Energy and environmental gains of warm and half-warm asphalt mix: quantitative approach

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ABSTRACT

The solutions, currently proposed to improve the energy efficiency of asphalt mixing processes are categorised in warm and half warm, depending on whether their manufacturing temperature is above or below 100°C. Evaluating the energy content of such asphalt mixes is essential for its environmental validation. To assume it, authors propose to use thermodynamic methods which they have used to study the half-warm process LEA, presented at TRB 2006 sessions, the method includes both approach:

- One global thermal model of energy management, applicable an industrial installation as well as the laboratory.
- One numerical simulation, of the kinetics of the transfers accompanying the changes in the physical and chemical properties of the constituents.

To illustrate it, a global thermal approach determines the energy content of six types of manufacture representative of hot, warm and half-warm mixes is presented. The method takes also into account the thermal losses related to the processes and the types of manufacturing installations as well as the fuel used. Such approach enables a better understanding and control of the physical phenomenas mobilized by the different warm, and especial half-warm processes. It offers a thermal model of process operation and allows the calculation of related energy parameters. Its application can be extended to all types of mixes, whether hot, warm or half-warm. All the players involved in the production and use of asphalt mixes will find an instrument measuring their effectiveness in terms of environmental compliance. The method gives answer to the question: how many joules was I able to save? Gas and fuel oil are not equal in terms of environmental discharges, whether from the qualitative or quantitative viewpoints. Everyone involved in the production and use of bituminous mixes will find an instrument for measuring their effectiveness in environmental protection.

Greg Harder, Yves LeGoff, Andre Loustau, Yves Martineau, Bernard Heritier, Alain Romier.

Keywords: asphalt mixture, energy saving, greenhouse gas emissions, half-warm asphalt mixer, hot-asphalt mixture, mix temperature under 100°C, thermodynamic model, warm asphalt mixture,
INTRODUCTION

Hot-mix asphalt is always considered to be the type of mix best suited for all road pavement layers. This supremacy is now called into question. The production of hot-mix asphalt calls for the heating and complete drying of all mix components, the aggregate skeleton and bitumen. It consequently represents:

- significant thermal energy consumption, generally involving the combustion of hydrocarbons (fuel oil, natural gas),
- major greenhouse gas emissions (GGEs).

Accordingly, many solutions are currently proposed to improve the energy efficiency of asphalt mixing processes. They lead to mixes obtained at substantially lower temperature which are classified as warm or half-warm depending on whether their manufacturing temperature is located above or below 100°C. The former make use of systems acting on the viscosity of the bitumen (wax, double coating, soft binder, hard binder, foaming agent) with an aggregate skeleton of uniform temperature maintained over 100°C and thus entirely anhydrous. The latter maintain a small amount of water so that the binder is in the form of a foam or emulsion and mixes can be produced at temperatures below 100°C. The water can be either introduced beforehand in the binder in foam and/or emulsion form, added to the materials used at ambient temperature, provided by the part of the materials left cold and wet, or finally be introduced (cold or hot) during mixing in the presence of all mix components.

These different processes have been sparking significant interest. Their energy parameters must be specified if one is to measure the effectiveness of their impact on GGEs. Temperatures measured at the manufacturing discharge are not the only indicator of energy expenditures. The analysis must be extended to the energy contents of the different components and to the heat transfers taking place between them. Account must be taken in particular of variations in the energy contents of each component during the different stages of a process, and inevitable heat losses of any industrial process taking place at higher than ambient temperature.

Based on the thermodynamics method used to study the half-warm process LEA® presented at TRB 2006 sessions, the method includes:

- One global thermal model of energy management, applicable an industrial installation as well as the laboratory.
- One numerical simulation, of the kinetics of the transfers accompanying the changes in the physical and chemical properties of the constituents.

