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HOT MIX ASPHALT MALAGASY: ENERGY CONSUMPTION AND CARBON FOOTPRINT

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ABSTRACT

The field of Civil Engineering, the birthplace of the global economy, is one of the most energy-intensive and the most emissive in greenhouse gases (GHG). In Madagascar, a multitude of road projects are currently being considered. However, the environmental assessment is often carried out in a very superficial way and its results did not really reflect the severity of the impacts. This study focused on the calculation of carbon footprint and energy consumption of 1m^3 of each Hot Mix Asphalt (HMA) product mainly used in a Malagasy road construction. The environmental review used the methodological frameworks of the Life Cycle Assessment (ISO 14040-14044). In this case study, “the cradle to the HMA construction phase” approach is chosen. The Life Cycle Inventory (LCI) takes into account the technical and technological standards of the road engineering and then the geographical and energy contexts of Madagascar. Modeling and processing of LCI data will be conducted in the SIMA PRO tool, to be translated into impact categories. On the road-paving materials side, Semi-Coarse Hot Asphalt revealed a GHG emission and an energy consumption of 116kgCO2eq/m3 and 1720 MJ/m3 for class 0/10 then 119kgCO2eq/m3 and 1760MJ/ m3 for class 0/14. Similarly, the classic Dense Hot Asphalt 0/12.5 has a GHG emission of 116kgCO2eq/m3 and an energy consumption of 1710MJ/m3. On the road base material side, Grave-bitume 0/14 has a GHG emission of 105kgCO2eq/m3 and an energy consumption of 1550MJ/m3.

Keywords: Hot mix asphalt, bitumen, Life Cycle Assessment, Greenhouse Gas emission, energy consumption

1- Introduction

In Madagascar, the government is planning a multitude of road projects as a socio-economic recovery factor.

At the same time, the big island is making great strides towards the policy of sustainable development. Consequently, this Malagasy economic emergence coveted by road construction must thus cohabit with a minimization of the environmental impact[1]. This environmental mitigation policy is only possible if we are in perfect and real knowledge of the “values” of the environmental impacts. Despite this, the environmental assessment of a Malagasy road project, conforming to applicable law, is based on the "archaic" methodology of Environmental Impact Studies (EIA)[2]. According to **A. Jullien and Al.**[3], the environmental assessment in accord with the EIA method, advocates results “without quantifications” far from being scientifically interpretable to avert climate imminent damage.

Particularly, in France, like so many other countries, the current law resulting from the "Grenelle Environment Forum" imposed a quantified assessment in terms of carbon footprint and embodied energy emanating from each project[3]. From now on, this process of “quantification” of impacts is a fundamental process of an environmental assessment. Since then, this study is focused on the establishment of greenhouse gas (GHG) emission and energy consumption (EC) factors for Malagasy Hot Mix Asphalt (HMA). For these purposes, this work used Life Cycle Assessment (LCA) standards and guidelines. Traditional HMA are key materials in the context of a Malagasy road project, obtained by drying and heating in first step the aggregates and after combining them with bitumen in a hot mixing plant.

In this LCA, as impacts category, we are interested in Global Warming Potential over 100 years of GHG (GWP 100) and in terms of depletion of primary energy resources. This choice is in perfect harmony with the critical global situations in terms of climate change and the depletion of energy resources[4], [5]. Moreover, according to **Milad et al., 2022**[6]27% of global GHG emissions are attributed to the transport sector, 72% of which are allocated to road construction, rehabilitation and use. Moreover, in the year 2007, **Androjić et al., 2020**[7]point out that nearly 0.28% of oil reserves are being depleted in favor of global HMA production. The same author[7]estimates that in 2030, this energy demand stimulated by the need for HMA will see a 50% increase, an alarming situation for the global energy context. For example, only in India and on a daily average, 27.4 km of roadways are paved with asphalt, between the 2019 and 2020 periods[8].

The knowledge of these emission and energy consumption factors is very helpful for achieving a LCA of road projects in Malagasy contexts. At this stage, we can put forward more objective interpretations in the impact assessment and why not, establish a sustainable road construction policy specifically for Madagascar.

2- Methodology

2.1. Life Cycle Assessment (LCA)

LCA is an environmental assessment method whose methodological frameworks are governed by ISO 14040 to 14044 standards[9]–[14]. This method consists of four steps including:

- Goal and scope definition
- Life Cycle Inventory (LCI)
- Impact assessment
- Interpretation

According to **Mazumder et al., 2016**[15], LCA is perfectly compatible for assessing the environmental impacts of bituminous mixes.

2.2. Goal and scope definition

This study focused on the evaluation of Greenhouse Gas (GHG) emissions and Primary Energy Consumption (CEP) of Malagasy Hot Mix Asphalt (HMA), namely:

- Semi Coarse Hot Asphalt 0/10 (SCHA 0/10)
- Semi Coarse Hot Asphalt 0/14 (SCHA 0/14)
- Dense Hot Asphalt 0/12.5 (DHA 0/12.5)
- Grave Bitume 0/14 (GB 0/14)

SCHA and DHA are road surfacing products intended for modest traffic. These materials experience two-step heating processes. First, the aggregates are heated and then dried to eliminate as much moisture as possible. Secondly, the aggregates and the bituminous binder are hot-mixed at around 170°C. Unlike a Semi Coarse Mix, a Dense Mix has a low void ratio with respect to its granular skeleton.

