ENERGY IN WARM MIX ASPHALT

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ABSTRACT

In line with the sustainable development concerns, various types of innovative asphalt mixtures such as warm mix asphalt (WMA) have been developed. These mixes aim in particular at reducing the energy and environmental impacts. The foreseen savings are commonly discussed, especially for warm mix asphalt production in plant.

In a first phase, the energy consumption for the asphalt mixture production is discussed for WMA in comparison with reference hot mix asphalt (HMA). In order to highlight the key phases and perform sensitivity analysis, a theoretical calculation has been conducted. This permitted to highlight for instance the impact of aggregates moisture. These information have then been compared with data gathered from various asphalt plants, permitting to calculate the efficiency of the installations. In order to increase this efficiency and optimize the energy savings, different ways of investigation have then been proposed.

In a second phase, the compaction energy of the mixtures has been discussed. Indeed, using WMA instead of HMA does not necessarily mean similar compaction energy. To achieve this, compaction energy has been related to the maniability of the mixture through various laboratory testing. Tests have been conducted on binders, mastics and asphalt mixtures as well. This permitted to analyse the properties of the different types of WMA and also define efficient compacting conditions in function of the mixture type.

Keywords: Energy, warm mix asphalt, asphalt plant, compaction

1. INTRODUCTION

Emissions and energy consumption are key elements to be considered for sustainable development. Indeed, according to the Swiss Federal Office of Energy, global Swiss energy consumption increased by a factor 8.7 during the last century. Numerous decisions have been taken by governments in order to decrease the environmental load, such as the Kyoto protocol (ratified by Switzerland in 2003) and some other national political policies (e.g. CO_2 imposition for fossil fuel emissions, tax for heavy vehicles). In order to bring a contribution to these environmental concerns, various types of warm mix asphalt (WMA) have been developed during the last fifteen years.
In the road infrastructure domain, an important part of the energy consumption and consequently environmental emissions can be attributed to the construction phase of the road. Stripple [1] highlighted the contribution of the construction phase regarding the energy consumption: 5 to 12% of the energy used from traffic on the same road section. Considering that road construction domain cannot directly affect traffic issues, asphalt mixture production is one of the major energy consuming phases during the road lifecycle. Thus, this paper puts a special emphasis on the evaluation and optimization of the energy consumed in asphalt plant. The compaction energy of the asphalt mixture is another important issue that can be significantly affected by the use of WMA. Thus, in a second phase, an analysis of the compaction energy has been performed. Note that the results presented in this paper are part of the findings of a Ph.D. research achieved in 2011 [2].

2. ENERGY CONSUMPTION IN ASPHALT PLANT

In a lifecycle analysis of asphalt mixture, the production phase represents 30% to 50% of the total energy consumption [2]. The in-situ measurement of this energy consumption in plant can be relatively complicated and varies in function of numerous factors such as: asphalt plant type, weather conditions, fuel type, burner calibration and efficiency, production rate, … Thus, a theoretical model of the energy consumption in plant has been built. This model permits to perform sensitivity analyses and therefore highlight the major parameters affecting energy consumption. The comparison of calculated data with data gathered from asphalt plants in Switzerland and literature data also permitted to evaluate the plants efficiency.

2.1 Calculation of the energy consumption

The energy consumption for the production of asphalt mixture can be divided into two main parts:
1) Energy for components heating and water evaporation
2) Energy for mixer heating

The energy needed for the heating of the components and water evaporation is the major contribution to the total energy consumption. It represents approximately 90% of this total energy. Due to the relative complexity and its associated hypotheses, the calculation of mixer heating energy is often neglected by authors. It however permits to better highlight the differences between hot mix asphalt (HMA) and WMA.