2 ENERGY CONTENTS OF COMPONENTS

The increase $\Delta H$ (in joules) of the energy content of a fluid or a material generally coincides with the heat input (in joules ISO. It can be express in BTU and 1BTU= 1055 KJ) required to obtain it:

- the sensible heat measures the energy increase associated with simple heating (temperature increase), with no change of state:

$$\Delta H = M \cdot c_p \cdot (T_f - T_i)$$

where

- $M$ = mass in kg
- $c_p$ = specific heat characteristic of the material in J/kg/K
- $T_i$ = initial temperature (°C or K)
- $T_f$ = final temperature (°C or K)

Thus, the energy increase of 100 kg of coarse aggregate ($c_p = 837$ J/kg/K) when heating from 22°C to 197°C is $\Delta H = 100.837 \cdot (197-22) = 14.6$ MJ

- the latent heat measures the energy increase associated with a physical state change: melting of a solid or vaporizing of a liquid. For vaporization:
\[ \Delta H = L_v (M_{vf} - M_{vi}) \]

where
- \( L_v \) = latent heat of vaporization in J/kg
- \( M_{vi} \) = initial mass of vapor in kg
- \( M_{vf} \) = final mass of vapor in kg

- In the case of bituminous mixes, the thermal properties of the different components present are the following:
  - \( C_{\text{gran}} \) = specific heat of aggregate = 0.837 kJ/kg°C
  - \( C_{\text{bitume}} \) = specific heat of bitumen = 2.093 kJ/kg°C
  - \( C_{\text{eau}} \) = specific heat of water = 4.185 kJ/kg°C
  - \( L_v \) = latent heat of vaporization of water = 2256 kJ/kg
  - \( C_{\text{vap}} \) = specific heat of water vapor = 1.830 kJ/kg

Thus, the vaporization of 10 kg of water requires 22.5 MJ, i.e. as much energy as the heating from 22°C to 197°C of 154 kg of coarse aggregate.

Papers published in the technical press and dealing with warm and half-warm processes, used in industrial applications report, fuel consumption gains without providing any manufacturing parameters other than mixing discharge temperature. Most of them are relatively discreet with regard to energy content.

It is for that the authors propose to extend their thermal approach method to any process and wish to compare their thermodynamic studies with all the processes most frequently mentioned.

To illustrate this first approach, they have distinguished six types of manufactured mixtures, based on differentiated warm or half-warm principles, using hot-mix asphalt as reference.

They were designated as follows:
- No.1 HMA Reference, hot-mix asphalt (HMA REF),
- No.2 Warm Mixture, coating with a bitumen including addition of a wax or a foaming agent,
- No.3 Warm Mixture, double coating, soft bitumen, hard bitumen, the latter in foam form,
- No.4 Half Warm, coating with emulsion*.
- No.5 Half Warm, coating with foam bitumen.
- No.6 Half-Warm, sequential coating by combination of, first hot coating of one heated part of mineral skeleton and then foam coating, when complementary cold and wet part is added; fine aggregate (sand) is preferentially maintained cold, cold (CS).

The mix design formula is that of a semi-granular bituminous concrete for wearing course. The granular mix design is broken down into two or more parts, one representing the fine aggregate 0/2mm and the others the 2/10mm coarse aggregate. The first contains the fines or part of the additional filler. During open-air stockpiling, the fine aggregate retains far greater amounts of water than the coarse aggregate. In certain recycled mix designs, the asphalt aggregate also has a water content equivalent to or even greater than that of the fine aggregate. Hence, the expression “cold sand” must be understood as “part of the aggregate skeleton introduced at moderate temperature and contributing water” as regards general terminology. (Table 1 & 2 compare the conditions common and differentiating the six processes).

Table 1: “Conditions common to the six processes”

| Table 2: “Conditions differentiating the six processes” |

* Different Warm or Half Warm processes using emulsion exist. In the present study, only one Half Warm coating, below 100°C has been considered here.
It is understood that below 100°C (case of half-warm mixes), a residual water quantity of the order of 0.7% at the mixer discharge was essential in order to ensure workability during lay-down. After manufacture and until final lay-down, a reduction in the water content of half-warm mixes is observed. The final water content of half-warm asphalt mixes is equivalent to that of hot-mix asphalt in which less than 0.5% is tolerated.