The Functional Unit (FU) corresponds to 1m^3 of each HMA product.

The system boundary in this LCA extends “from cradle to the construction phase”. Infrastructure and Equipment (machinery, power plants, material depots, etc.) are excluded from the study.

2.3. The Life Cycle Inventory (LCI)

a- The emission and extraction inventory data

As recommended by **Jiang and Wu, 2019**[16], the emission and extraction inventory data can be drawn from the literature dealing with a common aspect of the product system, if adjustment factors (geographical criteria, energetic criteria, others..) could be put.

These inventory data drawn from the literature are qualified as secondary data[16]. By the way, **Jiang and Wu, 2019**[16] argue that the method of collecting data from the literature was the most practical in LCI.

(Table 1) provides information on the secondary data used in this study.

b- Formulation of HMA

The formulation of the materials, in mass percentage, is based on the French AFNOR standardizations **(Table 2)**. The aggregates follow a well-balanced proportion conforming to the grading envelopes of HMA. For instance, we can have dense, coarse or semi-coarse HMA[17]. In Madagascar context, dense mixes and semi-coarse HMA are generally used[18]. The bitumen content of these mixes is around 3 to 5.5%[14], [16], [17]. In other words, aggregates dominate up to 95% of the mass of HMA[6].

c- Transportation

(Table 3) provides information on the maritime and road distances involved in the life cycle processes of Malagasy HMA.

2.4. Impact assessment

According to **Jiang and Wu, 2019**[16], SIMA PRO is widely used for the environmental assessment of road surfaces. In addition to this main functionality, this software also allows the storage of LCI databases of a product or a process.

In addition, SIMA PRO is an environmental certification tool recognized by European industries working in road hydrocarbon products.[16]. Not least, this tool includes several methods of impact or damage assessments. Among others, we will use the one called “IMPACT 2002 V2.13”, which is one of the “impact-oriented” evaluation methods of SIMA PRO. In addition to Greenhouse Gas (GHG) emissions and Primary Energy Consumption (PEC), this method allows the evaluation of a multitude of impact possibilities.

SIMAPRO translates the LCI into the value of impact indicators, according to the following formulas:

On the one hand for the case of GHG emissions:

$$AGHG_{ps} = \sum_{l} GHG_{psl} \times GWP_{l} \qquad (1)$$

Where:

$AGHG_{ps}$: Aggregated GHG emissions in "CO2 equivalent", generated by the process (p) that is an element of life cycle stage s

GWP_{l} : GHG (l) emissions that have a Global Warming Potential over 100 years PRG_{l} output of the process (p) element of life cycle stage s

Afterwards,

$$IGHG_{s} = \sum_{p} AGHG_{ps} \qquad (2)$$

Where:

$IGHG_{s}$: GHG emissions balance of the entire processes in the life cycle stage s

Likewise,

$$IGHG_{(SB)} = \sum_{(S)} IGHG_{(SB)(S)} \qquad (3)$$

Where:

$IGHG_{(SB)}$: Sum of GHG emissions throughout the system boundary (SB)

On the other hand,

$$IPEC_{p(s)} = E_{R_{P(s)}} + E_{D_{P(s)}} + E_{f_{P(s)}} \tag{4}$$

Where:

$IPEC_{p(s)}$: Primary energy of a process (p) element of life cycle stage s

$E_{R_{Ps}}$: Refining energy that turn primary energy into final energy, for a process (p) element of life cycle stage s

$E_{D_{P(s)}}$: Distribution energy of a final energy form, entering into a process (p) element of life cycle stage s

$E_{Du_{P(s)}}$: Final energy form of a product χ generated by the process (p) element of life cycle stage s, as such manner that:

$$E_{Du_{P(s)}} \begin{cases} 0 \textbf{ if } \chi \textbf{ is a combustible} \\ > 0 \textbf{ for other case} \end{cases} \tag{5}$$

Then:

$$IPEC_s = \sum_p IPE_{pS} \tag{6}$$

Where:

$IPEC_s$: PEC of each life cycle stage (s)

And finally:

$$IPEC_{(F)} = \sum_{(s)} ICEP_{(s)(F)} \tag{7}$$

Where:

$IPEC_{(F)}$: Balance sheet of the PEC throughout the system boundary (F)

3- Results

The results will relate to the following life cycle stages *(s)*:

- Step E1: bedrock mining
- Step E2: production of aggregates
- Step E3: bitumen production
- Step E4: maritime transport when importing bitumen
- Step E5: road transport of the system {bitumen, aggregates} to the mixing plant
- Step E6: production of hot mixes
- Step E7: road transport of hot mix asphalt to the site
- Step E8: construction phase

3.1. Greenhouse Gas (GHG) Emission

(Table 4) provides the calculated GHG emissions for each phase of the life cycle.

