International Journal of Engineering, Sciences and Technologies
ISSN : 3079-2045
https://www.ij-est.org/
Volume 2, issue 3,https://doi.org/10.70961/ZEFX8726

ENVIRONMENTAL ASSESSMENT OF MALAGASY PAVEMENT MATERIALS: CASE OF COLD MIX ASPHALT AND CHIP SEAL

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Abstract

Climate change and environmental issues force each country to establish the carbon balance and the energy balance in its sectors of activity. However, Malagasy road engineering, where the environmental assessment has not known a real quantification of environmental impacts, focuses more on the technical and financial aspect of the project. Thus, this present work has an interest in attaching to Malagasy cold hydrocarbon products, Greenhouse gas emission (GHG) and Primary Energy Consumption (PEC) factors. We use here the methodologies of the Life Cycle Assessment on System Boundaries (SB) going "from the cradle to the construction phase". Inventory data correlates with normative road engineering techniques and energy aspects, and then confirms Madagascar's insularity. The SIMA PRO software thus, translates the inventory data into terms of impacts. By using bitumen emulsion as a binder, the results conclude a greenhouse gas (GHG) emission factor and an energy consumption of 63.4 kgCO2eq/m3 and 904 MJ/m3 for Dense Cold Asphalt 0/12.5 (DCA 0/12.5), then 0.298 kgCO2eq/m² and 4.28MJ/m² for the single chip seal 4/6 (SCS 4/6), likewise 0.597 kgCO2eq/m² and 8.62MJ/m² for the Double Chip Seal 2/10 (DCS 2/10), also 0.85 kgCO2eq/m² and 12.3MJ/m² for double chip seal 4/14 (DCS 4/14). Using the Cut-Back, we retain the values of 109 kgCO2eq/m3 and 2440 MJ/m3 for DCA 0/12.5, 0.479 kgCO2eq/m² and 11.6 MJ/m² for the single chip seal 4/6 (SCS 4/6), 0.89 kgCO2eq/m² and 20.8MJ/m² for double chip seal 2/10 (DCS 2/10), also 1.28 kgCO2eq/m² and 30.2MJ/m² for double chip seal 4/10 (DCS 4/10).

Keywords: Cold Asphalt, Surface Coating, Bitumen Emulsion, Cut-back, Life Cycle Assessment, Greenhouse Gas, Primary Energy Consumption

1- Introduction

Madagascar has a large part of its road networks in a deplorable state, requiring imminent maintenance. This situation feeds a great state ambition to ensure long-lasting infrastructure by focusing more on technical and technological aspects. The environmental perspective is practically only raised in environmental permitting procedures for the road project. Also, the environmental assessment advocated in the Malagasy texts[1], [2]is based on the classic methodology of “Environmental Impact Studies” (EIS). Already, the word “sustainable development” is mentioned in these texts, but in reality, the results obtained are very qualitative and sometimes likely to render the environmental mitigation measures ineffective. At each Malagasy road maintenance project, its environmental records, which are often made public, do not really relate a serious global problem. Precisely, through lobbying and global conferences, each country has been pushed towards a commitment to reduce its greenhouse gas (GHG) emissions and its Primary Energy Consumption (PEC)[3]–[5]. Madagascar cannot immerse itself in such a policy without having quantified its GHG emissions and its PEC.

This study thus focuses on the development of GHG and PEC emission factors attached to each cold mix asphalt product, conventionally used in Madagascar. These cold products are used in various road maintenance works. We will elucidate in this study, the case of cold dense asphalt (CDA) and Cheap Seal (CS) technologies. In addition, each cold technology will be evaluated with two (02) hydrocarbon binder alternatives, namely ECR 60 bitumen emulsion and cutback 400/600.

To do this, we choose the Life Cycle Analysis (LCA) as an impact assessment method. LCA (ISO 14040-44) is a versatile environmental assessment method capable of leading to a better decision and orientation to reduce the environmental impacts of a product or service[6]. The application of LCA in a road project, greatly requested in several countries[7], still experiencing a small step in Madagascar. In this study, we retain the Global Warming Potentials over 100 years (GWP100) of GHG. Also, the PEC is the sum of the energy contained in its final form as fuel or volatile compound to the upstream energy necessary for its extraction, transformation processes and distribution. In other words, energies in the final form of non-combustible and non-volatile materials are excluded from PEC. Also, the mass allocation rule is used for the case of petroleum co-products.

At the end of this Study, road project designer can, on the one hand, immediately assess, prior to its execution, the GHG emissions and PEC balance sheet of a road maintenance project in order to anticipate decision-making. On the other hand, Madagascar, like other countries, could thus have strategic plans and even, why not, “sustainable” road maintenance policies.

2- Methodology

2.1.Life Cycle Assessment (LCA)

LCA is a method for quantifying the assessment of environmental impacts and damages (ISO14040-14044). Several case studies use LCA for the environmental assessment of road materials, or complete pavement structures and even going as far as comparative analyzes of technological variants[6].

2.2.Goal and scope of the study

The main objective of the study is to quantify the GHG emission and PEC balance in the context of cold mixes intended for Malagasy road maintenance works. Secondarily, the analysis aims to submit comparative analyzes to the results obtained in relation to other cases evaluated in other countries.