The manufacturing parameters indicated have been taken from publications and presentations obtainable from promoters of each process.

By convention, we have chosen respectively a temperature of 20°C and amount of binder of 7.3 % of the mass of the mixture for the emulsion coating process, and 160°C and 5.3 % for all the others. In fact, a 69% emulsion contains the same residual binder, and 2% of water.

The first three processes, i.e. the “hot-mix” reference and the two “warm” processes, function with mixing temperatures higher than 100°C and total elimination of the water contained in the aggregate skeleton on passing through the drum dryer.

The last three processes, i.e. the “half-warm” processes, produce mixes at temperatures lower than 100°C and are differentiated by the amount of aggregate going through the drum dryer, their temperatures, the sequences of mixing, and the control of quantity of water in the aggregate and the final mix. The emulsion water as well as the water added directly (if necessary) during mixing for generating foaming has been regarded as water introduced into the mixer. For these processes, the essential role of additives which allow the cohabitation of water, bitumen and the aggregate skeleton will not be discussed.

The calculation principle is the same for the six configurations: the final condition of the mix (water content and temperature) determines the temperature required for the aggregate skeleton (complete or partial) at the drum discharge and hence the energy gains required from the initial condition.

The energy content of the different processes is show in Figure 1.

**Figure 1: “Energy content of the different processes”**

### 3. INFLUENCES OF HEAT LOSSES DURING MIXING

Heat losses during manufacture depend essentially, for a given installation, on the difference between process temperature and ambient temperature: there is an acceptable approximate proportionality rule: the mixing of materials at 160°C with an ambient temperature of 15°C causes heat losses which are practically twice those accompanying the mixing of materials at 90°C because \((170-15) / (90-15) = 2.06\). Heat loss depend also of many other factors, type of equipment, type of dryer, exhaust systems of different pieces of equipment to the dust collector.

It has been compared, during industrial production, the measured present fuel consumption and equivalent figures obtained from global thermal model calculation, in the case of Hot Mix Asphalt and Half Warm Mixture.

Measurements carried out in a batch plant have shown that energy consumption attributable to such losses were on the order of 3 kg of fuel oil per metric ton of mix with final mixing at 160°C and an ambient temperature of 15°C. Figure comparative (Figure 2) is obtained by the application of the proportionality rule to each of the six processes.

It is then found:

- That, as could be expected, the existence of losses “smoothens” the comparisons somewhat;
- That poorly controlled addition of water during the process can greatly penalize energy consumption. Specially, a direct injection of water into the mixer can penalize the energy content. One part of water escapes in the exhaust system, and water can vaporize before contact with the mixture. It is more efficient to introduce dispersed water, with bitumen (foam or emulsion) or wet aggregate.

**“Figure 2: “Influence of heat losses on fuel consumption”**
4. REDUCTION OF GREENHOUSE GAS EMISSIONS

Environmental benefits are influenced by thermal parameters. For a given fuel, relative gains in carbon dioxide emissions (the main GGE generated during manufacture) are obviously the same as relative consumption gains. It is nevertheless worth pointing out the overall gains that can be achieved (Table 5):

“Table 3: “Influence of type of fuel on consumed energy and GGEs”

Table 3 and Figure 3 show that natural gas is both richer and less polluting than fuel oil. Introduced into the preceding calculations, these data lead to the conclusion that going from the most unfavorable process (HMA consuming fuel oil) to the most favorable (N°6 HW consuming natural gas) results in a 65% reduction in CO$_2$ emissions, i.e. one third the CO$_2$ emissions involved (8 compared with more than 22 kg of CO$_2$ per metric ton of mix).

“Figure 3: “CO$_2$ emissions according to type of fuel”

6 EXAMPLE OF GUIDELINE APPLIED DURING THE DEVELOPMENT OF THE HALF-WARM COATING PROCESS

Energy management does not pose a problem in the case of warm mix asphalt but it is more delicate when it comes to half-warm mixes. What is involved are unstable kinetic systems with constantly evolving energy contents. This is what led us to explore these phenomena during the study of half-warm mixes No.6, without fine aggregate heating and maintaining the presence of water during the mixing process, as the principle had been stated previously in our paper presented at TRB 2006 session. Ref [1] à [5].