On a SB going "from the cradle to the construction", we retain the GHG emissions of the following HMA:

- 116 kgCO2eq/m3 of GHG for SCHA 0/10
- 119 kgCO2eq/m3 of GHG for SCHA 0/14
- 116 kgCO2eq/m3 of GHG for DHA 0/12.5
- 105 kgCO2eq/m3 of GHG for GB 0/14

Also in this context, the emission related to the production of bitumen is spread over values between 24 and 35 kgCO2eq per m3 of HMA. In addition, there is an average emission of 62.75 kgCO2eq /m3 for the production of HMA. In other words, the production of HMA is at least 1.8 times the production of bitumen.

The production of aggregates shows an average GHG emission of 7.97 kgCO2eq/m3.

Maritime import of bitumen emits an average of 3.95kgCO2eq for 1m3 of HMA. The road transport of the system {aggregates, bitumen} to the HMA plant has an average emission of 4.79 kgCO2eq/m3. The transport of HMA to the construction site results in GHG emissions of 1.42 kgeqCO2/m3. In sum, transport processes cause emissions of 10.17 kgCO2eq/m3 where 61.14% comes from road transport.

(Figure 1) highlights the contribution of each life cycle stage during the production of HMA.

Like the other stages of the life cycle, the HMA production in plant is the most emissive in GHG, posting a contribution of 55.17%. Bitumen production, representing nearly 26.11% of emissions, is in second place in terms of the most GHG-emitting processes. By accumulating nearly 8.91% of emissions, transport (maritime and road) come in third place. We note that 61.23% of these transport emissions are mainly due to road transport. The production of aggregates contributes an average of 7.01% of emissions and ranks fourth among the most GHG-emitting items.

The extraction of bedrocks shows a contribution in GHG emissions of less than 1%. The construction stage, for its part, contributes on average to 1.86% of GHG emissions.

3.2. **Primary Energy Consumption** (PEC)

(Table 5) provides information on the cumulative PEC of HMA on the system boundary and the PEC in each phase of the life cycle.

For 1m3 of each Malagasy HMA product, this study deduces:

- A PEC of 1720 MJ with respect to SCHA 0/10
- A PEC of 1760 MJ with respect to SCHA 0/14
- A PEC of 1710 MJ with respect to DHA 0/12.5
- A PEC of 1550 MJ with respect to GB 0/14

A PEC, on average, of 1730MJ/m3 is thus displayed with regard to the HMA of the Malagasy road-paving materials.

The production of HMA in a hot mix plant ensures, on average, a PEC of 965.25MJ/m3. Also, the production of bitumen to make 1m3 of asphalt requires an average PEC of 421 MJ. Thus, to produce hot mix asphalt, the hot mix process is at least twice as energy intensive as compared to the production of bitumen. Thus, approximately, a PEC of 151.35MJ is attributed for the various transports involved in the production of 1m3 of HMA. In view of this previous energy consumption, 59.45% goes to road transport. The production of aggregates involved in the production of 1m3 of HMA requires an average PEC of 108.5MJ.

(Figure 2) illustrates a contribution analysis, in PEC, during the production of HMA.

On average, by 57.42% of the primary energy balances are caused by the hot mix processes. Bitumen production includes, on average, 24.91% of CEP balance. The hot mix asphalt plant and the production of bitumen, being all like the two most energy-intensive phases, alone accumulate nearly 82.32% of the CEP in SB. The third most energy-intensive phases are transport process, contributing an average of 8.96% of CEP balances. Of this previous energy figure, 59.53% is allocated to road transport. The production of aggregates, to which 6.46% of the CEP balances were attributed, was the fourth most energy-intensive process. The acquisition of the bedrocks and the construction phase are the lower energy consumption processes.

4- Discussions

First and foremost, this case of LCA carried out on the Malagasy road hydrocarbon concretes evokes the large PEC of the production of HMA. Admittedly, in this study, the contributions in calorific energy of the hot mix plant powered by the heavy fuel oil and diesel are respectively 8.45% and 36.4% of the total PEC. Obviously, to produce 1 ton of asphalt in this hot mix plant, **COLAS MADAGASCAR** advances a calorific energy requirement of 63.72 kWh in heavy fuel oil coupled with 12.09 kWh of diesel and 3 kWh of operating electricity[21]. This calorific energy requirement correlates with the statement of **Androjić et al., 2020**[7], which estimates a value between 70 to 100kWh. Among others, **Androjić et al., 2020,Thives and Ghisi, 2017**[7], [17]emphasized that this calorific energy expenditure is largely dependent on the initial moisture of the aggregates. At the same time, **Thives and Ghisi, 2017**[17]advanced a calorific energy of 300,000Btu, or 87.93kWh to dry and heat 1t of aggregates. According to IVL, the calorific energy inventory of a hot mix asphalt plant in Switzerland puts forward a need of 79.23kWh/t[22].

In addition to this, according to **Milad et al., 2022**[6], this famous hot mix process was ahead of the transport and construction phases, in terms of energy consumption, which again coincides with the results put forward in this study.

