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ABSTRACT: This paper reports the result of a study on the environmental impact of road construction techniques with bitumen emulsion. It describes the methodology used for data gathering in quarries for aggregates manufacturing, in emulsion plant, and in mixing plant during grave-emulsion manufacturing. Then calculations are performed with the IFSTTAR software ECORCE to compare a cold mix (grave-emulsion) with conventional techniques as Hot Mixes Asphalts. These calculations was limited to overall indicators (GreenHouse Gas emissions, energy and natural resources consumption) and validate favorable considerations on cold road construction techniques. Finally a sensitivity study shows the great influence of parameters as binder content, void content and transportation distances on environmental assessment of grave treated with bituminous emulsion.

1. Introduction

Cold techniques with bitumen emulsion are already known for a long time, but there are highlighted in several research projects, in a global context of reduction of the environmental impact of road construction techniques, and particularly since the *French Grenelle Forum on the Environment* in 2007. These cold techniques, avoiding heating the aggregates, achieve great energy savings during mixing in plant.

As part of the IFSTTAR research programs OPTIMIRR and EPEES, data gathering on implementation machines, emulsion and cold mixes manufacturing plant consumption and aggregates production in quarry were carried out by the IFSTTAR on an experimental site in grave-emulsion. This article is complementary to another publication, dealing more particularly with the comparison of realistic maintenance scenarios, for French roads with low traffic, [1].

These data gathering, which is detailed in this article have enabled the achievement of environmental assessment for techniques with bitumen emulsion. So an example detailed grave-emulsion and hot mix asphalt comparison: in a first time, the same quantities of materials are compared. In a second time, two usual maintenance scenarios with hot or cold mixes; both covered by a surface dressing, are compared. A sensibility calculation is then detailed to quantify the influence of realistic variations of binder content, void content and transportation distance on environmental assessments of cold or hot mixes.

2. Presentation of the IFSTTAR software: ECORCE

The IFSTTAR software ECORCE [2] was design to established environmental balance of road construction and is inspired by the Life Cycle Analysis methods (defined in standards NF EN ISO 14040, [3]).

Input data come from the process of road construction: also the method is based on the analysis of material flows within a system. The results are flows of inventories for the life cycle of studied pavement and values of indicators of potential environmental impacts, all for a fixed service life. The gathering of environmental data at all stages of the manufacturing of materials from their extraction as resources to their lives up in the road is an essential step in the evaluation. Internal calculations to the software are environmental, they rely on the indicators available in the literature *(some of the indicators selected are subject to a clear international consensus, others are still under discussion in the scientific community).*

ECORCE can conduct an evaluation a posteriori by conducting environmental assessments for existing road configurations (scenarios of construction and / or structural maintenance) or provide an assessment of environmental approaches to predictive scenarios of construction and / or structural maintenance at the tendering stage.

A **case** is defined by several **operations**, and each operation is a project of construction or maintenance, defined by a road structure or a part of structure (a set of **layers**), materials, machines consumption, transportation distances. The relationship between the input data and the environmental assessment is done through the masses and types of materials consumed.

3. Methodology

The data gathering was carried out mainly on an experimental site in grave-emulsion, during the IFSTTAR research program OPTIMIRR, [4]. This project was carried out on the departmental road n°44 (Goven, France), and the manufacture and implementation of emulsion and grave-emulsion were done by the Parc Département d'Ille-et-Vilaine.The calculations detailed in this article are performed using software ECORCE, and whose methodology is developed in [2].

3.1 Aggregates elaboration in quarry

The environmental protection has become a societal requirement. So IFSTTAR developed a software MEG (Module d'Elaboration des Granulats) to quantify the environmental impact of production sites. The quarries of natural aggregates are directly concerned considering the use of machines and energy throughout the process. The data gathering presented in this section aims to establish the environmental impact of the manufacturing of natural aggregates used in the construction of an French experimental site (Departmental road 44, Ille-et-Vilaine) within the IFSTTAR research program OPTIMIRR [4].