The Functional Unit taken into account for each material is given in **(Table 1)**.

A cold mix consists of mixing the granular fractions and the binder at room temperature[8]–[11]. According to LCPC[12], the cold mix manufacturing and spreading temperatures are below 60°C. On the side of **Milad et al., 2022**[13], these previous temperature values are below 30°C. Thus, cold mix technology, far from being universal, varies from one country to another.[10] [14]. However, regardless of the technologies adopted, cold mixes have a lower coating temperature than hot mixes and no process for heating the aggregates[15]. Cold mixes are products designed for the maintenance and rehabilitation of paved roads with low traffic[9], [11], [14]. The binders used are cationic emulsion with 60% residual bitumen (ECR 60) or cut-back 400/60. Having low viscosities compared to pure bitumen, they are obtained by adding emulsifiers or volatile solvent to bitumen[8], [9]. According to Malagasy technology, coating temperatures do not exceed 125°C for cold mixes with a cutback binder and 70°C with an emulsion binder.

The ECR 60, recommended in a tropical conditions[16], is a suspension of pure bitumen in water containing emulsifier[14], [17]. The bitumen content of an emulsion is generally 60% [7]. After the curing time, the water evaporates and the emulsifier will be incorporated into the mix. Cutback 400/600 is bitumen that has been made more fluid under the action of a volatile oil solvent. Generally, kerosene was used to obtain fluid asphalt with a slow curing time, easy to implement. Once the curing time has been reached, the petroleum solvent evaporates into the atmosphere [7].

The chip seal (CS) technology corresponds to an application of a layer of binder (ECR60 or cutback 400/600) followed by an aggregate cover. The repetition of this succession of layers is applied at once in the case of a Single Chip Seal (SCS) or twice in the case of a Double Chip Seal (DCS) [18]. According to Malagasy technology, if the binder layer is cut-back 400/600, the spreading temperature is around 100°C to 125°C. In the case of the bitumen emulsion, it varies from 50 to 70°C[15]. These binders are applied using a heat-insulated spreader with temperature indicators.

2.3.Delimitation of System Boundaries (SB)

This work is mainly focused on a "cradle to construction phase" life cycle assessment. **(Table 4)** and **(Table 6)** show the SB of the study: (F1) for the **CDA 0/12.5** and (F2) for the SCS /DCS. It should be noted that this work will exclude infrastructures and equipment in SB.

2.4.Life Cycle Inventory (LCI)

For this case study, apart from the specific literature, the SIMA PRO databases are mainly used. Note in passing that SIMA PRO is both an LCI and an impact quantification tool. These databases will be subject to adjustment factors to better align them as closely as possible with the contexts and circumstances of Madagascar. In SIMA PRO, the environmental databases or "processes" are organized in the form of "input-output". Inputs concern energy flows and material flows. The outputs are the emission streams and the waste streams. The "input and output" data inventories are always normalized per Functional Unit.

(**Table 2)** shows the different sources of LCI data used for this study. Likewise, (**Table 3)** provides information on the technical data useful and complementary to the LCI.

2.5.Life Cycle Impact Assessment (LCIA)

This step concerns the translation of LCI "input / output" database into impact indicator results. This is how SIMA PRO, based on the IMPACT 2002+ method, will convert and aggregate the values of the various GHG of the product system as equivalent emissions of carbon dioxide (CO_2eq). Also, using the previous method, SIMA Pro deducts the PEC balance sheet.

The impact quantification is displayed in two (02) levels:

- At the first level, we will quantify the impacts associated with each phase of the life cycle according to the mathematical models in **(formula 1)** and **(formula 2)**.

$$EG_j = \sum_k \sum_i \left(GHG_{jki} . GWP_i \right) \qquad \textbf{(1)}$$

Where:

EG_j : Emissions of greenhouse gases expressed as equivalent emissions of CO_2 of the life cycle phase j

GHG_{jki} : Emissions of greenhouse gases *i* per functional unit for a process *k* of the life cycle phase *j*

GWP_i : Global Warming Potential of greenhouse gases *i* compared to CO_2 over 100 years

$$PEC_j = \sum_k \sum_i EF_{jki} . CF_i \qquad \textbf{(2)}$$

Where:

PEC_j : Primary Energy Consumption for a phase of the life cycle j

EF_{jki} : Energy inflow i par functional unit into a process k of a phase of the life cycle j

CF_i : Characterization Factor in primary energy consumption of energy inflow i

- At the second level, we relate the impact assessments attached to the SB of the life cycle according to the (**formula 3)** and the (**formula 4)**.

$$EG = \sum_j EG_j \qquad \textbf{(3)}$$

Where:
EG : Emissions of greenhouse gases of the system boundaries

$$PEC = \sum_j PEC_j \qquad \textbf{(4)}$$

Where:
PEC : Primary Energy Consumption of the system boundaries

3- Results

3.1. Case of DCA 0/12.5

On the SB (F1), for the cold mix asphalt DCA 0/12.5 with the ECR60 binder noted (DCA 0/12.5, ECR), we conclude a GHG emission of 63.4 kgCO2eq/m3 and a PEC of 904MJ/m3. Similarly for DCA 0/12.5 with the cutback binder noted (DCA 0/12.5, cutback), a GHG emission of 109kgCO2eq/m3 and a PEC of 2440MJ/m3 are advanced. With regard to (DCA 0/12.5, ECR), the cold mix asphalt (DCA 0/12.5, cutback) has a surplus of GHG emissions up to 2 times and a PEC which rises up to 3 times.