The energy consumption for **components heating and water evaporation** can be calculated through thermodynamics laws. The input parameters are:
- Water content of aggregates, sand and filler [%]
- Initial and final temperature of aggregates, sand and filler [°C]
- Initial and final bitumen temperature [°C]
- Binder content [% mass]
- Asphalt mixture grading curve
- Potential additives with associated specific heat and latent heat characteristics

The equations below are used for the calculation of component heating and water evaporation energy.
- Heating energy, no change of state:

$$\Delta H = m \cdot C_p \cdot (T_f - T_i)$$

Where:

m	Mass [kg]
Cp	Material specific heat [kJ/kg·K]
T_f	Initial temperature [°C or °K]
T_i	Final temperature [°C or °K]

- Heating energy, physical change of state:
  $H=m \cdot L_v(T)$

Where:

m	Mass [kg]
$L_v(T)$	Latent heat of vaporisation at transition temperature T [kJ/kg]

One can highlight that 22.5 MJ energy is necessary for the vaporization of 10 kg of water, which is 1.85 more than the energy needed for heating 100 kg aggregates from 15 °C to 160 °C. An approximation of asphalt mixture final temperature can also be calculated using the thermodynamics relationships applied for a mix of liquids. An accurate calculation of temperature evolution in asphalt mixture is more complex; this issue has been addressed in particular by [3].

The energy consumption for **mixer heating** is based on the hypothesis that the aggregates are dry (energy needed to dry the aggregates calculated above). Thus, the humidity in the mixer is due to the air humidity. The energy consumption for mixer heating is then separated into two components:

$$\Delta H_{tot} = \Delta H_{air} + \Delta H_{vap} \text{ [kJ/t}_{enr}\text{]}$$

Where:

ΔH_{air}	Heating energy of the air in the mixer
ΔH_{vap}	Heating energy of the water vapour (air humidity)

The input parameters for the calculations are:

- Air flow in the mixer Q_{air} [m^3_{air}/h]
- Asphalt production rate P [t_{enr}/h]
- Air humidity (mixer entrance) H_a [%]
- Air temperature (mixer entrance) T_{ent} [°C]
- Drying temperature T_{dry} [°C]

The energy needed for heating of the air in the mixer can be determined using following equation:

$$\Delta H_{air}=m_{air,ent} \cdot Cp_{as} \cdot (T_{exit}-T_{ent})$$

Where:

$m_{air,ent}$	Mass of dry air at mixer entrance [kg]
Cp_{as}	Latent heat dry air [kJ/kg·K]
T_{exit}	Air temperature at mixer exit [°C or °K]
T_{ent}	Air temperature at mixer entrance [°C or °K]

In the above relation, $m_{air,ent}$ depends in particular on the saturation vapour pressure (calculated using Magnus-Tetens approximation), the water concentration in the air and the mixer air flow (see [2]).

The energy needed for heating the water vapour is calculated using the equation below:

$$\Delta H_{vap}=m_{wat,ent} \cdot Cp_v \cdot (T_{exit}-T_{ent})$$

Where:

$m_{wat,ent}$	Mass of water at mixer entrance [kg]
Cp_v	Latent heat water vapour [kJ/kg·K]

The details of the various equations and theoretical basis can be found in [2].

2.2 Hot Mix Asphalt sensitivity analysis

Based on the above developments, the energy needed for the production of a traditional Swiss hot mix asphalt AC T 22S (maximum aggregate size 22 mm) can be calculated. The thermal properties of asphalt mixture components are detailed in Table 1. These values have been kept for the various calculations performed in the research.

Table 1 : Thermal properties of the asphalt mixture components

Parameter	Unit	Value
Specific heat of aggregate Cp_{gra}	kJ/kg·K	0.837
Specific heat of bitumen Cp_{bit}	kJ/kg·K	2.093
Specific heat of water Cp_{eau}	kJ/kg·K	4.185
Latent heat of vaporisation of water L_v	kJ/kg	2256
Specific heat of water vapour Cp_v	kJ/kg·K	1.83
Specific heat of solid wax $Cp_{cire,s}$	kJ/kg·K	1.7
Latent heat of fusion of wax L_c	kJ/kg	240
Specific heat of iquid wax $Cp_{cire,l}$	kJ/kg·K	2.3
Specific heat of chemical additive Cp_{add}	kJ/kg·K	2