To complete an environmental assessment on the manufacture of various granular classes produced, it is necessary to follow the changes undergone by the raw material within the quarry from the extraction of the rock to the constitution of stocks of finished products. The two major rock type (solid rocks and loose rocks) lead to different organizational principles for the extraction and manufacturing of aggregates. This whole process is modelled and implemented in the MEG software to quantify the pressures on environment in three major areas: energy, atmospheric emissions.

The input parameters include all machines (loaders, dumpers, shovels, drills, ...), electrical equipment (conveyer belts, crushers, drills, ...) and explosives. The software quantifies electricity and fuel consumptions for each grain fractions, atmospheric releases (CO_2, CH_4, N_2O, NOx, SO_2, CO, COVNM, POP, PM2.5, PM10, NH_3, Cadmium, Copper, Chrome, Nickel, Selenium and Zinc) and impact indicators: greenhouse gas, eutrophication, acidification, ecotoxicity and toxicity.

3.2 Emulsion Manufacturing in plant

The raw materials quantities are calculated with editions of operating console from emulsion factory. To avoid any confusion with other production, this emulsion was product during a specific production, isolated from the others productions of the day.

- Water: bitumen emulsion uses water during his manufacturing process, and as a constituent. The water consumption was calculated on meter readings. However, there is no meter to isolate specific consumption of the emulsion factory. It was therefore necessary to address the main counter which feeds the emulsion plant and the mixing plant and then take up the meter of the mixing plant: the difference is the water consumed by the emulsion factory for the process.
- Gas: the emulsion plant uses gas to heating water during manufacturing and to maintaining the temperature of bitumen in the tanks. Gas consumption was obtained by the general gas meter reading and the meter of the boiler plant of emulsion reading.
- Electricity: power consumption consumed during the manufacturing of the emulsion is mainly related to the operation of various pumps and to the turbine. The emulsion plant does not have his own electricity meter. It was therefore necessary to install a device in the rack power distribution. This device was installed on the departure of the cable of the plant emulsion so the electric current consumed by the control station has been included.
- Energy for raw materials transportation: a transport distance and the corresponding average fuel consumption is associated with each calculated quantity (see detailed example section 5). As water is coming from the network of drinking water, the transport distance is zero.

3.3 Grave-emulsion Manufacturing in mixing plant

Consumption data for raw materials are obtained from the theoretical formula of the grave-emulsion (quantities of aggregates, emulsion, water) and the tonnage actually implemented on site.

- Water: The manufacturing of the grave-emulsion requires water in addition to the water supplied naturally by the aggregates. Therefore each dump truck is wetted before loading to avoid sticking. Water consumption was obtained from the meter reading of the mixing plant. From the theoretical formula and the estimated average water content of individual aggregates, the water used in the formula and irrigation water is deduced.
- Electricity: electricity consumption during the production of the grave-emulsion is mainly due to the weighing of materials, their transport by conveyer belts and their mixing. The plant does not have a proper electricity meter. It was therefore necessary to install a device in the rack power distribution. As the emulsion plant, the electrical energy includes that of the control station.
- Fuel (for wheel loader consumption): the wheel loader was fill up before and after construction and a transportation distance and the corresponding average fuel consumption is associated with each calculated quantity (see detailed example section 5).

3.4 Mix transportation and layering on jobsite

Each driver had filled up his machines (transport or implementation device) with fuel before and after construction: the difference is the fuel consumed. Data were recorded on a card for each vehicle, comprising: fuel consumption site, kilometres and number of round-trip completed.

In addition to the raw materials listed above, the consumption of anti-bonding product, bonding emulsion and water (for watering by the drum road roller) were also recorded.

4. Results of data gathering

4.1 Aggregates elaboration in quarry

The results of surveys conducted on the quarries that provided aggregates for the project are summarized in table 1 for greenhouse gas emissions and in table 2 for the different types of energy consumed. These quarries are particular cases, these results are not generalizable to other facilities.