However, the PEC factors differ from the heating fuels used and even from the energy sources exploited for their refining[6]. **Milad et al., 2022**[6] make, for example, a comparative analysis between the different fuels used as a heat source for an asphalt plant.

Precisely, the case of Madagascar mentioned in this study, advanced a PEC factor on average of 1730 MJ/m3, for 786.36 MJ/t for HMA used as pavement material and 1550MJ/ m3 or 704.54 MJ/t for GB 0/14. According to **COLAS France**[23], on the same System Boundary (SB) as this study, the PEC needs are estimated at 680 MJ/t and 591 MJ/t, respectively for the HMA road pavement and for the GB. On average, the PEC of this Malagasy case of HMA plant has found 14.82% less favor than the COLAS case.

It should be noted that **COLAS France**, at the HMA plant, looked into the IVL input energy flows[23]. These LCI data are very close to those of Madagascar. However, these primary energies displaying a difference of 14.82% on both sides of the two countries **(table 5)**, are due to the upstream refining energies of the HMA plant fuels. On the IVL side, crude oil refining used hydroelectricity[23], to the detriment of an electricity mix based on natural gas from the United Arab Emirates (UAE), a place of importation of Malagasy petroleum products[24]. Consequently, on the side of COLAS Madagascar and according to the (**formula 5)**, his PEC is very close to his final calorific energy. On the other hand, the use of UAE electricity mix to produce the diesels for heating in the Malagasy HMA plant gives a primary energy requirement at least 1.15 times higher compared to the IVL bases. No less, on a system boundary “from cradle to construction” **Mazumder et al., 2016**[15]put forward an energy consumption factor for hot mix asphalt at 1079.62MJ/t, almost 1.4 times higher than in this study and 1.7 times that of COLAS France. These authors[15]attribute 730.5MJ/t of total primary energy to the HMA plant, of which 424.745MJ/t is primary energy for petroleum refining. No doubt, **Mazumder et al., 2016**[15], integrate a large part of the fossil sources dedicated to crude oil refining energy of the final energy form used for the operation and for heating of the HMA plant. At the same time, **Khan et al.** [25]maintain that the electrical mix involved in the product system is a very determining factor in its environmental assessment.

In this way, **Chowdhury et al., 2010**[26]insist on the need for upstream energy studies (operating energy of refining equipment, etc.) of any form of final energy that can be used for the production of road construction materials. By the way, **Jiang and Wu, 2019**[16]argue that the different sources of road LCI data lead to different results for the same product.

Furthermore, **Huang et al., 2009**[27] placed bitumen production at 23% of total PEC, succeeding the HMA plant operation. This ranking order equals this case study for Madagascar. Similarly, according to **COLAS France**[23], the analysis "from the cradle to the construction" of HMA concludes a high energy consumption, with regard to the mixing plant and the bitumen which are positioned, respectively, in first and second place. Nevertheless, **Landi et al.**[28]argue that the production of bitumen is much more energy-intensive compared to the hot mix plant. This inversion of classification is justified by their choice to start their study on a system boundary going "from the cradle to the maintenances"[28]. Also, **Gulotta, 2019**[29]advance the energy of bitumen and this time, on a system boundary going "from the cradle to the end of life".

On the transport of materials side, their dominance in terms of energy impact depends entirely on the distance[17]. In this Malagasy case study, the values of the established distances put road transport in third place among the most energy-intensive processes.

As for GHG emissions, a study from "cradle to construction" by Colas France[23]and that of **Mazumder et al., 2016**[15]respectively cover a GHG emission of 54 kg eq CO2/t and 51.26 kgCO2 eq /t for HMA productions[23]. These emission values are very similar to this study for Madagascar (122.67 kgCO2 eq / m3). As for GB, on the same system boundary, **Colas France**[23]estimated an emission of 47 kg eq CO2/m3, a value which is also very close to the present study (109 kg eq CO2/t).

It is also undeniable that several authors such as **Jullien et al., 2014Milad et al., 2022Androjić et al., 2020, Mazumder et al., 2016, Thives and Ghisi, 2017**[3], [6], [7], [15], [17]agree on the high greenhouse gas emissivity of the HMA plant. The case of Madagascar is unanimous with these authors where a contribution of GHG emissions ranging from 55.17% of the life cycle was endorsed only by the HMA process.

Worse still, the analysis by **Peng et al., 2015**[30]show a contribution figure of 90% allocated only to the HMA plant. This extreme and isolated case of **Peng et al., 2015**[30]does not include the bitumen production phase among the life cycle processes and this justifies their strong contribution to the HMA plant operation.

Besides that, according to **Milad et al., 2022**[6], on a system boundary "from cradle to construction", the production of bitumen and HMA are the most significant in terms of GHG emissions, respectively 43.18% and 54.01% . According to the same authors, the transport processes of road transport and construction represent 1.35% and 1.47% of GHG emissions.

These clarifications from **Milad et al., 2022**[6], coincide with this case study for Madagascar. Also, **Gulotta, 2019**[29]analyze the impacts of the five pavement surfacing scenarios on a border going "from cradle to end of life" and also put forward a GHG contribution not exceeding 1% for their initial construction.