Following assumptions and limits have been considered for the calculations:

- Closed system, no heat or energy losses.
- Hypothesis related to thermodynamics laws.
- Continuous asphalt production in plant i.e. plant and bitumen tank heating have not been considered.
- Burner calibrated and optimized (perfect combustion process).
- No reclaimed asphalt pavement (RAP).
- Residual humidity of aggregates after drying is 0%.
- Without specific information, a plant efficiency of 100% is supposed in a first phase.

The base conditions for the calculation of the reference hot mix asphalt energy consumption are indicated in Table 2.

Table 2 : Base conditions for reference hot mix asphalt

Aggregates initial water content	2%
Sand initial water content	5%
Filler initial water content	1%
Aggregates temperature	initial : 15 °C, final 155 °C
Sand and filler temperature	initial : 15 °C, final 155 °C
Bitumen temperature	initial : 160 °C, final 160 °C

For the reference hot mix asphalt, the total energy needed in order to heat the components and evaporate water is 182 MJ/t. Note that this calculation does not take into account the mixer heating energy that will be analysed later. This total energy consumption can be divided between the various components in order to highlight the energy needs for each asphalt mixture constituents (Figure 1). The sand 0/2 consumes the highest proportion of the total energy (33%). From this energy, 54% is used in order to evacuate sand moisture, the rest being used in order to heat sand.

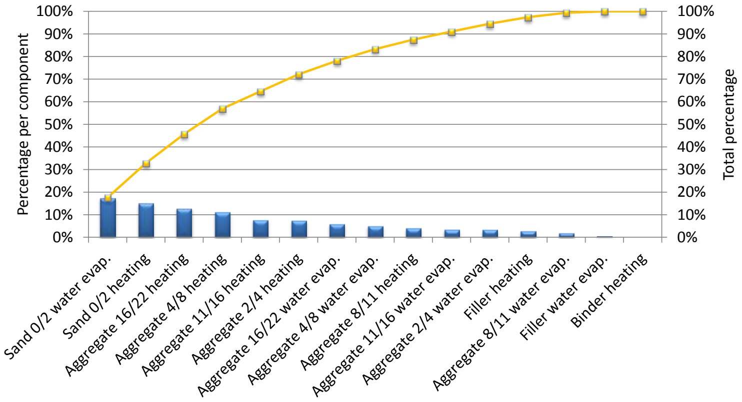

Figure 1 : Repartition of the energy needs for components heating and water evaporation (HMA)

The fine aggregates particle (filler and sand) are crucial elements as they present the ability to store an important amount of water. To evaporate this water requires a lot of energy. This is illustrated in Figure 2 which indicates that a 1% humidity of sand permits to save up to 14% energy in comparison with the reference case (5% humidity). Thus, considerable savings can be achieved by working with “dry” sand. Note that the use of filler with 3% or 5% humidity increases the total energy consumption by 1% respectively 3% in comparison with the reference case (1% filler humidity).

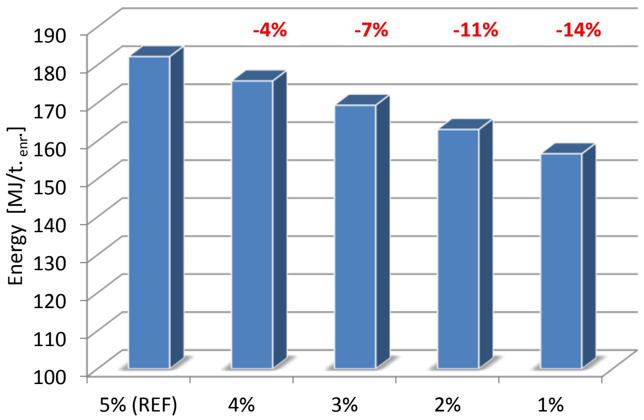

Figure 2 : Effect of sand 0/2 humidity on energy consumption (HMA)