The **(Table 5)** clarifies the GHG emissions and the PEC of each phase of the life cycle. With regard to (DCA 0/12.5; ECR), the binder production phase, the aggregate production phase followed by transport and the cold asphalt production phase have the most significant impact **(Table 5)**. According to the values displayed in **(Table 5)**, these four phases contribute respectively to 53.63%, 12.27%, 11.73%, and then 8.22% of total GHG emissions. Similarly, in terms of PEC, each of these four phases holds a share of 53.76%, 11.50%, 11.9% and then 8.22%.

For (DCA 0/12.5; cutback), the major contributor phases are the production of binders, the production of DCA, the production of aggregates and then transports. Each of them is responsible for 59.54%, 18.72%, 7.14%, and then 6.83 of total GHG emissions **(Table 5)**.
The "cutback" binder is both more GHG-emitting and more energy-intensive compared to the ECR. More precisely, the (DCA 0/12.5; cutback), experiences a surplus of GHG emissions of 71.92% and a PEC 2.7 times higher, compared to the (DCA 0/12.5; ECR).

The environmental life cycle impacts between (DCA 0/12.5; ECR60) and (DCA 0/12.5; cutback) are compared in **(Figure 1)**. The use of the "cutback 400/600" binder instead of ECR 60 puts the DCA in major environmental disadvantages. To this, we constant:

- an increase in GHG emissions of up to 91% and a PEC 3.7 times higher during the binder production phase
- a surplus of GHG emissions and PEC evaluated respectively by 2.91 and 3.9 times during the DCA production phase

3.2. Case of chip seal (CS)

(Table 6) provides the notations attached to each life cycle stage of the ES boundary (F2).

a. Case of SCS 4/6

(Table 7) records the impact assessment to SCS 4/6. Single chip seal SCS 4/6 with ECR binder (SCS 4/6; ECR), generates a GHG emission of 0.298 kgeqCO2/m² and a PEC of 4.28 MJ/m². The (SCS 4/6; cutback) emits 0.479 kgeqCO2/m² and a PEC of 11.6 MJ/m². By comparison, the (SCS 4/6; cutback) emits 1.6 times more GHG and requires 2.71 times more energy than (SCS 4/6; ECR). The most impactful phases are the production of binders, the production of aggregates and transports. In the case of (SCS 4/6; ECR), these three phases represent 61.07%, 20.07%, then 14.13% of GHG emissions. Likewise, for (SCS 4/6; cutback), these three phases hold the 72.44%, 12.48%, then 8.79% of total GHG emissions.

For (SCS 4/6; ECR), the production of ECR covers the 60.75% of the total PEC. This contribution increased from about 83.36% in the case of (SCS 4/6; cutback) **(Table 7)**.About this total PEC and for the production of aggregates this study report a contribution of 20.42% and 7.53% respectively with regard to (SCS 4/6; ECR) and (SCS 4/6; cutback). Road transport, in turn, accounts for 20.42% of PEC for the case of (SCS 4/6; ECR) and 7.53% for that of (SCS 4/6; cutback) **(Table 7)**.

b. Case of DCS 2/10

(Table 8) summarizes the life cycle impact assessments for the DCS 2/10. Roughly, the DCS 2/10 using the “ECR” binder (DCS 2/10; ECR), generates a GHG emission of 0.597 kgeqCO2/m² and a PEC of 8.62 MJ/m². At the same time, the (DCS 2/10; Cutback) records an emission of 0.89 kgeqCO2/m² and a PEC of 20.8 MJ/m².

Clearly, the binder production and the aggregate production are the most impactful. We conclude that:

- 51.76% of total GHG emissions and 51.16% of the total PEC of the (DCS 2/10; ECR) are provided by the binder production. The aggregate production phase includes 21.61% of GHG emissions and 21.93% of PEC
- For the (DCS 2/10; cutback), the binder production phase contributes 66.29% of GHG emissions and 78.85% of PEC. Moreover, the production of aggregates has a 14.49% share of the GHG emissions and a 9,09% share of CEP
- The (DCS 2/10; cutback) emits 1.5 times more GHGs and consumes 2.41 times more primary energy compared to the (DCS 2/10; ECR)
- Transport ranks third among the most impacted processes in the life cycle

International Journal of Engineering, Sciences and Technologies
ISSN : 3079-2045
https://www.ij-est.org/
Volume 2, issue 3,https://doi.org/10.70961/ZEFX8726

c. Case of DCS 4/14

(Table 9) displays the impact assesments for DCS 4/14. Overall, the DCS 4/14 technology with ECR binder, (DCS 4/10; ECR), emits 0.85 kgeqCO2/m² with a PEC of 12.3 MJ/m². For its part, the DCS 4/14 with cutback binder, (DCS 4/10; cutback), is ahead of (DCS 4/10; ECR), in terms of impact assessment. With regard to the latter, we display a GHG emission of 1.28 kgeqCO2/m² and a PEC of 30.2 MJ/m².