5- Conclusion

This study guides the actors of a Malagasy road project towards a good vision of sustainable development. Nowadays, Malagasy laws imposed the Environmental Impact Assessments (EIA) processes in each road projects that will lead to the acquisition of an environmental permit. Also, each time an EIA is carried out, there is always an Environmental and Social Management Plan, but this does not really relate the correct approach to targeting the sources and the severity of the impacts, no less than more, concrete mitigation measures. A road construction site is a positive spin-off factor for socio-economic development. For this study, the assurance of environmental impact mitigation measures, another pillar of sustainable development, was thwarted by the use of bitumen and the hot mix plant operation.

In the short term, decision-makers can be guided on the choice of heating fuel for a Malagasy asphalt plant. The form of energy used in the hot mix asphalt plant greatly influences its primary energy consumption and its GHG emissions. Authors like **Milad et al., 2022**[6]well support the use of refined gas for heating the asphalt plant could reduce the emission of GHG and the PEC of the asphalt. Also, according to the same authors, the use of gasoline instead of High Fuel Oil makes it possible to reduce this PEC[6].

This case study for Madagascar also shows that the refining energy upstream of the heat source of an asphalt plant contributes a lot to the HMA primary energies. By using the same type of fuel, more precisely diesel at the asphalt heating station, this case of Madagascar and that of COLAS France conclude that there are different PEC factors. On both sides, according to each energy inventory database for the refining of crude oil and diesel, COLAS France mentions hydroelectricity and that of Madagascar advances the electricity mix of the UAE which is far from being renewable.

In the long term, innovative research projects in road engineering must be promoted in Madagascar. It is interesting, for example, to reduce the bitumen content by adding a polymer additive to an asphalt mix, and to focus more on a formulation with a better compromise between mechanical performance and environmental performance. Also, biomass and solar thermal sources could be sustainable energy alternatives for operating an HMA plant.

6- Acknoweledgments

7- References

[1] Oanh, T. T. K.; Quoc, N. T.; Dieu, P. T. N. *Int. J. Energy Environ. Econ. 2020, vol28, 87-101*.

[2] MEDD. (2004). "Décret n° 99-954 du 15 décembre 1999 modifié par le décret n° 2004-167 du 03 février 2004 relatif à la Mise en Compatibilité des Investissements avec l'Environnement". https://www.pnae.mg/evaluation.html.

[3] Jullien, A.; Dauvergne, M.; Cerezo, V. « Environmental assessment of road construction and maintenance policies using LCA », *Transp. Res. Part Transp. Environ.*, vol. 29, p. 56‑65, juin 2014, doi: 10.1016/j.trd.2014.03.006.

[4] Siddik, M. A.; Islam, M. T.; Zamana, A. K. *Int. J. Energy Environ. Econ. 2020, vol28, 103-118*.

[5] Guliyeva, A.; Rzayeva, U.; Guliyeva, G. *Int. J. Energy Environ. Econ. 2018, vol26, 97-114*.

[6] Milad, A. « A Comparative Review of Hot and Warm Mix Asphalt Technologies from Environmental and Economic Perspectives: Towards a Sustainable Asphalt Pavement », *Int. J. Environ. Res. Public. Health*, vol. 19, nº 22, p. 14863, nov. 2022, doi: 10.3390/ijerph192214863.

[7] Androjić, I.; Alduk, Z. D.; Dimter, S.; Rukavina, T. « Analysis of impact of aggregate moisture content on energy demand during the production of hot mix asphalt (HMA) », *J. Clean. Prod.*, vol. 244, p. 118868, janv. 2020, doi: 10.1016/j.jclepro.2019.118868.

[8] Jain, S.; Singh, B. « Cold Mix Asphalt: An Overview », doi: https://doi.org/10.1016/j.jclepro.2020.124378.

[9] ISO. (1997). «ISO 14040 : Management environnemental – Analyse de Cycle de Vie – Principes et cadre ». https://www.iso.org/obp/ui/fr/#iso:std:iso:14040:ed-2:v1:fr.

[10] ISO. (1998). « ISO 14041 : Management environnemental – Analyse de Cycle de Vie – Définition de l'objectif et du champ d'étude et analyse de l'inventaire ». http://stockage.univ-valenciennes.fr [11] ISO, « ISO 14042 : Management environnemental – Analyse de Cycle de Vie – Évaluation d'impact du cycle de vie ». 2000.

[12] ISO. (2000). « ISO 14043 : Management environnemental – Analyse de Cycle de Vie – Interprétation ». http://stockage.univ-valenciennes.fr.

[13] ISO. (2006). « ISO 14040:2006a Environmental management – Life cycle assessment – Principles and framework ». http://stockage.univ-valenciennes.fr.

[14] ISO. (2006). « ISO 14044:2006b Environmental management – Life cycle assessment – Requirements and guidelines ». http://stockage.univ-valenciennes.fr.

[15] Mazumder, M.; Sriraman, V.; Kim, H. H. ; Lee, S.J. « Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA) », *Int. J. Pavement Res. Technol.*, vol. 9, nº 3, p. 190‑201, mai 2016, doi: 10.1016/j.ijprt.2016.06.001.