Another sensitivity analysis has been dedicated to the initial and final aggregates temperature. Following elements can be highlighted:

- An initial aggregates temperature of 5 °C increases the energy consumption by 3% in comparison with the reference case (initial temperature of 15 °C).
- An initial aggregates temperature of 25 °C decreases the energy consumption by 3% in comparison with the reference case.
- In case of asphalt mixture with a cold fraction of RAP and in order to guarantee an acceptable asphalt mixture temperature (approximately 160 °C), the aggregates might be heated up 210 °C (sometimes even more). An increase of the final aggregates temperature by 25 °C (180 °C) requires 12% more energy than for the reference case (155 °C). Heating the aggregates up to 210 °C increases the energy consumption by 26%.

Based on the assumption of a perfect combustion process in the plant burner, the air emissions can be calculated in function of the sort of energy used. This is illustrated in Figure 3 where various energy sources are considered for the reference HMA i.e. same energy consumption but various types of energy supply. Note that the case of a 100% electric asphalt plant is not realistic, but it illustrates the important emissions variation in function of the type of energy used. For a similar energy consumption per ton of asphalt, air emissions are approximately 30% higher with the use of fuel instead of gas that would be the recommended energy source.

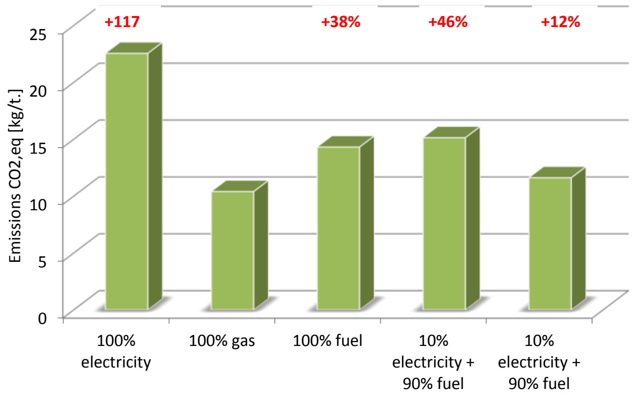

Figure 3 : Effect of the type of energy source on the air emissions

2.3 Energy consumption for WMA production

Based on the same basic hypothesis than for the reference hot mix asphalt (Table 2), the energy consumption for the production of warm mix asphalt has been calculated.

WMA selection

The choice of the WMA has been based on primary criterions (environmental savings and energy consumption related to the production in asphalt plant) and other secondary criterions (complexity of the production process and experience i.e. tons produced in Switzerland and neighbouring countries) with the objective to assess the major types of processes. The various processes and selection procedure are detailed in [6]. Following techniques have been finally selected (the code used in the research is indicated into brackets):

- Reference hot mix asphalt (REF)
- Warm Mix Asphalt with Fischer-Tropsch wax addition (ET-C). Wax content fixed to 3%/mass of bitumen.
- Warm Mix Asphalt with chemical tension-active additive (ET-P). Chemical additive content has been fixed to 0.4%/mass of bitumen.
- Half Warm Mix Asphalt with control of the moisture content (EST). The EST production requires a vegetal flux at a rate of 0.4%/mass bitumen.

In addition to the WMA selected above, namely ET-C, ET-P and EST, an additional half-warm mix asphalt (EBT) has been considered. This asphalt mixture consists in introducing the whole filler and sand 0/4 without heating i.e. cold. The sand water content is then adjusted in order to obtain a total aggregates humidity of 1.25% before mixing.

Note that except EBT mixture, the mechanical performances and major characteristics of the abovementioned WMA and the reference HMA have been assessed during an extensive laboratory analysis. More information about this research phase can be found in [2] and [7].