(Figure 2) shows in a comparative manner the GHG emissions at each stage of the CS life cycle according to the binders used.

The use of "cutback" instead of ECR60 only amplifies GHG emissions, especially in the binder production phase and in the construction phase.

By choosing as a reference scenario based on the use of the ECR emulsion, the following points are retained:

- In SCS 4/6 technology, the use of cutback leads to an amplification of GHG emissions up to 1.9 times and 2.69 times respectively during the binder production and construction phase
- Moreover, in DCS 2/10 technology, GHG emissions of 1.9 times and 1.3 times were observed for the case of (DCS 2/10; Cutback) during the binder production and construction phase
- In DCS 4/14 technology, the use of cutback increases GHG emissions by up to 1.9 times and 1.46 times respectively during the binder production and construction phase.

(Figure 3) compares each stage of the life cycle of the different CS technologies according to its respective PEC.

Compared to ECR 60, the use of cutback is more energy intensive in the CS technology, especially during the binder production phase and the construction phase. Precisely:

- In SCS 4/6 technology : up to 3.71 and 2.68 times higher during the binder production and the construction phase
- In DCS 2/10 technology : up to 3.71 and 1.32 times higher during the binder production and the construction phase
- In DCS 4/14 technology : up to 3.79 and 1.46 times higher during the binder production and the construction phase

4- Discussions

According to **COLAS France**[19], the cold mix asphalt technology has a GHG emission of 36 kgCO2eq/t and a PEC of 457 MJ/t, on SB going "from the cradle to the construction". To this, the cold asphalt plant requires a primary energy of 14MJ/t[19]. **COLAS France**[19], in its study, used ECR 60 whose inventory data were established by **EUROBITUME**[17]. Also on the same SB, according to **Jain S. and Singh B.** [14], their study about cold mix asphalt retained a GHG emission of 36.1 kgCO2eq/t for and a PEC of 454 MJ/t. These two literatures show contributions of 55% in GHG emissions and 68.7% in CEP linked to the production of the ECR60. The other items with significant impact are in the transport and production of aggregates.

On the Madagascar side, cold mix asphalt with ECR binder (CDA 0/12.5, ECR 60) combines a CEP of 847MJ/m3, or 385MJ/t, and a GHG emission of 59.7kgCO2eq/m3, or 27.14kgCO2eq/t. On this point, the most influential life cycle phases are the production of the emulsion (ECR60), the production of aggregates followed by transport. This ranking of the most impactful positions aligns with the case of **COLAS France**[19]. Despite the prior moderate heating process of the ECR60, this case of Madagascar nevertheless has 15.75% less GHG emissions and 24,61% less PEC compared to the case of **COLAS France**. Indeed, **EUROBITUME** inventory data[17]operated by **COLAS France** attribute a long transport distance for crude oil to then produce bitumen and then ECR60 on European territory.

Many studies on asphalt[10], [11], [14], [19]agree on the good environmental performance of cold mix technology. On this point, the Malagasy cold mix technology (CDA 0/12.5; ECR) is of the same view by minimizing of 56.19% energy consumption and by reducing of 47.05% the GHG emission to the detriment of the hot mix technology.

However, the Malagasy cold mix technology (CDA 0/12.5; cutback) has a primary energy of 2390MJ/m3, or 1086.36MJ/t and a GHG emission of 106kgCO2eq/m3, or 48.18kgCO2eq /t. This energy consumption factor of this asphalt technology classified as "cold" is "paradoxically" close, even higher than that of conventional hot mixes. Regarding the authors **Mazumder et al., 2016**[20] Malagasy cold mix (CDA 0/12.5; cutback) has a slight energy consumption difference of 0.6% compared to hot mixes. Not least, this Malagasy cold mix technology has an energy surplus of 59.75% compared to the energy consumption factor of hot mix asphalt according to **COLAS France**.[19]. In fact, at first glance, a primary energy of 291MJ/t is advanced from the Malagasy cutback CDA 0/12.5 plant, a value very close to the classic hot mix asphalt plant (between 70 and 100kWh). Consequently, the heating energy of the cutback binder (290MJ/t) makes it possible to justify this energy consumption. Indeed, according to Malagasy technology, the cutback should be heated to a temperature not exceeding 125°[21]. Moreover, the ultimate reason for this “paradox” of energy consumption in Malagasy (CDA 0/12.5; cutback) lies in the production of cutback, which is bitumen fluidized with kerosene (12.5% by volume). Note that kerosene, a crude oil refining product, is a volatile solvent. Therefore, the primary energy of the kerosene "material", according to the LCA concept, is the sum of the energy necessary for the extraction of its raw form, of the various energy means spent on refining and its distribution and then energy contained in its final form. Also, the primary energy of the bitumen "material" totals the energy necessary for the extraction of the crude oil then the various energy means expended to transform the crude oil into bitumen. In other words, for the cutback, primary energy includes energy in its final form which would be lost due to the volatility of kerosene. On the other hand, in the case of bitumen, the extracted crude oil does not lead to a depletion of fossil resources; this energy persists in the bitumen “material” which is not exploited here as being a fuel. In this case, according to the LCA concept, there is no question of counting in the heading of primary energy, the final form of energy contained in the bitumen material. Consequently, the primary energy consumption factor of bitumen (4900MJ/t) is far ahead of that of cutback (9670MJ/t). This energy consumption factor of the cutback, evaluated almost twice with respect to bitumen, leads to Malagasy **(CDA, cutback)**, which is very energy-intensive.