Table 1: Global warming potential of pollutants and greenhouse gas emissions (machines and explosives) for 1 ton of aggregates

Polluant	*Allocation*	*Contribution*	*Quarry A (kgCO$_2$e)*	*Quarry B (kgCO$_2$e)*
CO_2	1	1	2.21	2.30
N_2O	1	298		
CH_4	1	25		

Table 2: energy consumption for each grain fractions (for 1 ton of aggregates) versus quarry

Site	*Fraction*	*Electricity (MJ)*	*Fuel (MJ)*
Quarry A	0/2 mm	29.43	20.3
	0/4 mm	28.47	20.3
	2/4 mm	27.84	20.3
	4/6 mm	27.1	20.3
	6/10 mm	22.59	20.3
	10/14 mm	21.44	20.3
Quarry B	10/14 mm	26.07	21.01
	4/6 mm	21.37	21.01
	6/10 mm	21.37	21.01
	0/4 mm	18.81	21.01
GE Stone skeleton		26.40	20.64

The most elaborate granular fractions consume more energy than the fractions that do not require multiple passes through the stages of screening and crushing (for example, the primary crushing from quarry B consumes only 6.64 MJ per tonne). Fuel consumption is only due to the transport of materials between the rock face and the installation: it is constant for each fraction, but depends on the quarry. As the formula of grave-emulsion implemented is confidential, the granular detail of the stone skeleton will not be exposed here, only the assessment of energy consumption is presented in Table 2.

Although environmental data are available for each granular fractions or rock type (solid or alluvial rock) in MEG, ECORCE does not offer these distinctions. The data on the aggregates used in ECORCE refer to a massive rock quarry that produces road aggregates (all grain fraction combined) and take into account an energy consumption of **25.57 MJ** per tonne and GHG emission of **1.74 kgCO_2e** per tonne produced.

4.2 Emulsion and grave-emulsion manufacturing in plant

The greenhouse gas emissions and each pollutants due to emulsion and Grave-Emulsion manufacturing are detailed for in Table 3. The global greenhouse gas emissions is expressed in kgCO_2e / t taking into account the contribution of each pollutant:

- production of emulsion: 2.04 kgCO_2e / t
- production of grave-emulsion: 0.53 kgCO_2e / t

The energy consumption during emulsion and GE manufacturing is detailed for each type of energy in table 4. Emissions of internal combustion engines were calculated from environmental unit data provided by the standard FD P01015, [5].

Table 3: Global warming potential of pollutants and greenhouse gas emissions (emulsion and GE manufacturing)

Pollutants	*Allocation*	*Contribution*	*Emulsion (kg/t)*	*Grave-emulsion (kg/t)*
CO_2	1	1	2.04	0.51
N_2O	1	298	0	$7.09\ 10^{-5}$
CH_4	1	25	0	0

Table 4: energy consumption (emulsion plant and GE mixing plant) for 1 ton of grave-emulsion

	Emulsion (MJ / t)	*Grave-Emulsion (MJ / t)*
Natural Gas	63.22	0.00
Electricity	2.45	1.25
Machines	0.00	6.94
Total	**65.67**	**8.19**

5. Application example: comparison between cold and hot mixes

The environmental impact of each material was calculated for a model section with a surface of 1000 m^2 (200 m long and 5 m wide), similar to the departmental road 44 (geometry, transportation distances). Bitumen emulsions used in cold mixes have been considered as a mixture of water and bitumen, whose proportions are specified for each use. Because of a lack of available data, the minor components (emulsifiers, flows) were not taken into account. For each material, standard conditions of manufacture and implementation have been taken into account (speed of spreading, compaction workshops...).

The data taken into account for the calculation of the impact of emulsion and grave-emulsinon manufacturing are those detailed in section 4.2. The data on the aggregates are averages from French massive rock quarries, whose impact calculations are detailed in [6]. Data on bitumen are from [7], taking into account an average European refineries (electricity production was subtracted).

In this example, a grave-emulsion is compared to a hot reinforcing technique (road base asphalt) during manufacturing, transportation and implementation. First, both materials are layered with 10 cm thick. Then two structural maintenance scenarios on road with low traffic volume will be compared in Section 4.4.