Calculation of the energy consumption

The energy consumption for the production of the different asphalt mixtures is represented in Figure 4. We can highlight:

- With the consideration of the energy needed for mixer heating, the WMA processes ET-C, ET-P and EST present rather comparable energy consumption. In comparison with the reference hot mix asphalt, the savings in energy represent between 12-13%. From a theoretical point of view, the energy savings with the production of these WMA are rather moderated. The calculated gains are less important than the savings that are sometimes announced in the literature [6].
- If the reference HMA is produced with aggregates heated at 210 °C instead of 155 °C as supposed in the calculation of Figure 4, then the savings with the production of warm mix asphalt ET-C, ET-P and EST represent approximately 30%.
- The calculation of the mixer heating energy has been performed with the assumption of a 30'000 m^3/h air flow and 200 t/h asphalt production. This part of the energy represents between 11.9 MJ/t for EBT mixture and 20.2 MJ/t for the reference hot mix. In proportion, the mixer heating energy represents between 7% (EST) to 10% (REF and EBT) of the total energy consumption.

- The consideration of the energy used for mixer heating does not modify the trends but it permits to calculate more accurate theoretical energy consumptions.

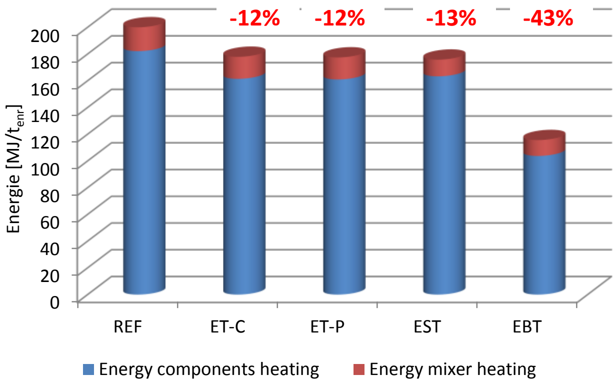

Figure 4 : Energy consumption for reference HMA and WMA production

2.4 Asphalt plant efficiency

The calculation procedure developed above can be used in order to assess the theoretical efficiency of asphalt plants. To achieve this, data have been obtained for a set of typical Swiss mixing plants and some additional information has been gathered in the literature.

The Figure 5 represents the results of a survey of the energy consumption in 7 discontinuous plants in Switzerland. Plant 7 is the only installation producing WMA. Considering HMA production, the energy consumption range from 84 kWh/t to 118 kWh/t with an average energy consumption of 99 kWh/t (356 MJ/t). The standard deviation is 11 kWh/t (40 MJ/t).

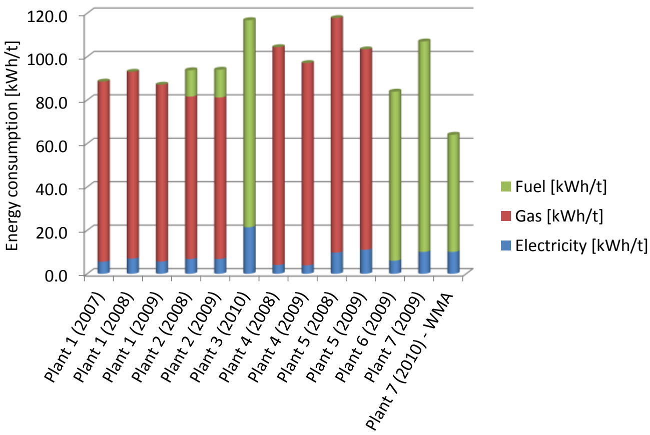

Figure 5 : Repartition of the energy consumption for different Swiss plants

Data regarding the energy consumption in asphalt plant can also be found in the literature. In Table 3 the average energy consumption is 259 MJ/t, that is 27% less than for the abovementioned Swiss plants survey. The standard deviation is however comparable (42 MJ/t). The rather important variability of the energy consumption in plant can be noticed. Indeed numerous factors affect the energy consumption, in particular the type of plant, the energy source, type of mixture produced, meteorological conditions, measurement method… This important variability in the energy consumption is illustrated by [8] where energy consumption ranging from 276 MJ/t to 389 MJ/t are mentioned. [9] indicates typical energy consumption between 252 MJ/t and 360 MJ/t. We can also mention [10] where a survey of more than 200 asphalt plants in UK has been performed. The author reports that energy consumption varies from 252 MJ/t to 540 MJ/t, with a weighted average value of 403 MJ/t. This illustrates the important variability in the energy consumption measurement in plants.