Comparatively, Malagasy cold technology using ECR shows good environmental performance compared to that using cutback, reducing energy consumption by 64.56% and GHG emissions by 74.40%. **Takamura and James, 2015**[15]support the low energy consumption and GHG emissions attributed to cold mix asphalt with the ECR60 binder than that of cutback 400/600 binder.

For the Malagasy CS technology, the most impacting parameters are the production of the binder (greater than 66.67%) and that of the aggregates (greater than 20.51%). Authors like **Wang and Gangaram, Torres-Machí et al., 2015**[18], [22]share the same opinions in relation to this case of Madagascar. The PEC and the more GHG-emitting aspect of a cold mix technology with cutback are also revealed in that of CS. On this point, many of the literatures[14], [15], [23]–[25]warn about the use of cutback in the CS technology, given its heavy environmental impacts. Particularly, for the case of Canada[23], the state establishes a code proposing standards and control measures aimed at environmental management at the location of the cutback. Moreover, this case of Madagascar also agrees with that of **Torres-Machí et al., 2015**[22], sharing the same opinion on the good environmental performance of the chip seal with ECR compared to other cold technologies.

However, according to **Wang and Gangaram**[18], the single chip seal (SCS, ECR) has a primary energy consumption of 15.94MJ/m². Also, for 1m² of this same product, these previous authors identify 0.00147kg of SOx, 0.00198 kg of NOx, 0.43 kg of CO2, 0.0015kg of CO, 2.066E-6 of kgN20 then 0.001 kg of CH4[18]. By aggregation in PRG100, we would have in this case a GHG emission of 0.44kgCO2eq/m². Obviously, the energy consumption and GHG emission factors of **Wang and Gangaram**[18]are respectively 4.31 times and 4.30 times higher than in the case of Madagascar. Indeed, **Wang and Gangaram**[18], according to their inventory, show a quantity of ECR binder 1.6 times greater than that of the Malagasy (ESM 4/6, ECR).

5- Conclusion

Even in very low mass quantities compared to aggregates, binders, more specifically their production, have a strong impact on the environment. The methods of heating the binders and maintaining the temperature of spreading the Malagasy cold mix asphalt product only amplify the heaviness of the impacts. Also, indisputably, the choice of an LCI database is very influential to the results of the LCA.

The choice of bitumen emulsion as the basic binder for a Malagasy cold mix responds well to the criteria of “energy sustainability”. However, the mechanical performance of cold mixes with ECR is often discussed and has sometimes been questioned. This constant thus guides Malagasy road engineers to focus on the optimization of techniques from cold mix asphalt using ECR, in order to compete well with hot mix asphalt in terms of mechanical aptitude. Thus, it is necessary to avoid, if possible, the use of cutback in the Malagasy road maintenance site. However, if we find ourselves in the inevitable face of the integration of cutback on the construction site, we must minimize the environmental impacts by using refined gas as heating fuel.

International Journal of Engineering, Sciences and Technologies
ISSN : 3079-2045
https://www.ij-est.org/
Volume 2, issue 3,https://doi.org/10.70961/ZEFX8726

In the end, we hope that this study on cold mix asphalt and chip seal will encourage Malagasy decision-makers to adopt a real policy to mitigate environmental impacts in the context of road maintenance work.

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International Journal of Engineering, Sciences and Technologies
ISSN : 3079-2045
https://www.ij-est.org/
Volume 2, issue 3,https://doi.org/10.70961/ZEFX8726

7- Tables

Table 1. Functional units

Cold hydrocarbon products	Symbol	Hydrocarbon binders	Functional Unit
Dense Cold Asphalt 0/12.5	DCA 0/12.5	Bitumen emulsion (ECR 60)	1m3
		Cutback 400/600	
Single Chip Seal	SCS	Bitumen emulsion (ECR 60)	1m²
		Cutback 400/600	
Double Chip Seal	DCS	Bitumen emulsion (ECR 60)	1m²
		Cutback 400/600	