5.1 Hypothesis

The characteristics of the materials (formulation, implementation characteristics) are summarized in Table 5 and the transportation distances used in the calculations are summarized in Table 6. For grave-emulsion, calculation data come from the departmental road 44, during the construction phase. For hot mix asphalts, data (components, manufacturing, implementation) resulting from ECORCE, are supplemented by data from consumption of a wheel loader and of a tank farm to obtain a homogeneous system with the grave-emulsion.

Table 5: constituents and characteristics of formulation for road materials

Materials	*Constituents*		*Characteristics*	
Grave-Emulsion	Emulsion: 6.05% (bitumen content in emulsion: 60%)	Water content: 3.72%	Volumetric mass: 2.580 T/m3	Voids: 12.7%
HMA	Bitumen content: 3.85%		Volumetric mass: 2.609 T/m3	Voids: 8.0 %
Double Layer Surface dressing	Aggregates: 5 L/m^2 + 6 L/m^2 + 8 L/m^2 Emulsion: 1.5 kg/m^2 + 1.5 kg/m^2 (bitumen content in emulsion : 69%)			
Tack Layer	Emulsion: 0.5 kg/m^2 (bitumen content in emulsion: 69%)			

Table 6: transport distances for constituents and implementation devices

Distances (km)		*Comments*
Quarry / Mix plant	55.5 km	For hot or cold mixes, in plant
Mix plant / Jobsite	22.1 km	For hot or cold mixes, in plant
Raffinery / Mix plant	323.0 km	For hot or cold mixes, in plant
Raffinery / Emulsion manufacture	323.0 km	Emulsion manufacturing
Emulsion manufacture / Jobsite	22.1 km	Surface dressing, tack coat
Quarry / Jobsite	77.6 km	Surface dressing
Storage area / Jobsite	22.1 km	Implementation devices

5.2 Influence of the coating process on energy consumption

As a first step, a grave-emulsion is compared to a hot reinforcing technique (road base asphalt) during manufacturing, transportation and implementation. Hot and cold mixes are both layered with a thickness of 10 cm, and all assumptions are kept constant (transportation distances, binder content, thickness of implementation and material quantities...). Only the step of manufacturing in plant differentiates these 2 materials. The construction of the layer of grave-emulsion requires 80000 MJ, which is two times less energy than GB (152000 MJ) and emits 4650 $kgCO_2e$, or 40% less than the GB (7470 $kgCO_2e$).

Energy consumption of both types of materials are also detailed by item on Figure 1, and greenhouse gas emissions are detailed on Figure 2. These graphs show that for the hot mix asphalts, manufacturing plant is the main energy user (72 000 MJ or 50% of the total energy consumption for GB). For grave-emulsion, which do not require aggregates heating, the higher consumption step is the bitumen production in refinery. And the difference in greenhouse gas emissions between GE and HMA (about 2800 $kgCO_2e$, see figure 2) become zero if the transportation of GE between mixing plant and jobsite is increased from 22 km to 170 km. This calculation on transportation is theoretical: it ignores the economic context (cost of transport) and any required changes in the formulation to maintain a proper workability. The difference between GE and HMA may be accentuated in case of recycling. Indeed, for the same materials quantities, Cold in place recycling technique allows a significant reduction of the impact due to the tranpsort, [1]. Reuse of existing materials also saves natural aggregates and bitumen: especially as by coating the fine, the old bitumen reduces strongly the binder content in the cold mix.