Table 3 : Energy consumption in asphalt plant ([2])

Reference	Energy source	Asphalt type	Energy MJ/t
Stripple 2000	Fuel, electricity	HMA	276.00
Stripple 2001	Fuel, electricity	HMA	321.00
Ventura, Monéron et al. 2009	Gas, electricity	HMA	189.00
Ventura, Monéron et al. 2009	Gas, electricity	WMA	87.60
Abdo, Agnesina et al. 2005	n.a.	HMA	251.70
Groz, Alvarez et al. 1996	n.a.	HMA	260.43
Cholava 2009	Gas, electricity	HMA	285.85
Chappat et Bilal 2004	n.a.	WMA	234.00
Gonzalez, Ligier et al. 2009	Gas	WMA	181.04
Gonzalez, Ligier et al. 2009	Gas	HMA	227.18

Considering the limited number of data for WMA energy consumption in plant, the theoretical efficiency is calculated using data concerning hot mix asphalt. The various data are represented in Figure 6 where the blue bars correspond to measurements on Swiss plants, the green bars correspond to data coming from literature and the discontinuous lines correspond to the average value for the two groups of data used. The theoretical energy consumption (energy for heating aggregates and water vaporisation, and energy for mixer heating) is then weighted by a factor representing the theoretical efficiency of the asphalt plant. The calculated theoretical efficiency is 65%. If the calculation is based only on Swiss plants data or literature data, then the theoretical efficiency is 56%, respectively 78%. Asphalt plant owners usually announce plant efficiency between 75% and 85%. The determination of the theoretical efficiency permits to correct the calculated data in order to fit as good as possible to reality.

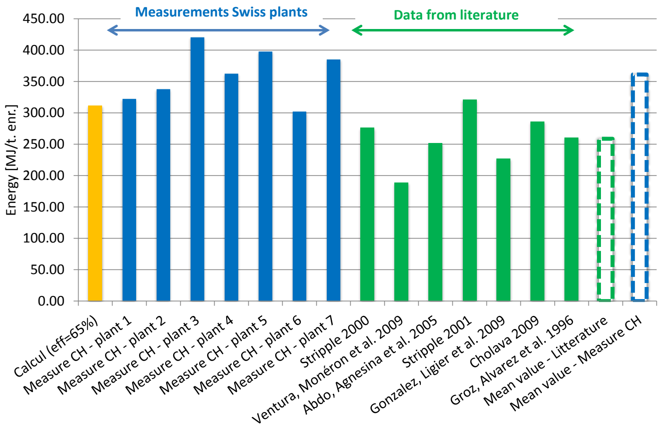

Figure 6 : Comparison of energy consumption literature – Measurements on Swiss plants – Calculated value

3. CONSIDERATION RELATED TO ASPHALT COMPACTION ENERGY

Another key parameter related to asphalt mixture and energy is the compaction energy. This issue is particularly important while considering WMA as the compaction energy of hot and warm mix asphalt is not necessarily similar. The compaction energy of asphalt cannot be determined in a straightforward procedure. Thus, the binder, the mastic (mix between binder and filler) and the asphalt mixture have been analysed separately in order to better understand the compaction energy needs for the different sorts of asphalt mixtures tested.

