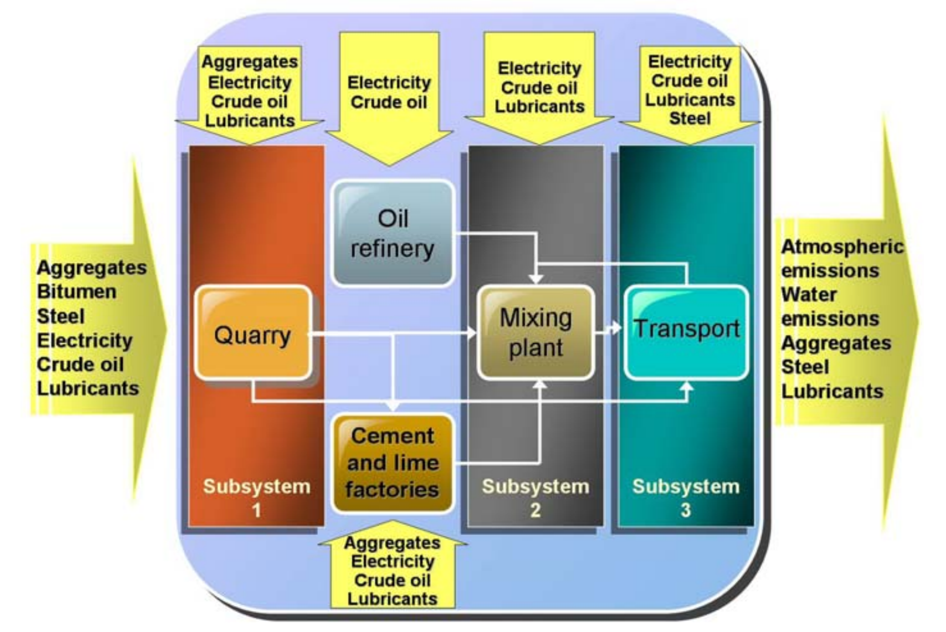


Figure 1. Diagram of the *HMA* manufacturing process with associated subsystems: inputs and outputs for the *Life Cycle Analysis* model

Table 1. Suggested parameters to quantify the system inputs and outputs

		Parameter	**Unit of measurement**
Inputs	**Energy resources**	Crude oil, Electricity	MJ
	Non-renewable resources	Aggregates, Bitumen, Lubricants, Steel	kg
Outputs	**Atmospheric emissions and Water emissions**	CO_2, SO_2, NO_x, N_2O Hydrocarbons, CH_4, Phenols (aq) DQO, N-Total Dust	g, kg
	Waste	Lubricants, Steel	kg

2.1 Consumptions

In order to assess the energy consumptions within each process, a direct data capture has been performed, which has been related to raw material consumption by means of conversion factors. The ones used for vehicle and machinery fuel have been obtained from the data bases described by *Stripple* (2001)(4), who worked out generic values for a low-consumption diesel engine. In the same study this author assumes that fuel is of environmental class 2 with a sulphurous content of 0.05%.

With respect to fuels used in the mixing plant boiler and burner (natural gas, fuel oil and diesel oil), the data bases included in the german manual *ETH-ESU ("Energie-Stoffe-Umwelt")* have been consulted. For bitumen and recycling materials it is also possible to employ the research data of *Stripple*, although with regard to bitumen, this author is based on the *Eurobitume* study, in which the bitumen class is restricted to 50/70.

In relation to lubricants, the resource consumption during its manufacturing process is not considered since it is insignificant compared to the whole system. With the aim of quantifying the cement input into the system in terms of filler, the results of *De Carvalho* (2001)[2] have been used, who has obtained these data from the international inventories prepared by *CEMBUREAU* (European Cement Industry Organization). Concerning limestone filler, our data have been obtained from a report of the *IVL Swedish Environmental Institute Ltd.*

Primary resource consumptions related to vehicle and machinery manufacture have not been considered in this analysis. The construction processes of refineries, cement factories and hot asphalt mixing plants have been neither included in this study, although the consumptions within their different operations have been taken into account.