[16] Jiang, R.P.; Wu. « Estimation of environmental impacts of roads through life cycle assessment: A critical review and future directions », *Transp. Res. Part Transp. Environ.*, vol. 77, p. 148‑163, déc. 2019, doi: 10.1016/j.trd.2019.10.010.

[17 Thives, L. P.; Ghisi, E. « Asphalt mixtures emission and energy consumption: A review », *Renew. Sustain. Energy Rev.*, vol. 72, p. 473‑484, mai 2017, doi: 10.1016/j.rser.2017.01.087.

[18] MTPT, « Banque de données routières malgaches », 2004.

[19] AFNOR, « Norme française NF P 98-130, revêtement de chaussées, Bétons Bitumineux Semi-Grenus (BBSG), Définition – Composition – Classification »; Normes nationales et documents normatifs nationaux; Edition AFNOR : Paris, 1998, pp: 1-12.

[20] AFNOR, « Norme française NF P 98-138-assises de chaussées-Graves bitumes-Définition – Composition – Classification »; Normes nationales et documents normatifs nationaux; Edition AFNOR : Paris, 2000, pp : 1-11.

[21] Sitraka H. R. (2014). « Bilan énergétique et recherche d'économie d'énergie sur le poste d'enrobage du site industriel RN7-PK 13 de COLAS Madagascar ». http://biblio.univ-antananarivo.mg/pdfs/ranaivoSitrakaH_ESPA_ING_14.pdf.

[22] Hakan, S. (2001). « Life cycle assessment of road: a pilot study for inventory analysis ». https://www.ivl.se/download/18.34244ba71728fcb3f3f57f/1591704221839/B1210E.pdf

[23] Chappat, M. ; Bilal J. (2003). « La route écologique du future-Analyse du cycle de vie-Consommation d'énergie et émission de gaz à effet de serre », COLAS, sept. 2003.

[24] OMH (2021), « Bulletin pétrolier ». http://www.omh.mg/index.php?CL=loadpdf&entete=Marche-petrolier-au-4trim-trimestre-2021.pdf&file2=bulletinpetrolier/2021/Marche-petrolier-au-4trim-trimestre-2021.pdf.

[25] « DETERMINANTS OF CARBON EMISSION, ENVIRONMENTAL KUZNETS CURVE HYPOTHESIS: AN EMPIRICAL EVIDENCE FROM INDIA ».

[26] Chowdhury, R.; Apul, D.; Fry, T. « A life cycle based environmental impacts assessment of construction materials used in road construction », *Resour. Conserv. Recycl.*, vol. 54, n° 4, p. 250‑255, févr. 2010, doi: 10.1016/j.resconrec.2009.08.007.

[27] Huang, Y.; Bird, R.; Heidrich, O. « Development of a life cycle assessment tool for construction and maintenance of asphalt pavements », *J. Clean. Prod.*, vol. 17, n° 2, p. 283‑296, janv. 2009, doi: 10.1016/j.jclepro.2008.06.005.

[28] Landi, D. « Comparative life cycle assessment of standard, cellulose-reinforced and end of life tires fiber-reinforced hot mix asphalt mixtures ».

[29] Gulotta, T. M. « A life cycle scenario analysis of different pavement technologies for urban roads », *Sci. Total Environ.*, 2019.

[30] Peng, B.; Cai, C.; Yin, G. ; Li, W. ; Zhan, Y. « Evaluation system for CO2 emission of hot asphalt mixture », *J. Traffic Transp. Eng. Engl. Ed.*, vol. 2, n° 2, p. 116‑124, avr. 2015, doi: 10.1016/j.jtte.2015.02.005.

[31] JIRAMA (2018). « Statistiques de production électrique ». http://www.ore.mg/Publication/Rapports/RapportAct2018.pdf.

8- Tables

Table 1. LCI secondary data sources and adjustment factors

	Input flow (materials and energies)	Output flow (air emissions)	Adjustment factors
Extraction Source rock	SIMA PRO	SIMA PRO	Malagasy hydrocarbon supply circuit[24]
Aggregate production	SIMA PRO	SIMA PRO	Electric mix of the RIA (Interconnected Networks of Antananarivo)[31]
Crushing sand production	SIMA PRO	SIMA PRO	RIA Electric Mix[31]
Production Filler	SIMA PRO	SIMA PRO	RIA Electric Mix[31]
Bitumen production	SIMA PRO	SIMA PRO	-Electric mix from United Arab Emirates - allocation rule between co-products
Hot mix asphalt plant	**Sitraka H., 2014**[21]	**Thives and Ghisi, 2017**[17]	Malagasy hydrocarbon supply circuit[24] RIA Electric Mix[31]
Truck transport	SIMA PRO	SIMA PRO	Malagasy hydrocarbon supply circuit[24]
Maritime transport	SIMA PRO	SIMA PRO	Malagasy hydrocarbon supply circuit[24]
Stationary transport	SIMA PRO	SIMA PRO	Malagasy hydrocarbon supply circuit[24]
Construction phase	**Peng et al., 2015**[30]	SIMA PRO	Malagasy hydrocarbon supply circuit[24]