3.1 Tests on binders and mastics

The compaction energy can be related to the viscosity of the mixture. Indeed, at a similar temperature, a reduced viscosity means less compaction energy needs. Thus, viscosity measurements have been performed on following materials:

- Virgin binder and mastic (REF)
- Binder and mastic modified with 3% wax (ET-C)
- Binder and mastic modified with 0.4% chemical additive (ET-P)

Note that the test has not been performed on EST mixture that applies a foaming of the bitumen when mixed with the moist aggregates. The mastic composition (57% filler and 43% bitumen) is based on the richness modulus criteria. In order to achieve the various measurements, a rheometer with parallel plates has been used. The major testing characteristics are:

- Plate diameter: 25 mm
- Dynamic loading: 0.5 Hz (3.14 rad/s)
- Strain amplitude: 0.1% (Newtonian behaviour)
- Initial gap: 0.8 mm to 1 mm
- Temperature screening: 155 °C to 15 °C
- Temperature variation: 5 °C/min

The obtained results for complex viscosity of binders and mastics are presented in Figure 7 for binders and Figure 8 for mastics. Following comments can be made:

- The binder and mastic behaviour are rather comparable. Indeed, the difference between both viscosity curves is smaller than the test repeatability (coefficient of variation CV=20%). The chemical additive (ET-P) acts as a tension-active agent between aggregates and binder and consequently has no (or marginal) effect on the mastic. The chemical additive effect can be observed on the asphalt mixtures properties and performances but not on binder and mastic behaviour.
- Wax addition has a direct effect as it decreases the mastic viscosity when wax melts at around 90 °C, thus allowing a better maniability in the asphalt compaction temperature domain. When wax is melt (above 90 °C) the viscosity decreases by approximately 40%. On the other hand, when the wax is solid (below 80 °C in service temperature domain), an important viscosity increases is observed. The viscosity of ET-C bitumen increases by a factor 7.5 between 45 °C and 75 °C in comparison with the reference mixture, while an increases by a factor 22 has been measured on mastic in the same temperature range (45 °C – 75 °C).
- The viscosity at a given temperature and for a selected mixture is about 5-6 times smaller for binder than for mastic.

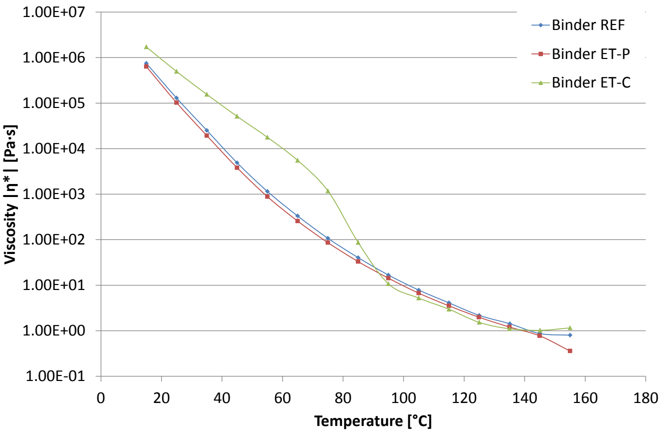

Figure 7 : Complex viscosity of binders

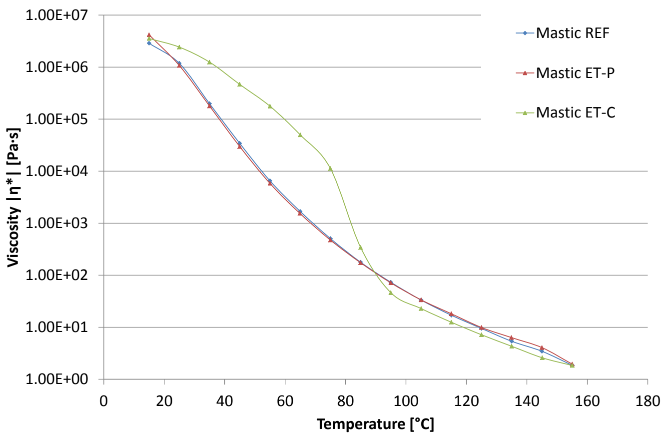

Figure 8 : Complex viscosity of mastics

3.2 Tests on asphalt mixtures

The analysis of the asphalt mixture compaction energy can be performed in different ways. For instance, measurements using a Nynas workability tester [11] or the measurements of a paddle oscillation torque as proposed by [12] permit to assess the compaction energy in a qualitative way. In this paper, we propose to analyse the compaction energy of the various asphalt mixtures through the use of the gyratory compactor.