Reflections were conducted along two lines:

- making the best use of bitumen state changes as a function of its temperature during contact with aggregate surfaces and water, in particular the ability of foamed bitumen to suitably coat cold elements of small dimensions (competing surface effects and volume effects)

- possibility of optimizing energy inputs during the manufacturing process through the use of specific functions that may be performed by
  - all the elements making up the mix: coarse aggregate, fine aggregate, bitumen, water
  - an element deliberately conserved during manufacture: water
  - the transformation of bitumen into foamed bitumen

Some of these functions are outlined in Table 4.

Table 4: “Functionality of components”

The interplay between energy content and obtaining physical properties comparable to those of hot mix asphalt, leads to the definition of a sequential process in five phases, keeping part of the aggregate skeleton (generally the fine aggregate part containing the fine elements and/or asphalt aggregate in the case of recycling) at ambient temperature and wet.

1. Heating and drying preferentially the coarse elements, representing for example 60% of the mass of the final mix, bringing them to a temperature of about 150°C.

2. Mixing for a few seconds the hot and dry coarse aggregate and all the bitumen previously heated to about 160°C (complying with the bitumen grade used).
3. Incorporating the cold and wet aggregate in the mix. Water and bitumen contact causes bitumen foaming and water vaporization. The incorporation of suitable additives in the bitumen facilitates foaming and ensures that the bitumen film already fixed on the coarse aggregate is kept in place.

4. Coating of fine, wet & cold elements.

5. Heating the wet & cold aggregate, during its foam coating to yield the final mix with the homogeneity of all components; three phenomena intervene independent of mixing to reduce the cooling speed of the coarse aggregate:
   - the slow diffusion of heat from the core of the coarse aggregate, the duration of which may be estimated according to the mean diameter D of the coarse aggregate by the equation:
     \[ t (s) = 0.52 \times D^{2} \]  
     (typically 50 s for coarse aggregate of 10mm)
   - the insulating effect of the air and water vapor contained in the foamed bitumen
   - the restitution of “latent heat” by the recondensation of the water vapor contained in the foam.

6. The final mix contains a small amount of residual water indispensable for workability

The variable that sets the final temperature of the mix is essentially the coarse heating temperature, even though this final temperature also depends on the ventilation conditions existing during the second mixing.

This temperature must be sufficient to maintain proper workability of the mix and can be reduced to a level between 80 and 90°C. A higher level would be:
   - more costly in terms of coarse aggregate heating energy and losses during transport to the jobsite
   - harmful from the workability standpoint since it is more favorable to water elimination

It is important to point out that the energy saving allowed by the process stems from the fact that only the coating of coarse aggregate by the bitumen requires temperatures higher than 100°C. Partial vaporization of fine aggregate water to form the foam takes place in fact when the air at the bitumen-water interface is sufficiently warm so that it is no longer saturated with water vapor, which occurs well below 100°C under normal humidity conditions. In particular, no energy is required for either heating or drying the fine aggregate.

Such a model is perfectly capable of making understanding a process of producing quality asphalt mixes ensuring good distribution of bitumen between all the elements of the aggregate skeleton, whatever their particle sizes, while heating and drying only the coarser elements. Its originality is based precisely on “the rational use of energy by differentiating the coating process according to the particle size of mix elements”.

7 NUMERICAL SIMULATION OF COATING KINETICS

It is obviously difficult to measure separately the evolving temperatures of the different components to validate quantitatively the scenarios described. It is nevertheless possible to build a physical-mathematical model taking into account the diffusion of heat in the coarse elements (coarse aggregate), heat transfers between coarse aggregate, bitumen and fine aggregate and partial evaporation of water, greatly dependent on ventilation conditions. Temperature and humidity measurements at the start and end of the process are in satisfactory agreement with the results of this simulation.