2.2 Emissions

Atmospheric and water emissions of the complete system (see Table 1) are calculated by means of connections with the energy, bitumen and raw material consumptions, the production of these inputs, and transportation vehicle and asphalt plant emissions. Hot asphalt coating plant consumptions are directly obtained using iso-kinetic measuring and gas analysers, or by an approximate assessment depending on the engine efficiency. All the emissions can be summarized in only one parameter defining the global warming (kg CO_2-eq). The employed equivalence ratios with other greenhouse gases are:

$$21 \text{ kg } CH_4 \,/\, \text{kg } CO_2\text{-eq} \quad \text{(Eq. 1)}$$

$$310 \text{ kg } N_2O \,/\, \text{kg } CO_2\text{-eq} \quad \text{(Eq. 2)}$$

The rest of emissions are also calculated to have them available for subsequent studies analysing, if necessary, other aspects related to these pollutants.

2.3 Waste

It has been considered that lubricants leave the system with a rate of 99.5%. Steel comes from metal hard-wearing materials used during all the processes, leaving the system as a waste. These data are real values and have been obtained from the information available about different facilities provided by the manufacturers.

2.4 Suggested constants and computing procedure

Table 2 summarizes those constants utilized in the calculations. The pavement maintenance management subsystem has been excluded from this study, as it exceeds the objectives of this work, but its inclusion in subsequent studies would enable us to complete the bituminous mixes' life cycle.

Table 2. Constants in the *Life Cycle Assessment*

Property	Value and unit
Hot mix asphalt density =	2.4 T/m^3
Aggregate apparent density =	1.6 T/m^3
Aggregate real density =	2.6 T/m^3
Recycling material apparent density =	1.6 T/m^3
Liquefied natural gas density =	448.108 kg/m^3
Fuel oil density =	984.01 kg/m^3
Diesel oil density =	840 kg/m^3
Liquefied natural gas calorific capacity =	3.13 MJ/m^3
Fuel oil calorific capacity =	42.5 MJ/kg
Diesel oil capacity =	45.5 MJ/kg

To make easier the computing problem a specifically simple software has been developed. The application program shows the three different subsystems to product 1 tonne of hot bituminous mix, allowing the users to work with two subsystems at the same time:

Subsystem 1: Aggregate extraction, processing and treatment: the following variables can be considered:

- Aggregate source: from quarry or gravel pit.
- Crushing, grinding and screening procedures: type of grinders and round-hole screens can be chosen and also the characteristics of the conveyor belts.
- Loading operations: features of the mechanical loader to transport aggregates from processing plant to stockpiling.
- Type of vehicles to transport aggregates from extraction area to processing and treatment facilities and to storage facilities.

Subsystem 2: Hot bituminous mix production: it has been divided in three sub-sections:

- Asphalt plant facilities: type of mixing plant, its features and production conditions are defined.
  - Typology: continuous or discontinuous mixing plant.
  - Production: it is considered within the limits of 120 Tonnes/hour and 360 T/h.
  - Type of fuel (differentiating boiler, burner, and electrical system): it can be natural gas, fuel oil, or diesel oil for the boiler and the

burner, and for the electrical system it is possible to differentiate if the plant is fed directly from the mains supply or from a generator.

- Manufacturing conditions: where we have characterized:
  - Production range: depending upon the production plant capacity: this data basis allows to choose a range from 50% to 120%.
  - Outside temperature: from –10 ºC to 40 ºC.
  - Mixing temperature: 140º C to 190 ºC.
  - Aggregate moisture content: 0.5% to 7%.
  - It has also been considered if the mixing plant has some energy saving system.
- Mix design: here, the inherent features of the asphalt mix are described:
  - Type of mixture: dense or semi-dense asphalt concrete, porous asphalt, stone mastic asphalt (SMA) or high modulus asphalt.
  - Recycling rate: it can be considered the mix recycling and with different ratios (%).
  - Filler: the percentage of stone dust contained within the aggregates, the total filler content in the mix, the inclusion of added filler to the mixture or not, and in which proportion, are detailed.
  - Aggregates: source and percentage ratios.
  - Other admixture materials: type (tyre waste, fibres) and percentages.
- Type of vehicles employed for transportation from aggregate processing and treatment facilities to mixing plant, and distances involved.
- Type of machinery and vehicles used for aged pavement milling and transport to recycling plant, and distances involved.