The applied procedure consists in performing gyratory compactor compacting procedure at various temperatures. Thus, the optimal compaction temperature can be determined and the differences in the compaction energy needed at various temperatures identified.

The following asphalt mixtures have been tested and compared to the reference HMA (see section 2.3 for description): REF, ET-C, ET-P and EST. The Figure 9 illustrates the results obtained with the gyratory compactor where the optimal compaction temperature for each mixture can be identified. By compacting above this temperature, the benefit in compacity is negligible and the energy consumption higher. The same trends as in Figure 9 have been obtained by analysing the Marshall compaction results. It has been finally decided to compact the WMA with wax (ET-C) and the WMA with chemical additive (ET-P) at a temperature of 120 °C and to compact the EST (WMA with moisture control) at a temperature of 100 °C, this in order to obtain a compacity comparable to the reference hot mix.

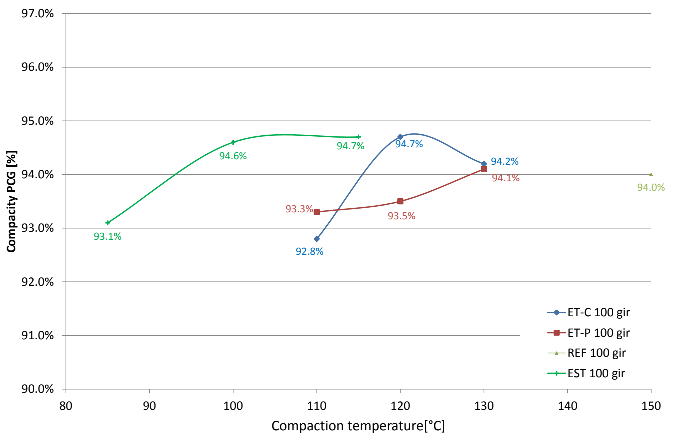

Figure 9 : Gyratory compactor results at various temperatures

4. CONCLUSIONS AND FURTHER DEVELOPMENTS

This paper discusses the production and compaction energy of asphalt mixtures, with a special emphasis on warm mix asphalt.

The analysis of production in plants permits to evaluate the effect of various parameters on the energy consumption. It also appears that the production of WMA allows reducing considerably the energy consumption. The use of WMA has to be pursued with the general idea of decreasing the energy consumption and air emissions as well. However, in order to avoid a direct loss of these savings, one can say that WMA production will be energy efficient only if the whole asphalt plant production process is analysed and optimized. In order to optimize the energy consumption in plant, a special emphasis has to be put in particular on following aspects: aggregates moisture (sand), heating temperature, burner calibration and combustion process, choice of the energy sources, plant insulation, reuse of the heat loss (stack), avoid production discontinuities, uses of a monitoring and control system, losses decreases, …
The calculation procedure discussed in this document has been further integrated in a global model developed in the framework of [2]. The model aims at helping in the choice of the optimal asphalt mixture type by taking into account various criterions such as energy consumption, emissions, mechanical performances, production complexity, recycling potential, …. The procedure, implemented in a flexible way, permits to take into account various additives and multiple aggregates fraction with different temperature and humidity conditions. More details can also be found in [4] and [5].

In a second phase, an analysis of the compaction energy is proposed. To do this, the compaction energy has been related to the maniability of the mixture through laboratory testing. The complex viscosity measurements on binders and mastics, in a large temperature range permitted to highlight the differences between the tested WMA. A modification of viscosity can be further related to better maniability and less compaction energy. The gyratory compactor analysis at different temperatures permitted to define the most efficient compaction conditions for the different asphalt mixtures.

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