ESTIMATING THE DEGREE OF COMPACTION OF ASPHALT USING PROPRIOCEPTIVE SENSORS AND DYNAMIC MODEL

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Abstract: The paper is about a new method, aiming at estimating in real time the compaction degree reached by an asphalt compactor. This method was developed at LCPC in the frame of a European project called OSYRIS (Open SYstem for Road Information Support). This method is based upon various measurements using proprioceptive sensors and a dynamic model of the machine, necessary to extract the desired information from the measured one. This information is foreseen to be profitable to the new "intelligent" compacting system developed in the frame of the OSYRIS project. First is introduced the methodology for establishing the model, based upon a well-known industrial robots modeling method, and the model itself. Then is presented the principle of the method of estimation, based upon the correlation between the resisting force of the fresh material and its degree of compaction. Finally is described how the method was validated thanks to full-scale experiments, carried out with a real compactor, on real hot materials, in September 2000. The paper ends with the practical questions raised by the industrial implementation of the method.

Keywords: dynamic model, asphalt compaction, automation, resistive effort

1. INTRODUCTION

This article focuses on the compaction of the base course, the binding course and the wearing course of road made with asphalt. The goals of the compaction are to improve the mechanical performance of the materials, to decrease the attrition, to decrease the permeability. Therefore, the compaction of the asphalt is an essential step in the road construction. So, the compacity required has to be reached and, in order to reduce the costs, with the minimum number of passes. The measurements of the compacity are difficult to carry out, expensive and, more restrictive, it can only be made at the end of the process. Several methods have been proposed to ensure the final objective of the compacity by controlling the compaction during the process itself. We propose here a new system of control.

In France, the current way to specify the number of passes is to use an official guide of the compaction process established by some French experts, knowing the type of the layer, the nature of the material, the weather condition, the thickness or the kind of compactor. Some other organisations propose a system of control of the compaction which uses some accelerometers mounted on the drums of the machinery. In the case of a vibrating compactor, the signal given by the accelerometers can be correlated with the stiffness of the soil and therefore with the compacity of the soil. In the new method presented here, on contrary to the classical method, we do not measure the reaction of the soil with an accelerometer but we measure the effort needed by the compactor to advance: the resistive effort. This principle of measure is illustrated by Figure 1.

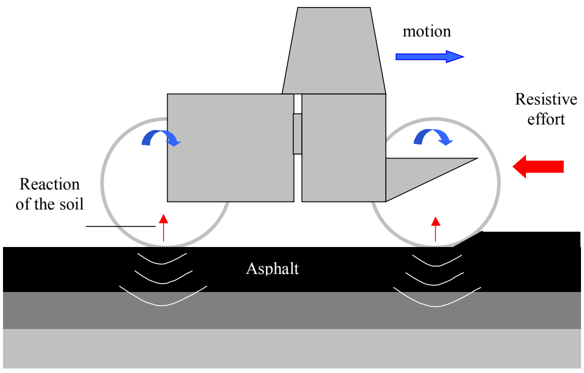

Figure 1: llustration of our new principle.

The main advantage of this principle is that we measure a surface effort whereas the classical principle measures the reaction of the road which includes the reaction of the sublayers under the layer considered. This remark means that even when thin layers are compacted, the method we propose can provide relevant information whereas methods based on the acceleration of the equipment provide information coming mainly from the under layers.

Our new method of control supposes to know the relationship between the compacity (measured after the process) and the resistive effort (calculated during the process). It was one of the goals of our study to quantify this relationship. We carried out a specific experiment on a real case of compaction process to find the relationship, to know its accuracy and its domain of validity.

This article presents the essential steps, results and conclusions of this study about our new method. We begin by a brief description of the modelling needed to calculate the resistive effort. Then we described the full scale experiment. A data analysis is given in the following part. This document ends with the final results about the relationship which summarises the data analysis. A conclusion shows the drawbacks and the possibilities of our new method.