Subsystem 3: Transport to roadworks: it takes into account:

- Transportation vehicles: carrying capacity, power and distances from mixing plant to roadworks.

3. RESULTS OF THE *LCA* APPLIED TO AVERAGE FACILITIES

As a practical example of the described calculation methodology, the Life Cycle Assessment has been applied to the production of one tonne of hot-mixed asphalt by an ordinary coating plant. Considered inputs are defined on Table 3.

Using a four-axis graph, the consumed finite resources or inputs into the second subsystem (mixing plant) are represented in Figure 2. In the same way, Figure 3 illustrates the atmospheric and water emissions, and the different kind of waste from this subsystem. Results are expressed per 1 tonne of *HMA* production. It is necessary to indicate that the CO_2 emission representation has been omitted on the upper graph to avoid distortion because of its high value compared with the rest of emissions. This result is only numerically expressed in the table beside.

Table 3. Input parameters applied in the calculation example for *Subsystem 2: hot mixing plant*

Type of mixing plant: Production =	Discontinuous 220.0 T/h	**Type of hot mix asphalt:**	S-12 (semi-dense)
Burner: Fuel = Consumption =	 Fuel oil 9.11E+6 MJ/m	**Filler (added):** Content (rate) = Source =	 0.0 % ---
Boiler: Fuel = Consumption =	 Diesel oil 391.00E+3 MJ/m	**Admixture:** Content (rate) = Type =	 0.0 % ---
Electrical system: Fuel = Consumption =	 Mains supply 15.00E+3 MJ/m	**Natural aggregates:** Content (rate) =	 0.0 %
Production variables: Production range = Mixing temperature = Outside temperature = Aggregate moisture content =	 100.0 % 180.0 °C 20.0 °C 4.0 %	**Transport (aggregate treatment facility - mixing plant):** Dumper = Mechanical loader =	Mercedes LK-2638 Volvo-L330E
Co-generator:	NO	**Transport (recycling material-mixing plant):** Milling machine = Mechanical loader =	 --- ---

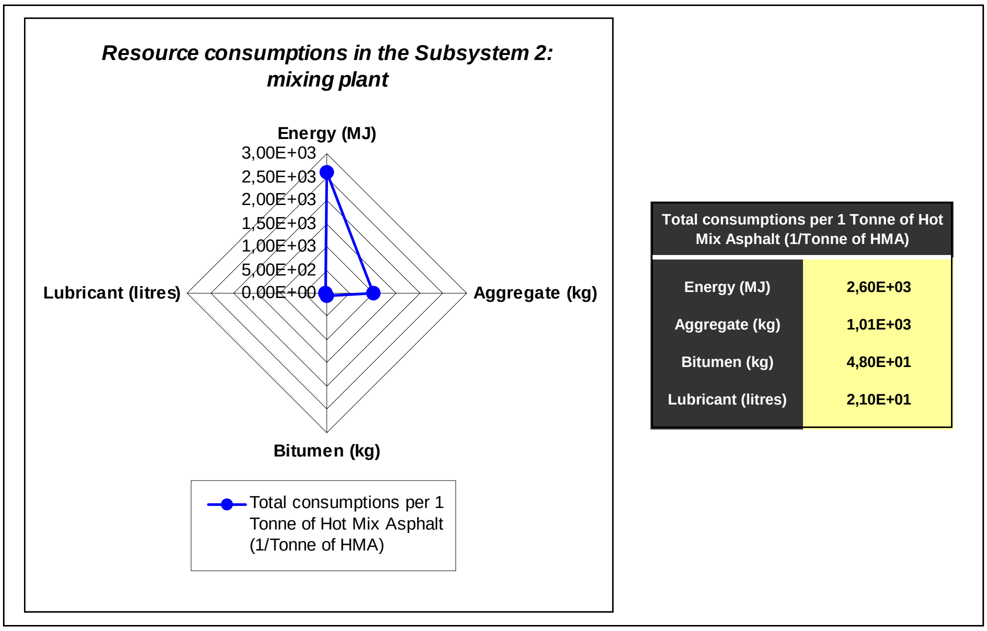
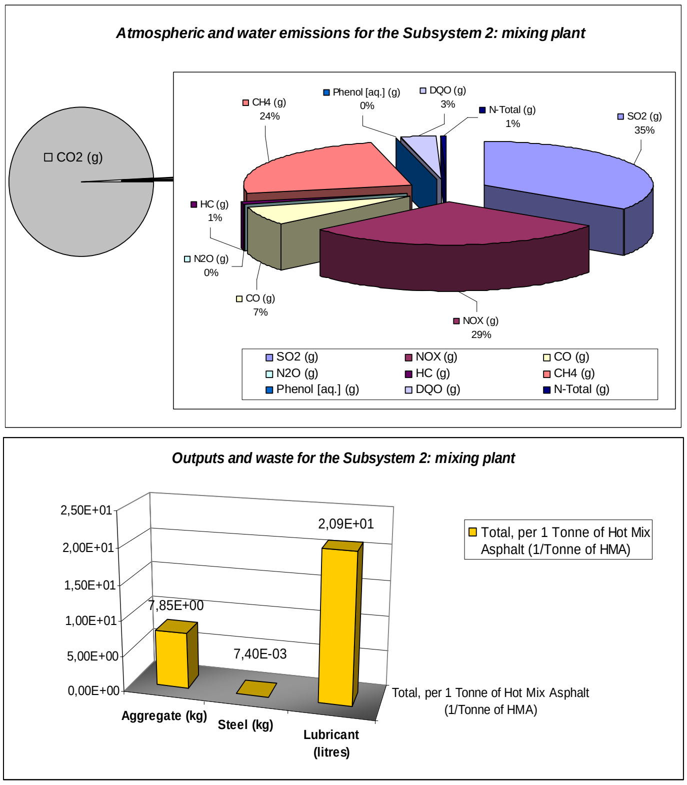