The physical-mathematical representation of these phenomena can be considered only by numerical means. Given the IT hardware and software facilities currently available, the validity of such a study is strongly contingent on the quality of the data available to describe:
   - the thermal and physical behavior of materials: thermal conductivities, specific enthalpies, surface tension,
   - the characteristics of equipment: volume/surface ratio of mixes, mixing speed.
The kinetic model has been conceived in 2005, by Prof Yves LeGoff, Head of Thermodynamic Department
ENSAM PARIS.
The adopted model is a single-dimensional non stationary model based on nodal methods: a component, or part of a
component, is regarded as a thermal “node” whose temperature evolves under the effect of fluxes of heat and
material that it exchanges with neighboring nodes. Node temperatures play the role of “potentials” applied to the
“branches” which convey the fluxes from one node to the other. According to a very classical principle of causality,
knowledge of the potentials at each time step determines the fluxes, which themselves determine the potentials at the
next time step.

The expected results have to do with thermal kinetics and the evolution of mix water content for different operating
conditions (in particular initial temperature and humidity values, mixing speed, in-process addition of water,
atmospheric conditions), different particle sizes (coarse aggregate and fine aggregate), different properties of
bitumen and additives, etc.

The software tool used, Matlab Simulink, is well known to specialists of dynamic systems analysis and lends itself
readily to the simulation of nonlinear, non stationary systems with acceptable guarantees of convergence. The data
taken into account may be imported directly from spreadsheet files, and the results may themselves be exported to
the same type of file.

The temperature gradient in the coarse aggregate during cooling is approximated by internal discretization into two
nodes or three nodes of spherical symmetry: a core surrounded by a peripheral layer, or an intermediate layer itself
surrounded by a peripheral layer.

Transformation of water to vapor is taken into account on two levels:
- on the volume level, where the presence of air is neglected but where pressure is assumed to be close to
  atmospheric pressure, and the change of phase is assumed to take place under normal boiling conditions
  (100°C at 1013 hPa),
- on the surface level, where ventilation conditions and the relative humidity of the surrounding air (partial
  pressure of water vapor) are what determine the change of phase, linked to a drying process (Sherwood
  analogy).

The gradual loss of mix water is the result of the superposition of these two effects; coupled by the mixing process.

The surface active behavior of the bitumen together with its additives is evaluated by the introduction of a latency
time for the removal of water vapor, deduced in an initial approach from measurements carried out under certain
given conditions.

Mixing speed is taken into account by a mixing time influencing the kinetics of heat transfer between hot and cold
elements as well as removed water vapor.

The model is in good agreement with surface temperature measurements conducted on real mixes.

Figure 4 shows the thermograms calculated for the different fractions present in the mix.

The curves represent, in decreasing order of temperatures at a given instant (for example t = 30s), the changes in:
- bitumen temperature
- core temperature of coarse aggregate,
- surface temperature of coarse elements
- temperature of wet fine aggregate

**FIGURE 4:** “Heat transfer thermograms obtained during the mixing of components of a half-warm mix
without heating the fine aggregate”
8 ADVANTAGE OF HAVING AN ENERGY MANAGEMENT MODEL FOR A MIXING PLANT

A simple model for simulating the thermal phenomena mobilized during the manufacturing process makes it possible to define the heating temperatures of elements going through the dryer according to the mix design to be obtained, the water content of the elements kept wet at ambient temperature and climatic conditions during manufacture. Basic information is made available in real time to plant operating personnel. The operator can thus ensure the proper adjustment of the heating/drying line and “control” the mix discharge parameters as well as the desired residual water content and temperature.

The model applies to laboratory studies and, here again, makes it possible to determine precise thermal parameters to be complied with in order to produce samples and mechanical test specimens for mixes having homogeneous properties. It moreover offers an indispensable tool for the control of energy consumption.