2. Modelling.

Our modelling of mobile machines is based on the Denavit Hartenberg parameterisation which is widely used in the robotics field. The compactor used in the experiments is an ALBARET VA12DV shown on Figure 2. The model of this compactor was fully solved by E.Guillo and al. ([1], [2]). In this section, we just give the essential results required for the understanding of the article : the equations of the resistive effort and the identification of the parameters.

Figure 2: The Albaret VA12DV compactor.

We call 'tractive effort' the effort produced by the compactor to move and 'resistive effort' the effort, due to the ground, that brakes the motion.

In the case of a compactor moving along a straight line, the tractive efforts F^t_4 and F^t_7 and the resistive effort Fr are given by the next 3 equations:

$$F_4^t = \frac{1}{r_{c4}}(\mathrm{u}_4 + \mathrm{u}_{04} - ZZ_4\ddot{\theta}_4 + F_{v4}\dot{\theta}_4 + F_{s4} sign(\dot{\theta}_4))$$

$$F_7^t = \frac{1}{r_{c7}}(u_7 + \mathrm{u}_{07} - ZZ_7\ddot{\theta}_7 + F_{v7}\dot{\theta}_7 + F_{s7} sign(\dot{\theta}_7))$$

$$F^r = \mathrm{M} r_{c4}\ddot{\theta}_4 - \mathrm{M}g\sin(dc) - F_{x4}^t - F_{x7}^t$$

where,

- -i=4 : front drum; i=7 : rear drum.
- -M is the total mass of the compactor,
- -ZZ_i is the inertia of the drum Ci ,
- -F_{vi} and F_{si} are the viscous and striction friction parameters for the drums i
- -u_{0i} is an offset on the motor torque ui,
- -d_c, is the longitudinal slope (declivity) of the rolling plan,
- -r_{ci} is the radius of the drum Ci ,

The radius of the drums is a data given by the constructor, the declivity has to be measured for each trajectory, the rotations θ_i and the motor torques u_i have to be measured during the compaction but all the other values are not directly available. The mass, the inertia, the viscous and striction friction parameters and the offsets of the motor torques are not data given by the constructor and so have to be calculated. The process used to calculate these parameters is the identification.

The principles of the parameter's identification, the description of its practical implementation and the application of them to the compactor is described in [3]. We give in Table 1 the results of the identification made on the ALBARET VA12DV. Xs is the calculated value, σ_{xs} its standard deviation and $\sigma_r = \sigma_{xs}/$ Xs.

Parameters	Units	Xs	σ_{xs}	σ_r(%)
M	Kg	10216	65.6	0.64
ZZ_4	$Kg.m^2$	638.1	4.1	0.64
F_{v4}	N.m.s	63.3	5	7.89
F_{s4}	N.m	122.7	7.5	6.13
U_{04}	N.m	-253.5	3.8	1.49
ZZ_7	$Kg.m^2$	667.1	3.1	0.47
F_{v7}	N.m.s	210.2	4.8	2.31
F_{s7}	N.m	70.2	7.9	11.26
U_{07}	N.m	-391.6	4.2	1.06

Table 1 : Identified parameters.

3. Experiments

A full scale experiment was made in CETE of Rouen in September 2000. The goals of this experiment were: (i) to obtain all the variables needed to calculate the resistive effort and, (ii) to measure the real compacity, in order to evaluate the relationship between these two values.

The experiment consisted in 4 tracks of asphalt (track 2, track 4, track 8, track 16) identically prepared but compacted 2,4,8 and 16 times so that the differences of compaction can be compared. A set of points were measured with a theodolite station (Sokkia Net2). Track 8 was chosen to have a complete set of topographical measurements.

On each track, the asphalt was laid on 25m length and 4m width. The asphalt is a base course asphalt 0/14. We performed gyratory shear compacting press tests to determine the capability of this material to be compacted. The tests show that the minimum voids content are about 5%, i.e., the maximum of compacity for the material used is about 95%. This result means that over this value, the evolution of the compacity can not be linked to the number of passes.