Figure 2. Finite resource consumption result chart in the Subsystem 2: hot bituminous mix production



	Total, per 1 Tonne of Hot Mix Asphalt (1/Tonne of HMA)
Atmospheric and water emissions:	
CO_2 (g)	8,78E+04
SO_2 (g)	2,72E+02
NO_x (g)	2,33E+02
CO (g)	5,47E+01
N_2O (g)	1,40E+00
HC (g)	7,76E+00
CH_4 (g)	1,92E+02
Phenol [aq.] (g)	1,25E-01
DQO (g)	2,51E+01
N-Total (g)	5,35E+00
Waste:	
Aggregate (kg)	7,85E+00
Steel (kg)	7,40E-03
Lubricant (litres)	2,09E+01

Figure 3. Emission result chart for the Subsystem 2: hot bituminous mix production

The observation of these results shows that the energy consumption (crude oil and electricity) for this asphalt plant would be around 2600 MJ/T $_{(HMA)}$ and global warming due to the process could approximately reach 100000 g CO_2-eq/ T $_{(HMA)}$. With regard to the rest of gases, the two greater emissions are the NO_X and the SO_2 ones.

3.1 Influence on the analysis of different variables

In attempting to study the environmental effects of different variables, this paper section explores the *Life Cycle Assessment* considering different calculation possibilities. The values considered in the analyses are given in Table 4.

Tables 5, 6 and 7 illustrate the constants utilized for computing with respect to the three studied subsystems.

Table 4. Calculation values employed in the *Life Cycle Assessment*

Item	Worked example Values
Production of *HMA* (Tonnes/month) =	15000; 60000
Distance from aggregate processing and treatment facilities to mixing plant (km) =	0; 20; 50; 100
Type of mixing plant =	Continuous; Discontinuous (with *Double Barrel* dryer drum mixer)
Asphalt plant fuel =	Fuel oil; Gas oil; Natural gas
Co-generator =	Yes; No
Mixing plant production (Tonnes/hour) =	120; 20; 300
Outside temperature (ºC) =	5; 20; 35
Filler (added) =	Yes; No
Recycling material content (%) =	0; 10; 50
Distance to roadworks (km) =	10; 20; 50; 100; 200

Table 5. Considered constants for Subsystem 1: Aggregate extraction, processing and treatment