Tables 5a and 5b below offer a calculation example based on an energy management model. In this form, it is possible to compare the energy consumed to produce hot-mix asphalt and that required to produce half-warm asphalt of equivalent mix design while providing essential process control elements.

Tables 5a & 5b: “Operating assistance thermal model allowing the comparison of heating energy required for HMA and WMA”

The simple computer model developed and experimented for the half-warm process, taken as an example, provides operating personnel with all the information required for the setup of plant equipment to produce a mix having the expected physical properties (water content and temperature), taking into account the plant’s operating process. Operating personnel has all the parameters required for production quality and optimized energy consumption. The model can be adjusted to suit the type of plant involved and tailored according to its particular drying and mixing systems.

9. CONCLUSIONS

The thermal method used in connection with the development of a half-warm mix showed that evaluating the energy content of an asphalt mix is essential for its environmental validation. The thermodynamic approach enables a better understanding and control of the physical phenomena mobilized by the different warm, and especially half-warm processes. The thermal control of process operation allows the calculation of related energy parameters.

The road industry is striving to find a response to present and future environmental and public health challenges. Thermodynamics sheds light on the elements essential for this undertaking. It is a great tool for understanding physical and chemical phenomena and for process control. It moreover allows its application to all types of mixes, whether hot, warm or half-warm.

All the players involved in the production and use of asphalt mixes will find an instrument measuring their effectiveness in terms of environmental compliance. The question will be simple: how many joules was I able to save?

The equipment manufacturer, who was a forerunner in this area, will be able to propose solutions that the method will make it possible to validate. Energy content depends on the type of installation and the type of fuel used for heating. The latter moreover has an effect on gas emissions, and in particular the greenhouse gases discharged. Gas and fuel oil are not equal in terms of environmental discharges, whether from the qualitative or quantitative viewpoints. (Figure 5)

Additive and bitumen suppliers have become aware of the wide-open scope of their respective areas of investigation. Additives can yield significant gains by improving performance while cutting energy costs.

The producer will have a predictive method facilitating plant operation. The thermal model is particularly valuable for the adjustment of manufacturing parameters relative to half-warm mixes by taking into account the climatic
conditions, the physical properties of the materials used (water content, temperature of components, ambient temperature, bitumen grade) and the production equipment. Energy consumption can thus be increasingly optimized.

Highway infrastructure officials are paying great attention to the energy gains that warm and half-warm mixes can offer. This awareness has led to expectations related to the definition of evaluation and selection criteria. The thermodynamic approach quantifies the gain with respect to GGEs. Thanks to its use, warm and half-warm mixes will be able to demonstrate their value and face competing hot-mix processes. Researchers must improve such models to make them clearer to users. As we all fully realize, there is more to be gained than just knowledge.

REFERENCES

(7) WAM. Shell & Kollo Veidekke Informations
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Fig 1: Energy content of the different processes
FIGURE 2: Influence of evaluated heat losses on fuel calculated consumption

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- evaluated losses
- consumption without losses
FIGURE 3: CO2 EMISSIONS ACCORDING TO TYPE OF FUEL

kg CO2 / metric ton of mixture (losses included)
FIGURE 4: HEAT TRANSFER THERMOGRAMS DURING THE MIXING.
FIGURE 5: Cortland, NY, production of LEA mixture for wearing course, continuous asphalt plant. September 2006 on Left side up & down

France, may 2007, High Modulus asphalt mixture using 10/20 pen asphalt binder for base course on right side up and down
Table 1: Conditions common to the six processes

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Table 2: Conditions differentiating the six processes

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<td>N°5</td>
<td>Half-Warm, Foam coating</td>
<td>50</td>
<td>1</td>
<td>0.7</td>
<td>90</td>
</tr>
<tr>
<td>N°6</td>
<td>Half-Warm, Sequential coating</td>
<td>0</td>
<td>0</td>
<td>0.7 *</td>
<td>90</td>
</tr>
</tbody>
</table>

* Water content obtained during testing of half warm mix, sand not heated (N°6)
### Table 3: Influence of type of fuel on consumed energy and GGEs