Note : results of gyratory shear compacting press tests are represented by a graph showing the compacity versus the number of gyrations, generally there is a logarithmic law between these two parameters in the domain 75-95% compacity rate and there is no more relation out of this domain .

The target thickness was about 13cm just after laying for an expected thickness after the process of compacting about 10cm. The temperature of the asphalt was controlled during the laying and stayed constant at about 135°C. Track after track, the compaction was immediately made after the laying.

Each track was divided in two bands of 1.70m width (size of the drums) with a 40cm width overlap band. The driver began the compaction on the right band and drove the compactor 'there and back' for the 2 bands. This process was repeated until the expected number of passes was reached.

The parameters of the compactor correspond to the NFP 98 736 classification (French standard):

- linear mass : 27.9 kg/cm.
- Amplitudes : 0.86mm.
- Frequency : 38 Hz.
- Speed : 5km/h

4. Data analysis

4.1. Declivity (longitudinal slope)

An inclinometer was embedded on the roof of the compactor to measure the declivity. Signal processing showed that the signal of the inclinometers is too much perturbed by the vibrations induced by the system. After filtering the signal can not give better than the mean of the declivity on the total length of the track (25m).

We computed too the declivity using the coordinates of the compactor given by the GPS measurements. The results fit quite well the 'real' slope evaluated with the help of the topographical measurements done on track 8. The results are quite better with the GPS measurements than with the inclinometer.

4.2. Compacity

We measured the compacities every 2 meters of each axis, (i.e. 10 compacities per axe) Measurements of compacity have been done with a Variable-depth Point Gammadensitometer. Figure 3 shows the evolution of the mean of the compacities obtained on each axis of the tracks represented with its standard deviation, the X axis is logarithmic scale in order to be coherent with the representation associated to the gyratory shear compacting press test.

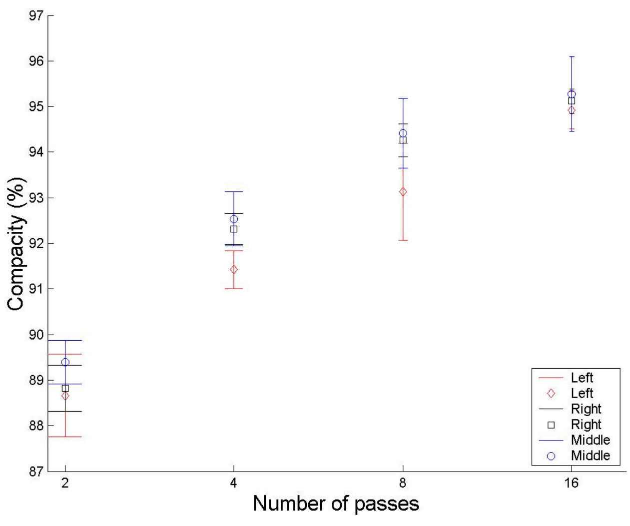

Figure 3: Evolution of the compacity.

As expected, the compacity increases with the number of passes. Furthermore, the compacity on the middle axis is above the compacity on the left and right axis which is logical since there was an overlap band in the middle of the tracks.

We notice that the compacity on the right axis is always above the compacity on the left axis; we do not have a clear explanation for that but we assume this result can be linked to the fact that we began the compaction on the right axis.

Generally the relationship between the number of passes and the compacity is a logarithmic law. Actually, the number of passes represents the energy of compaction as in the gyratory shear compacting press test the number of gyrations represents the energy of compaction. However we can notice on Figure 4 that the relation does not seem to be linear any more above 8 passes. We assume that around 94% of compacity, the law is no more logarithmic but is an intermediate law between logarithmic law and saturation.