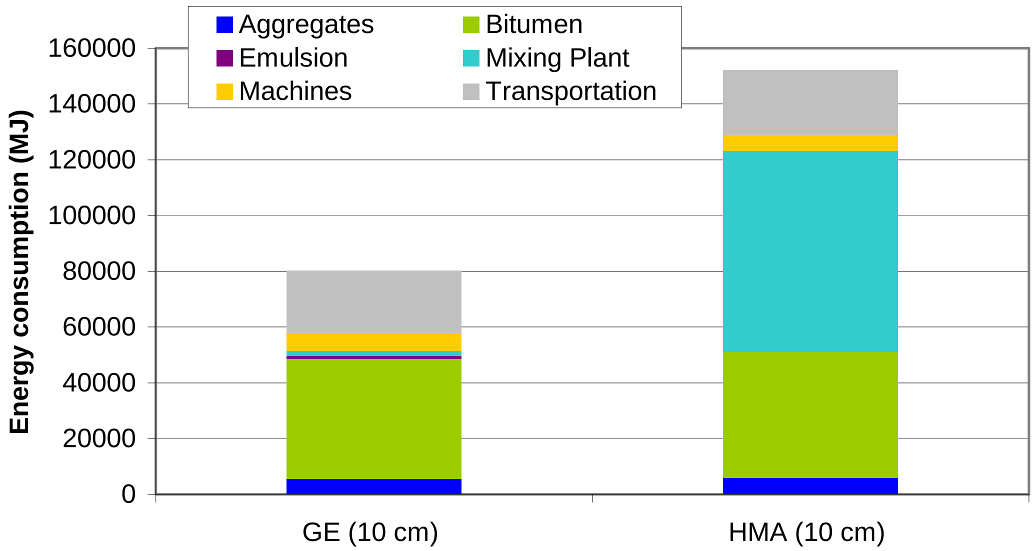

Figure 1: energy consumption for grave-emulsion and HMA

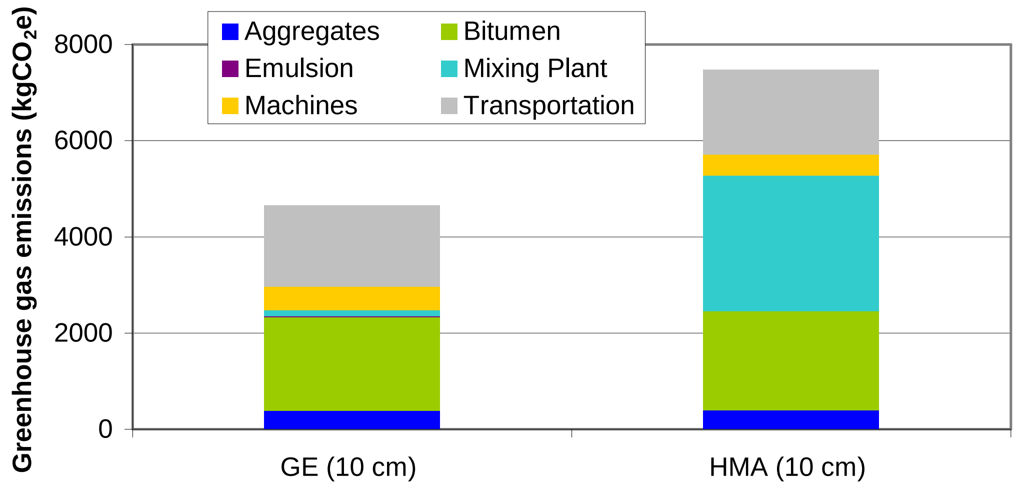

Figure 2: greenhouse gas emissions for grave-emulsion and HMA

5.3 Influence of road maintenance scenarios on emissions, energy and materials consumption

Differences between materials with bitumen emulsion and conventional HMA were calculated on the basis of two structural maintenance scenarios (on road with low traffic volume, as the departmental road 44).This design of maintenances cases is based on French catalogue ([8], [9], [10]) and feedbacks:

- grave-emulsion (12 cm thick) covered by a Double layer Surface Dressing (DSD)
- hot mix asphalt (10 cm thick) covered by a Double layer Surface Dressing (DSD)

Greenhouse gas emissions, energy and materials consumption for both structures are detailed in table 7. For grave-emulsion, which does not require heating, the energy gain on the manufacturing plant compensates for the greater thickness of the structure (more energy related to the fabrication of bitumen and to the materials transportation).

Table 7: greenhouse gas emissions, energy and materials consumption per structure

Structures	*GHG (kgCO$_2$e)*	*Energy (MJ)*	*Aggregates (t)*	*Bitumen (t)*
GE (12cm) + DSD	6492	113133	286	13.0
HMA (10cm) + DSD	8428	169709	257	11.6

5.4 Sensitivity study

Three parameters were taken into account to achieve this sensitivity study, on a layer of 10 cm of grave-emulsion. In this study, only the parameter whose impact is calculated varies in a range of realistic values, all other variables being held constant.