Table 2. The different sources of LCI data

Life cycle process	Literatures / tool for LCI	Adjustment factor
Production of aggregates	SIMA PRO	Malagasy electric mix[26]
Bitumen production	SIMA PRO, Eurobitume[17]	Electric Mix United Arab Emirates (UAE)
Kerosene production	SIMA PRO	Electric Mix United Arab Emirates (UAE)
Production of the ECR emulsion	SIMA PRO, Eurobitume[17], **Marwa et al., 2020**[27]	-
Production of cutbacks400/600	SIMA PRO, Eurobitume[17]	-
Mixing DCA 0/12.5 with binder Cutback	**Redelius et al., 2016**[28]	Malagasy electric mix[26] Malagasy hydrocarbon import circuit[29]
Mixing DCA 0/12.5 with binder ECR60	**Redelius et al., 2016**[28]	Malagasy electric mix[26] Malagasy hydrocarbon import circuit[29]
Volatile Organic Compound Emission for Cutback 400/600	**Environment Canada, 2014**[23]	-
Implementation of DCA 0/12.5	**Peng et al., 2015**[30]	-
Implementation of SCS/DCS	**texas state department of highway** [25]	-

Table 3. The different sources of LCI data

Life cycle process / Material flows	Formulation	Calorific energy
ECR 60	Residual bitumen at 60% by mass and water at 40% by mass	-
Production of 400/600 cutbacks	12.5% by volume kerosene and 87.5% by volume bitumen	-
Heating the ECR60	-	100 Btu/Gal[25]
Cutback heater 400/600	-	400Btu/gal[25]
DCA 0/12.5	Residual bitumen at 5% by mass and aggregates at 95%	-
Spreading DCA		27 Btu/Gal[25]
Single chip seal 4/6 (SCS 4/6)	*Cut-back 400/600 /ECR: 1kg/m² * Gravel 4/6: 6l/m²[21]	-
Double Chip Seal 4/14 (DCS 4/14)	**1st layer** *cut-back 400/600 / ECR: 1.1kg/m² * Gravel 10/14: 10l/m²[21] **2nd layer** *cut-back / ECR: 400/600: 1.4kg/m² * Gravel 4/6: 8l/m²[21]	-
Double Chip Seal 2/10 (DCS 2/10)	**1st layer** *cut-back 400/600 / ECR: 0.8kg/m² * Gravel 10/14: 7l/m² **2nd layer** *cut-back / ECR: 400/600: 0.9kg/m² * Gravel 4/6: 6l/m²[21]	-
Spreading cutback 400/600 for DCS / SCS	-	0.1237MJ/l[25]
Spreading ECR60 for DCS / SCS	-	0.04MJ/l[25]

Table 4. The symbols attached to each stage of the life cycle / case of DCA 0/12.5

Life cycle stages	Meanings
(a)	The bedrock mining
(b)	Production of aggregates
(c)	Production of binders
(d)	Maritime transport of binders
(e)	Road transport of aggregates and binders to the asphalt plant
(f)	Production of asphalt in the plant
(g)	Transport of the asphalt to the construction site
(h)	Construction phase

Table 5. GHG emissions and PEC of each phase of the life cycle / case of DCA 0/12.5

Life cycle stages		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	Cumulative impact
GHG emissions (kgC02eq/m3)	(DCA 0/12.5; ECR)	0.708	7.78	34	5.84	6.05	5.21	1.39	2.36	63.4
	(DCA 0/12.5; cutback)	0.708	7.78	64.9	5.84	6.05	20.4	1.39	2.36	109
CEP (MJ/m3)	(DCA 0/12.5; ECR)	6.46	104	486	90.7	87.5	74.3	20.1	35.8	904
	(DCA 0/12.5; cutback)	6.46	104	1810	90.7	87.5	291	20.1	35.8	2440

Table 6. The notations attached to each life cycle stage of the CS system boundaries (F2)

Life cycle stages	Meanings
(a')	The bedrock mining
(b')	Production of aggregates
(c')	Production of binders
(d’)	Maritime transport of binders
(e')	Transport of binders and aggregates to the site
(f')	Construction phase

Table 7. Impact values / case of SCS 4/6

Life cycle stages		(a')	(b')	(c')	(d’)	(e')	(f')	Cumulative impact
GHG emissions (kgC02eq/m²)	(SCS 4/6; ECR)	0.00488	0.0598	0.182	0.0118	0.0303	0.00941	0.298
	(SCS 4/6; cutback)	0.00488	0.0598	0.347	0.0118	0.0303	0.0253	0.479
PEC (MJ/m²)	(SCS 4/6; ECR)	0.0445	0.874	2.6	0.183	0.438	0.143	4.28
	(SCS 4/6; cutback)	0.0445	0.874	9.67	0.183	0.438	0.384	11.6

Table 8. Impact Values / case of DCS 2/10

	Life cycle stages	(a')	(b')	(c')	(d’)	(e')	(f')	Cumulative impact
GHG emissions (kgC02eq/m²)	(DCS 2/10; ECR)	0.0106	0.129	0.309	0.0584	0.0532	0.0359	0.597
	(DCS 2/10; cutback)	0.0106	0.129	0.59	0.0584	0.0532	0.0475	0.89
PEC (MJ/m²)	(DCS 2/10; ECR)	0.0965	1.89	4.41	0.907	0.769	0.545	8.62
	(DCS 2/10; cutback)	0.0965	1.89	16.4	0.907	0.769	0.721	20.8