Table 2. HMA Formulation

Mass percentages of materials (%), coated density = 2.2					
HMA	Fillers (%)	Crushing sand (%)	Gravel (%)	Bitumen (%)	Sources
BBSG 0/10	7.1	20.85	66.7	5.35	NF P 98-130[19]
BBSG 0/14	-	37.9	56.95	5.15	NF P 98-130[19]
EDC 0/12.5	4.75	45.1	45.15	5	NF P 98-130[19] *percent voids less than 10%
GB 0/14	-	6.24	89.76	4	NF P 98-138[20]

Table 3. Typologies of transport and distance

Stage	Distance (km)	Typologies of transport	Materials
Step E4	5783	Maritime	Bitumen
Step E5	5	Road	Aggregates, Bitumen
Step E7	5	Road	HMA

Table 4. GHG emissions from HMA

HMA	GHG emissions by life cycle phase (kgeqCO2/m3)								Cumulative impacts (kgeqCO2/m3)
	Step E1	Step E2	Stage E3	Step E4	Step E5	Step E6	Step E7	Step E8	
BBSG 0/10	0.722	7.84	30	4.13	6.77	62.4	1.41	2.36	116
BBSG 0/14	0.717	8.13	34.9	4.64	4.24	62.4	1.41	2.36	119
EDC 0/12.5	0.741	7.78	30.6	3.95	4.15	63.8	1.45	3.12	116
GB 0/14	0.732	8.13	24	3.09	4.03	62.4	1.41	0.786	105

Table 5. CEP of HMA

HMA	Impact by life cycle phase (MJ/m3)								Cumulative impacts (MJ/m3)
	Step E1	Step E2	Stage E3	Step E4	Step E5	Step E6	Step E7	Step E8	
BBSG 0/10	6.54	110	422	64.2	98	960	20.5	35.8	1720
BBSG 0/14	6.5	110	491	72	61.3	960	20.5	35.8	1760
EDC 0/12.5	6.71	104	433	61.3	60	981	20.9	47.4	1710
GB 0/14	6.64	110	339	48	58.2	960	20.5	11.9	1550