- <u>Influence of Binder Content (BC):</u> 3 Binder Content were selected (3.8%, 4.2%, 4.5%)
- <u>Influence of Voids Content (VC):</u> 3 Voids Content were selected (12%, 16%, 20%)
- <u>Influence of transportation Distances (D):</u> 3 distances between mixing plant and jobsite were selected (20 km, 40 km, 60 km)

The results in terms of energy consumption and GHG emissions are presented in Table 8. The sensitivity study is then analysed while avoiding the reference value and the ranges of variations chosen for each parameter. So the parameter whose effect is studied is called *i*. We define the relative variability of this parameter (*vi*, dimensionless) by equation (E.1), the parameter value being chosen as a reference (*iref*) and the value *ivar* chosen as an alternative for the parameter *i* (*iref* and *ivar* are expressed in the unit of measurement for this parameter *i*).

$$v_i = (i_{var} - i_{ref})/i_{ref} \qquad (E.1)$$

The influence of the variation *ri* on the environmental results can then be calculated by:

$$r_i = (r_{var} - r_{ref})/r_{ref} \qquad (E.2)$$

where *ri* is the relative variability of output related to the variation of the parameter *I* (dimensionless), *rref* is the result obtained for the reference case and *rvar* is the result obtained for the variation of the parameter *i* (*rref* and *rvar* are expressed in the unit of measurement for outcome). *Ei* is defined as the relative effect of the variation of a parameter on environmental result such as:

$$E_i = r_i/v_i \qquad (E.3)$$

Ei is then independent of reference values and ranges of variations. The relative variability of the selected parameters (*vBC*, *vVC*, *vD*), the relative variability of energy and GHG and the relative effects on energy and GHG are presented in Table 8.

The results of the sensitivity study summarized in table 8 show that the relative effect of variation in value of residual binder content is greater on energy consumption (about 58%) than on GHG emissions (approximately 46%). The relative effect of variation in voids content of the Grave-Emulsion is also lightly greater on energy consumption (about 90%) than on GHG emissions (approximately 87%) but the relative effect of varying distances between mixing plant and jobsite is more important on GHG emissions (about 9%) than on energy consumption (approximately 7%). The greater relative effect on energy and GHG is due to variations of voids content. According to quantities of bitumen and material transported, this parameter influences all input data.

Table 8: results of the sensitivity analysis (energy consumption and GHG emissions)

Parameters		*v i*	*Energy (MJ)*	*r_{Energy} (%)*	*E_{Energy} (%)*	*GHG (kgCO2e)*	*r_{GHG} (%)*	*E_{GHG} (%)*
Reference	BC: 3.9% VC: 87.3% D: 22.1 km		80054	/	/	4646	/	/
Variation of BC, VC: 12.7%, D: 22.1 km	3.8%	-3%	78851	-2%	59%	4590	-1%	47%
	4.2%	8%	83588	4%	57%	4810	4%	46%
	4.5%	15%	87141	9%	58%	4975	7%	46%
Variation of VC, BC: 3.9%, D: 22.1 km	12%	1%	80625	1%	89%	4678	1%	86%
	16%	-4%	77321	-3%	90%	4492	-3%	87%
	20%	-8%	75669	-5%	90%	4307	-7%	87%
Variation of D,BC: 3.9%, VC: 87.3%	20	-10%	79538	-1%	7%	4606	-1%	9%
	40	81%	84454	5%	7%	4980	7%	9%
	60	171%	89370	12%	7%	5353	15%	9%

Figures 3 and 4 respectively show the evolution of energy consumption and emissions of greenhouse gases, for each item, depending on the parameters of the sensitivity study (residual binder content, voids content, transportation distances). All parameters affect in a linear manner on energy, materials consumption and greenhouse gas emissions because input data and environmental impacts are related by the masses of materials consumed.