Table 9. Impact values / cases of DCS 4/14

	Life cycle stages	(a')	(b')	(c')	(d’)	(e')	(f')	Cumulative impact
GHG emissions (kgeqC02/m²)	(DCS 4/14; ECR)	0.0146	0.179	0.455	0.0859	0.0775	0.0381	0.85
	(DCS 4/14; cutback)	0.0146	0.179	0.868	0.0859	0.0775	0.0557	1.28
PEC (MJ/m²)	(DCS 4/14; ECR)	0.134	2.62	6.49	1.33	1.12	0.579	12.3
	(DCS 4/14; cutback)	0.134	2.62	24.2	1.33	1.12	0.845	30.2

International Journal of Engineering, Sciences and Technologies
ISSN : 3079-2045
https://www.ij-est.org/

Volume 2, issue 3,https://doi.org/10.70961/ZEFX8726

8- Figures

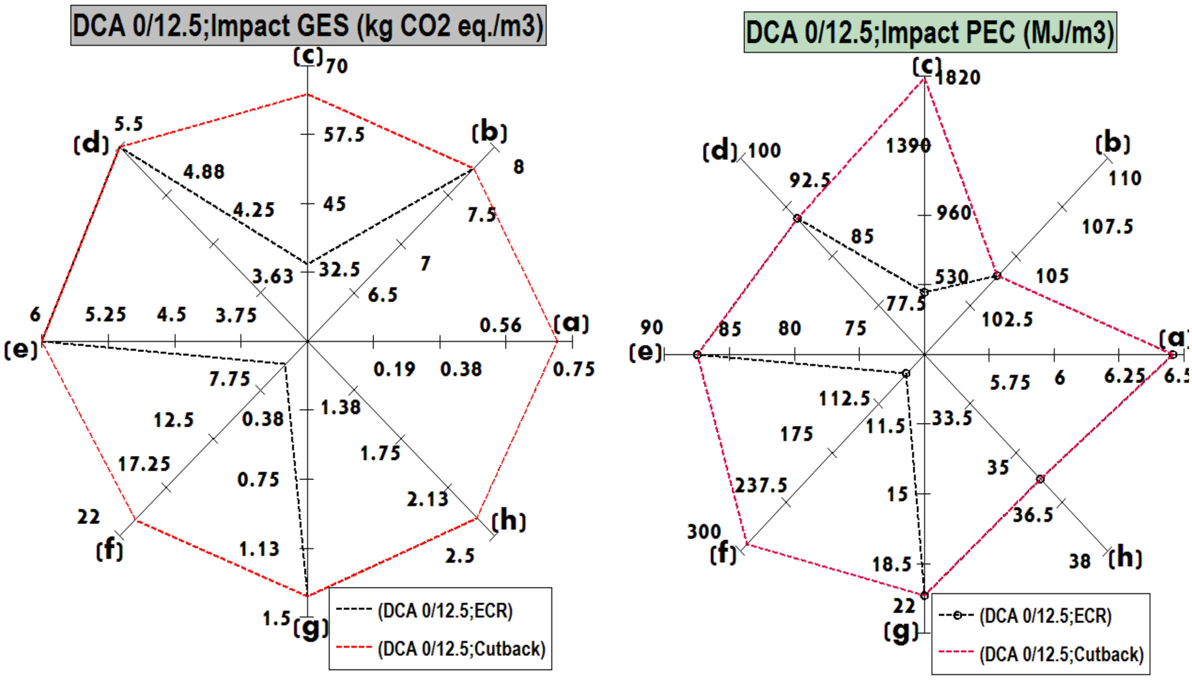

Figure 1. Comparisons of life cycle impacts between (DCA 0/12.5; ECR60) and (DCA 0/12.5; cutback)