9- figures

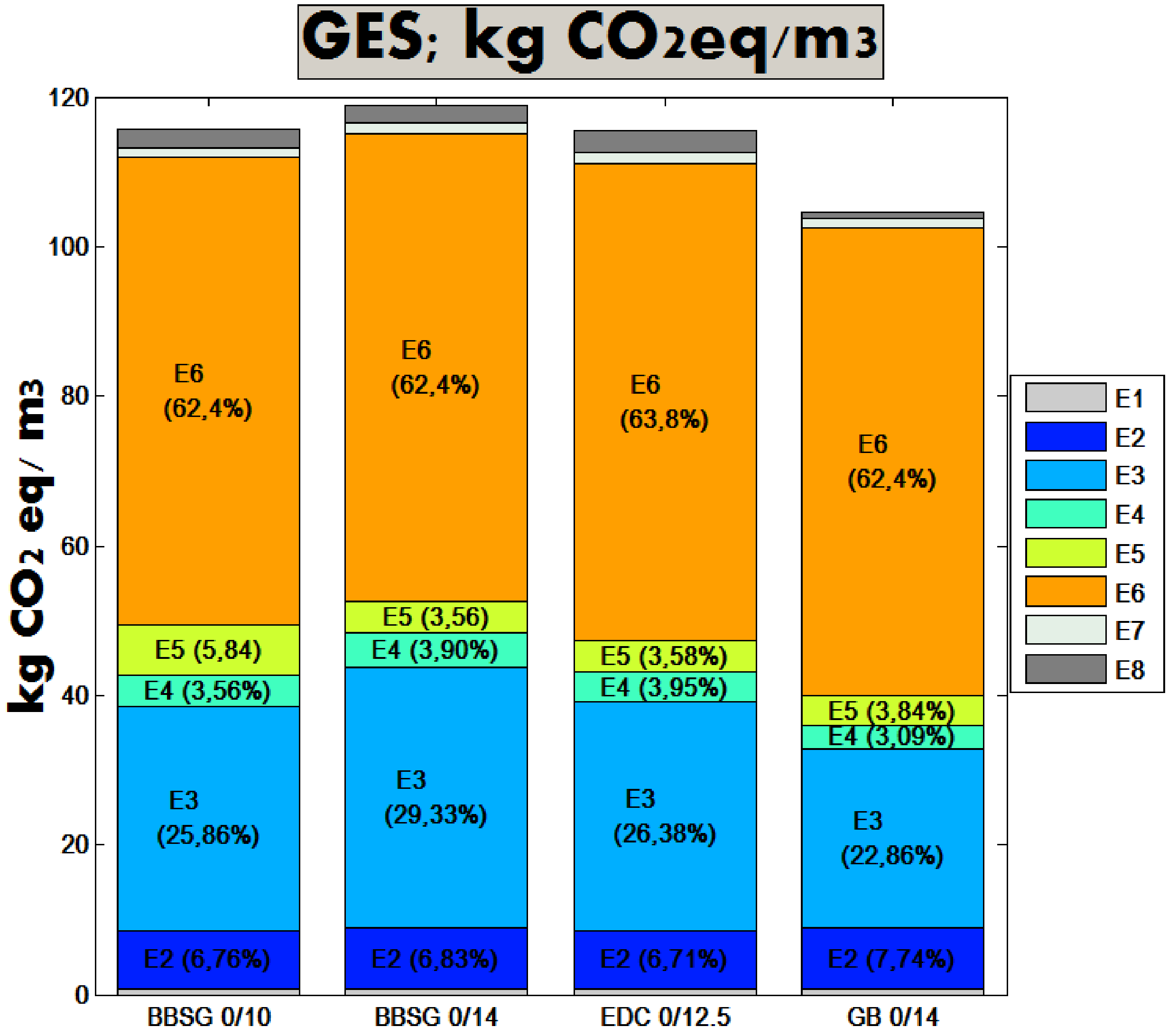

Figure 1. Contribution in GHG emissions of each phase of the HMA cycle

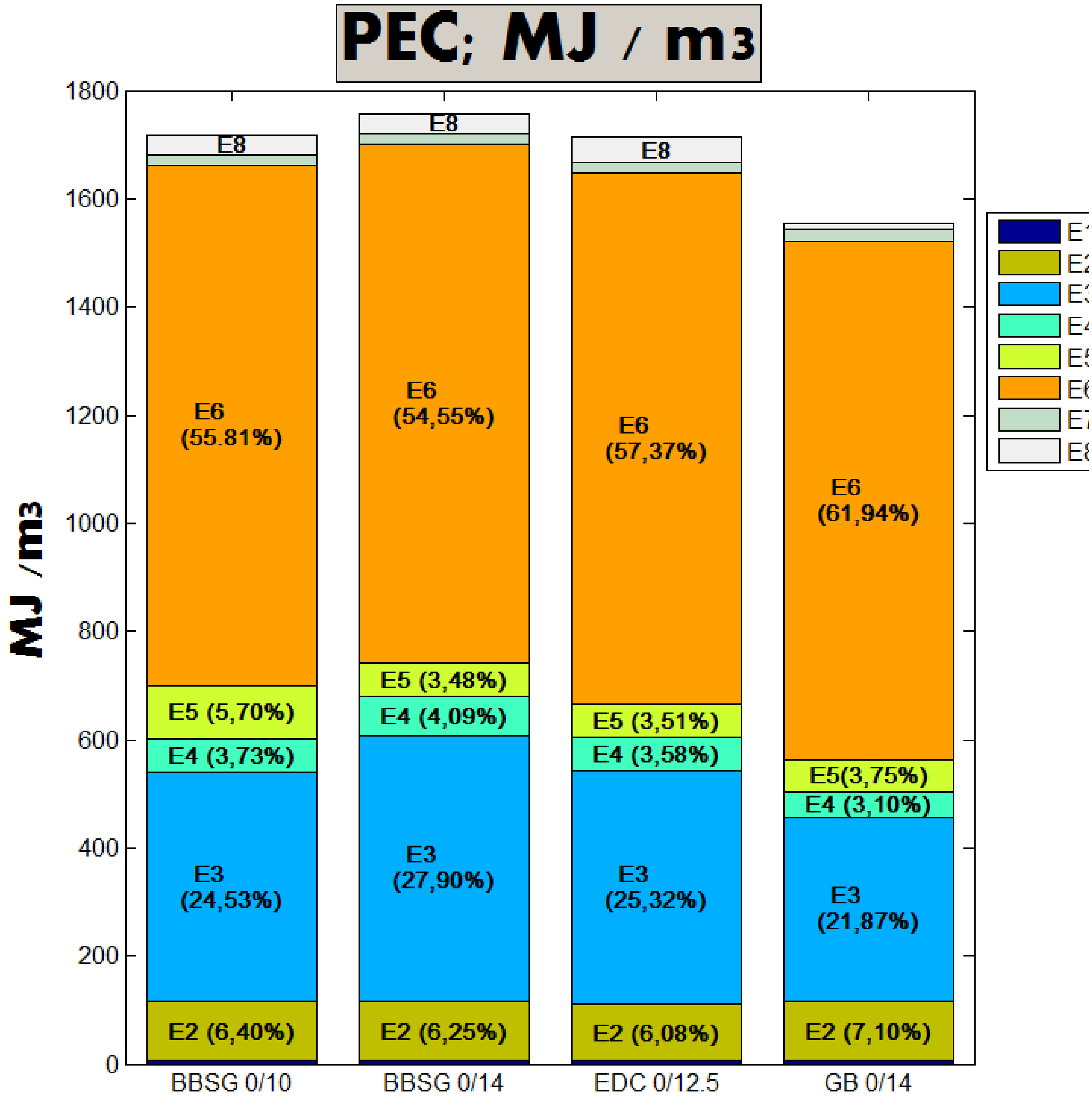

Figure 2. Contribution in PEC of each phase of the life cycle of HMA