This sensitivity study was also conducted on the binder content of HMA whose formula is detailed in section 5.1. The results are presented in Table 9 and the comparison with grave-emulsion is detailed in Figure 5.
For the same quantity of bitumen, the relative effect of variation of residual binder content is much more important for cold mixes than for the HMA:

- Approximately 57% of energy consumption for cold mixes against 31% for HMA
- Approximately 46% of emissions of greenhouse gases for cold mixes against 30% for HMA

Indeed, the amount of bitumen is 54% of the total energy consumption for a 10 cm thick layer of GE whereas bitumen represents only 30% of the energy consumption of HMA.

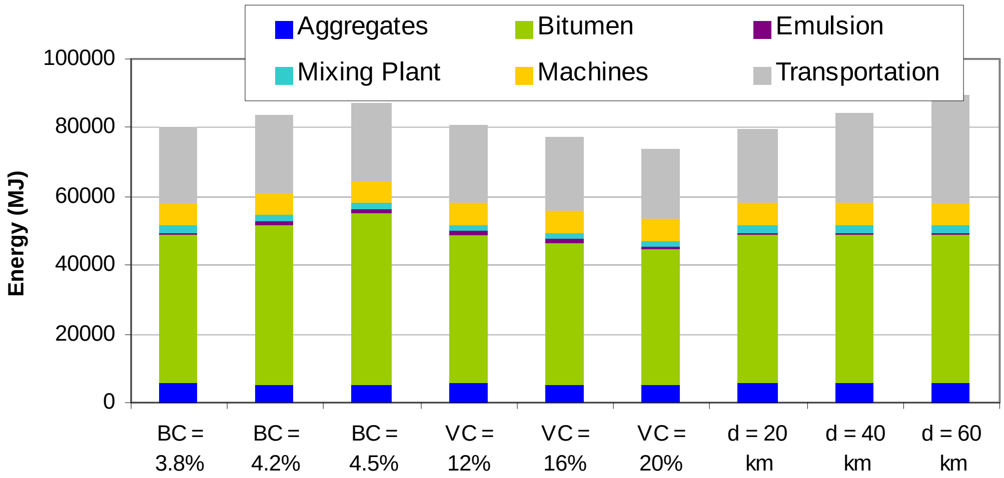

Figure 3: influence of Binder Content (BC), Voids Content (VC) and transportation distances (d) on energy consumption of GE

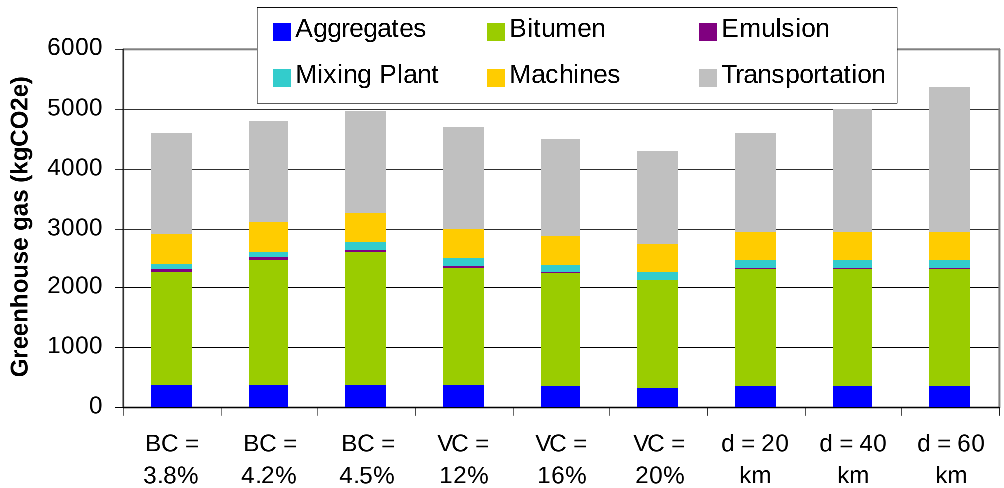

Figure 4: influence of Binder Content (BC), Voids Content (VC) and transportation distances (d) on greenhouse gas emissions of GE