			Value
Grinders and round-hole screens			Consumption = 4.48E+05 MJ/m
Conveyor belts	Length (m) =	40	
	Rate of flow (T/h) =	400	
	Angle (º) =	18	
	Operation (h/m) =	145	
Vehicles	Extraction:	Liebherr R 984 CLI	Operation = 208 h/m
	Load:	Volvo L 180 E	Operation = 156 h/m
	Transport:	CAT 771 D	Operation = 220 h/m

Table 6. Considered constants for Subsystem 2: Hot bituminous mix production

			Value
Energy supply	Mains supply		Consump. = 1.50E+04 MJ/m
Manufacturing conditions	Capacity (%) =	100	---
	Mixing temperature (ºC) =	180	
	Aggregate moisture content (%) =	4	
Mix proportioning	Type of hot mix asphalt:	S-20 (semi-dense)	---
	Natural aggregates:	NO	

				Value
	Admixtures:	NO		
Vehicles	Aggregate treatment facilities - mixing plant:	Load:	Volvo L180E	110 h/m
		Distance (m) =		150 m
	Recycling material extraction:	Milling machine:	Wirtgen 100	114 h/m
		Dumper:	MAN 33364 DFAK	140 h/m
		Mechanical loader:	Volvo L180E	110 h/m
		Distance (km) =		55

Table 7. Considered constants for Subsystem 3: Transport to roadworks

			Value	Emissions
Vehicles	Dumper:	MAN 33364 DFAK	140 h/m	767.84 g CO_2/km 0.0990 g CH_4/km 0.0344 g N_2O/km
	Conventional dump truck:	Mercedes 1844 LS	140 h/m	511.89 g CO_2/km 0.0683 g CH_4/km 0.0244 g N_2O/km

Assessment results clearly reveal that the highest production of CO_2-eq is emitted by the second subsystem (hot-mixed asphalt production) as expected, but this methodology enables us to quantify these emissions. Consequently, on this production stage the main engineering efforts should be made to reduce them.

It has been studied the so-called *Example 1* in which the coating plant has some co-generating system. The resulting values show that the emission rates are reduced by 25%. A second possibility named *Example 2*, where the mixing plant consumes natural gas instead of oil fuels, has been assessed. This study reveals that it decreases the greenhouse-gas emissions by 85%. Moreover, if the production process is performed in a plant equipped with a co-generator and using natural gas (*Example 3*) the CO_2-eq reduction can be up to 90%.

However, the analyses show that there are no important differences in terms of gas emissions between a continuous and a discontinuous mixing plant, among different plant capacities and among various outside temperatures. As it can also be seen, the inclusion of added filler to the mix can multiply by 1000 the CO_2-eq global atmospheric emissions. Furthermore, the use of recycling materials provides substantial savings in primary resource consumption. Finally, the increase of distances to roadworks also increases the consumption and emission proportions and the latter are even more important if a dumper is employed for transport instead of a conventional dump truck.

4. CONCLUSIONS

This work has described the development of a method for comparing the most sustainable options to produce hot-mixed asphalt which could have considerable benefits in the decision-making stages. Results related to the implementation of the *Life Cycle Assessment* to hot bituminous mixes manufacturing and laying processes have enabled us to precisely quantify the environmental consequences:

- With regard to global emissions, the importance of modernizing production facilities using less pollutant fuels, such as natural gas and mixed co-generating systems, has been revealed as very significant (CO_2-eq reductions from 85% to 90%).
- When quality of resultant *HMA* enables it, there should be avoided to add filler to the mixture, as its inclusion can multiply by 1000 the CO_2-eq global atmospheric emissions. This will be specially important for those countries having serious difficulties to observe the Kyoto Protocol agreements.
- The recycling material consumption should be increased, both to avoid the generation of great amounts of waste and to reduce the finite non-renewable raw materials.
- It is very important to employ the most suitable vehicles for transport. Moreover, the distances from facilities (aggregate processing and treatment, mixing plant) and roadworks increase economical and environmental costs.

On the other hand, using *Warm Mix Asphalt* technologies and *Low-Energy Coating* techniques, the emissions could be reduced above 50% in comparison with conventional bituminous mixes at high temperatures.

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