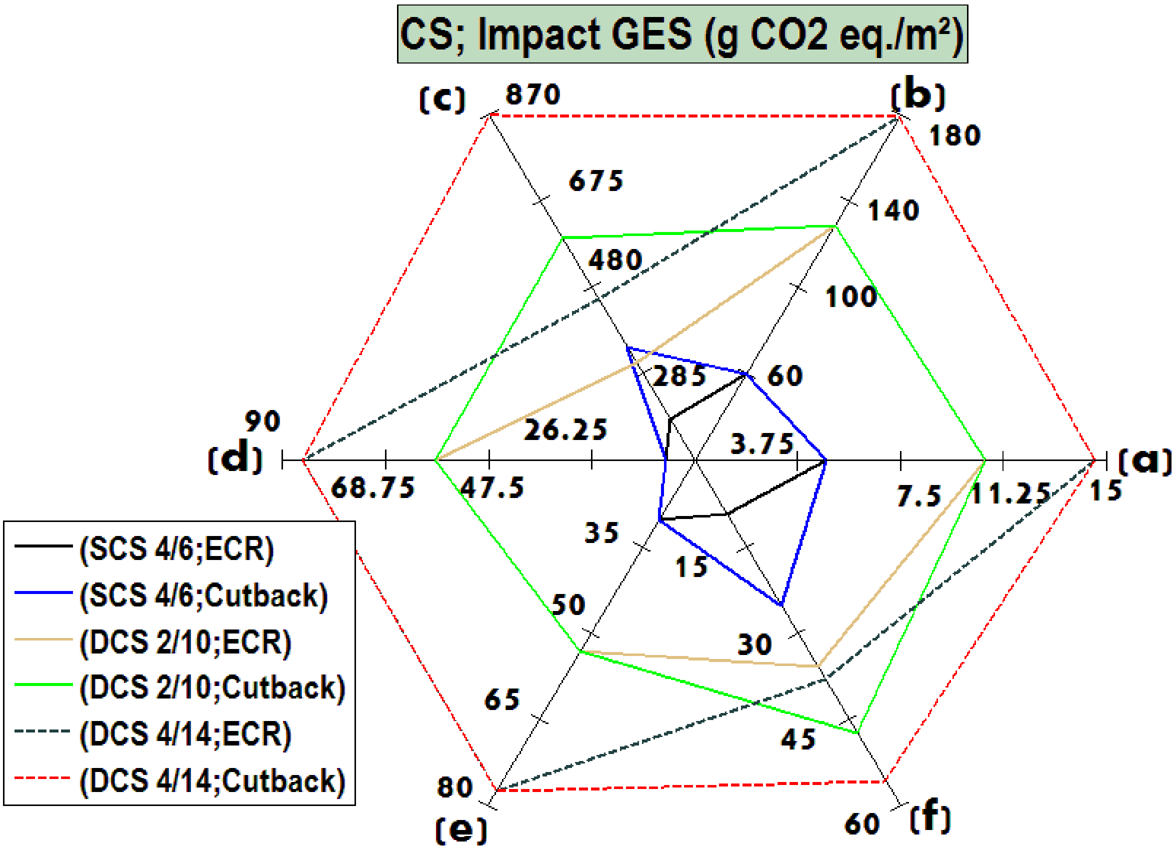

Figure 2. GHG emissions at each stage of the CS life cycle according to the binders used

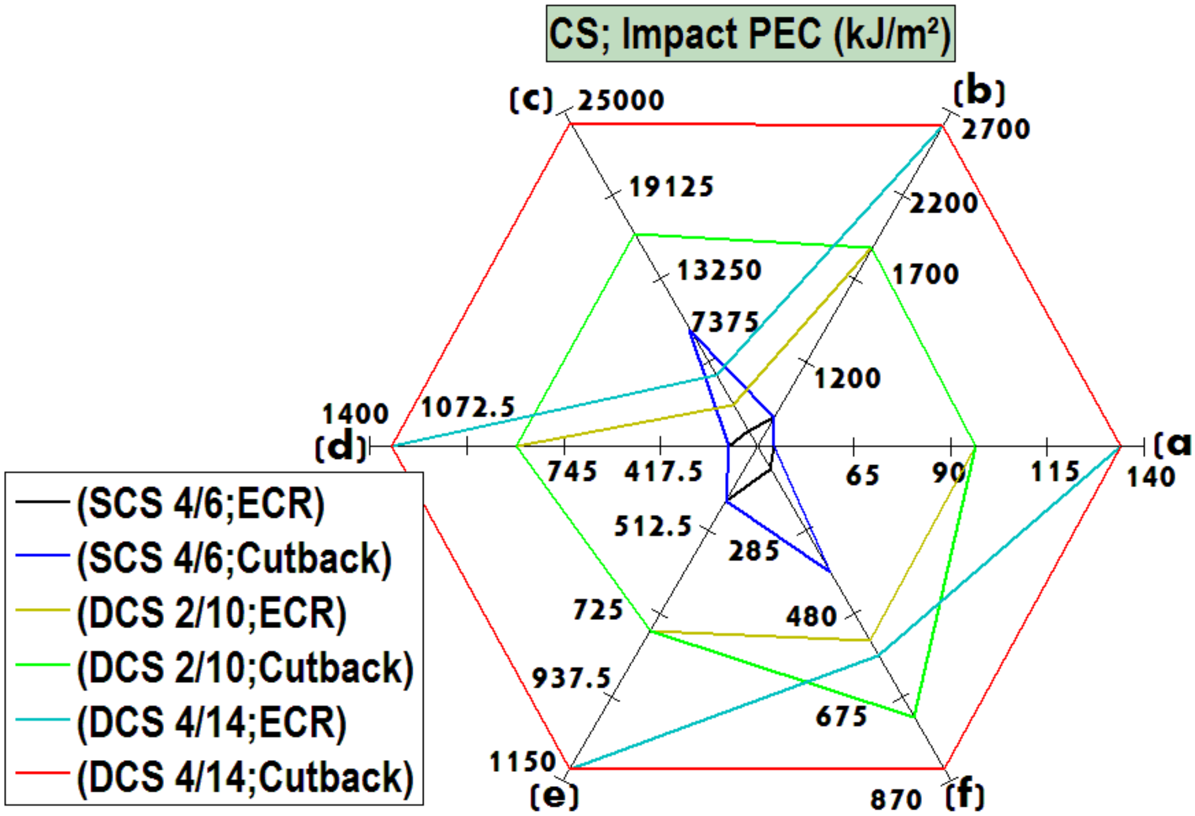

Figure 3. The PEC at each stage of the CS life cycle according to the binders used