Table 9: effect of binder content on energy consumption and GHG emissions for HMA

Parameters		*v i*	*Energy (MJ)*	*r_{Energy} (%)*	*E_{Energy} (%)*	*GHG (kgCO2e)*	*r_{GHG} (%)*	*E_{GHG} (%)*
Reference	BC: 3.85% VC: 8% D: 22.1 km		152124	/	/	7472	/	/
Variation of Binder Content	3.8%	-3%	151556	-0.4%	31.3%	7446	-0.4%	29.7%
	4.2%	8%	156500	2.9%	31.3%	7677	2.7%	29.7%
	4.5%	15%	160209	5.3%	31.3%	7850	5.1%	29.7%

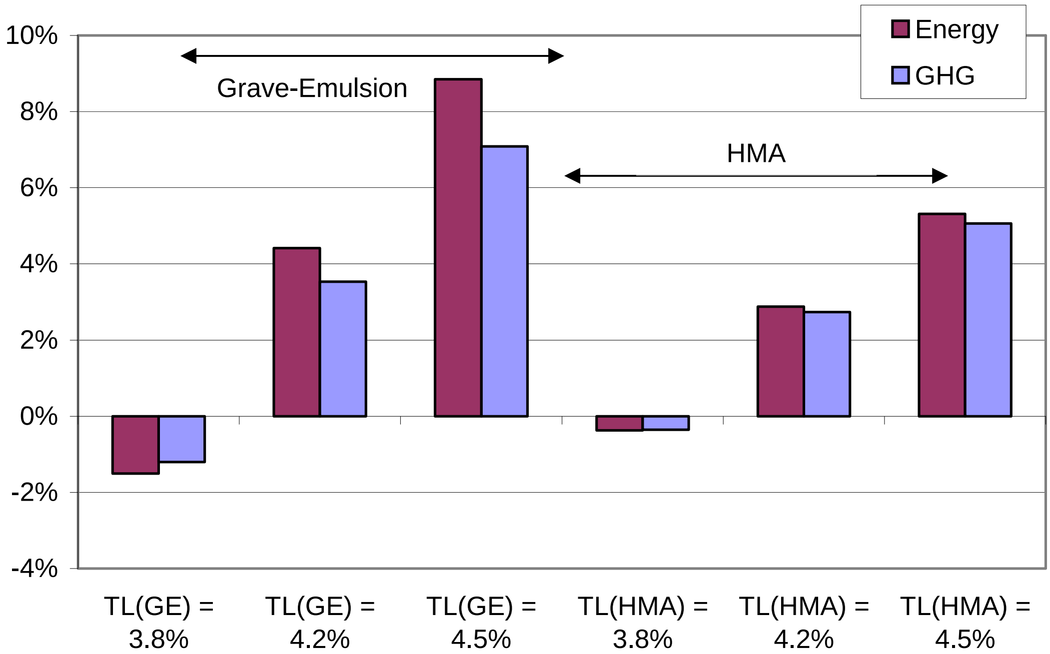

Figure 5: effect of Binder Content (BC) on energy consumption and GHG emissions of GE and HMA

6. Conclusions

Data collection carried out on an experimental site in grave-emulsion in the framework of the IFSTTAR research program OPTIMIRR, has achieved the balance sheet of aggregates elaboration and of emulsion and grave-emulsion manufacturing.

These data were used to produce the assessment of a cold road construction technique, and to validate their environmental benefit over conventional techniques as HMA.

The sensitivity study carried out show that environmental assessments are affect (in a linear manner) by all the studied parameters (binder and voids content, transportation distances…). Evolution of energy consumption and emissions of greenhouse gases for cold mixes are particularly important because their results are mainly due to the quantities of bitumen (see figure 1).

The difference between the hot and cold techniques may be accentuated in case of recycling. Indeed, by coating the fine, the old bitumen reduces strongly the binder content in a grave-emulsion with high rate of recycled aggregates, and reduce its environmental impact.

7. Acknowledgements

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