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>NHV MJ/kg</th>
<th>Mass of CO₂ emission / mass of fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel oil</td>
<td>40.4</td>
<td>3.11</td>
</tr>
<tr>
<td>Natural gas</td>
<td>49.8</td>
<td>2.75</td>
</tr>
</tbody>
</table>

### Table 4: Functionality of components

<table>
<thead>
<tr>
<th>Element</th>
<th>Usage function</th>
<th>Manufacturing function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate</td>
<td>Bearing structure</td>
<td>« Specific heat » reservoir</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>Filling of voids in bearing structure</td>
<td>Transport of water capture of heat</td>
</tr>
<tr>
<td>Bitumen</td>
<td>Warm, it has the capacity to coat the coarse aggregate</td>
<td>Heat bridge between coarse aggregate and fine aggregate</td>
</tr>
<tr>
<td>Water</td>
<td>Emulsion and foam support</td>
<td>Foaming and lubricating agent, heat bridge and temperature limiter</td>
</tr>
<tr>
<td>Foam bitumen</td>
<td>Binder coating the fine elements preferentially</td>
<td>Heat insulator and “latent heat” reservoir</td>
</tr>
</tbody>
</table>
TABLES 5: Comparison of heating energy, required to produce the same mixture, according to HMA and WMA LEA processes

**Table 5a: Heating energy to produce a hot mix asphalt**

<table>
<thead>
<tr>
<th>Table 5: Comparison of heating energy required to produce the same mixture, according to HMA and WMA sequential coating, processes</th>
<th>Data % in mixes</th>
<th>Mass in kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial water content of fine aggregate (sand) in %</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Water content of coarse aggregate in %</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Initial temperature of aggregate in °C</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>Initial temperature of asphalt binder in °C</td>
<td>160.0</td>
<td></td>
</tr>
<tr>
<td>Input of dry and hot aggregate (coarse aggregate, part of fine aggregate, sand and filler) in %</td>
<td>66.0</td>
<td>625.00</td>
</tr>
<tr>
<td>Input of wet aggregate in dry weight (fine aggregate, sand) in %</td>
<td>34.0</td>
<td>321.97</td>
</tr>
<tr>
<td>Asphalt binder in pph</td>
<td>5.6</td>
<td>53.03</td>
</tr>
<tr>
<td>Water remaining in hot mix in %</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>Eliminated coarse aggregate and sand water</td>
<td></td>
<td>15.91</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>1000.00</td>
</tr>
<tr>
<td>Final temperature of mix in °C</td>
<td>165.0</td>
<td></td>
</tr>
<tr>
<td>Heating energy in KJ</td>
<td></td>
<td>176,294.49</td>
</tr>
<tr>
<td>Heavy fuel oil consumption not including losses in kg/t</td>
<td></td>
<td>4.36</td>
</tr>
</tbody>
</table>
Table 5b: Heating energy to produce half-warm mix LEA-Sequential coating.

<table>
<thead>
<tr>
<th>Data in mixes</th>
<th>Mass in kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>620.80</td>
</tr>
<tr>
<td>1.0</td>
<td>319.81</td>
</tr>
<tr>
<td>15.0</td>
<td>52.67</td>
</tr>
<tr>
<td>141.1</td>
<td></td>
</tr>
<tr>
<td>160.0</td>
<td></td>
</tr>
<tr>
<td>66.0</td>
<td>620.80</td>
</tr>
<tr>
<td>34.0</td>
<td>319.81</td>
</tr>
<tr>
<td>5.6</td>
<td>52.67</td>
</tr>
<tr>
<td>0.67</td>
<td>6.72</td>
</tr>
<tr>
<td>6.21</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>2.88</td>
</tr>
<tr>
<td>1000.00</td>
<td></td>
</tr>
<tr>
<td>95.0</td>
<td></td>
</tr>
<tr>
<td>91,489.77</td>
<td></td>
</tr>
<tr>
<td>2.26</td>
<td></td>
</tr>
</tbody>
</table>