4.3. Resistive effort

We calculated the average resistive effort on each track, for each pass and each axis. The results are represented on Figure 4, with a logarithmic scale for the x-axis.

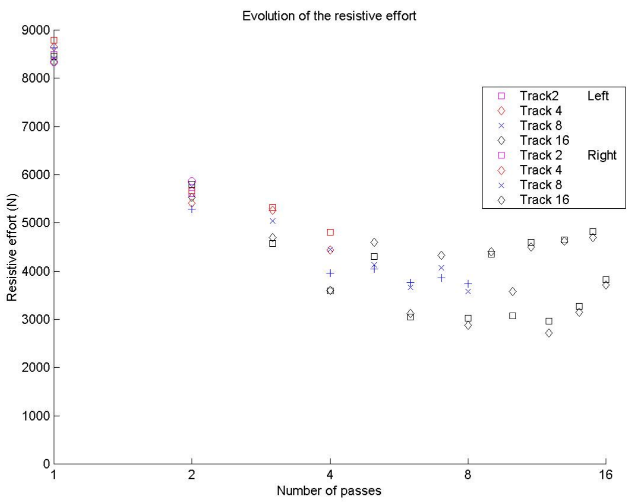

Figure 4: Average resistive effort.

The evolution of the resistance is not linear, so, that it has not a logarithmic law. As expected, the resistive effort is decreasing with the number of passes. For track 8, there is no more evolution of the resistive effort from the 4th pass. The case of track 16 is discussed later.

We observe, for both left and right axis, that the values of resistive effort are very closed for passes 1 and 2, only passes for which the comparison of the results is possible for all tracks. From the 4th pass we observe an increase of the dispersion of the results.

On Figure 4 we observe for track 16, an important dispersion (about 1200N.m) between even and uneven passes (i.e. forwards and backwards). We tried to explain this fact helping with two observations made during the compaction of track 16: (i) the driver and the people around the track could feel the vibrations, (ii) the wind was stronger. We propose an analysis of the influence of these two phenomena that the modelling used to compute the resistive effort does not take into account and finally we propose an other way to estimate it.

Influence of the vibrations

2 accelerometers were embedded on the front frame and drums, to record the x and z vibrations. So we made a frequency analysis on the signal of these accelerometers to study the evolution of the vibrations of the compactor on track 16. Using the Fast Fourier Transform we calculated the frequencies and their amplitudes. The fundamental of the signals corresponds to the frequency of the vibration equipment (about 38Hz).

The evolution of the ratio of the amplitudes of the first harmonic on the fundamental can be observed on Figure . This ratio increases with the number of passes and reaches a saturation at 10 passes, except for the 8th pass (problem of acquisition). We can assume a change in the response of the soil at the 10th pass. Before this 10th pass, the soil absorbs the vibration and after, the soil forwards the vibration to the compactors and excites other modes of it. So, the impact of the vibration on the movement of the compactors becomes more important. Actually we suppose the vibrations have a privileged direction that supports the motion in a way and brakes the motion in the other way. Of course, this explanation is only our interpretation : we do not have enough data to confirm it.

Currently our model does not take into account the vibrations. However, it is possible to include this effect via a more complicated model, more expensive sensors and more expensive experiments in order to identify the parameters of the vibrations.

Influence of the wind

In the case of the existence of wind, the compactor is subjected to an additive tractive or resistive effort. We evaluate this effort by this formula:

$$R_{wind} = \rho S V^2$$

where,

ρ, is the volumetric mass of the air,

S, is the surface of the compactor exposed to the wind, a rectangle of 2m width and 3m high

$V = V_{compactor} + V_{wind}$, is the relative speed.

$V_{compactor}$=5km/h, V_{wind}=20km/h

We estimate that during the compaction of track 16 the compactor was subjected to a tractive or resistive effort about 380N. The influence of the wind does not explain alone the dispersion between even and uneven passes but, it can be a part of it.

'There and back solution'

In order to remove the influence of the privileged direction due to the vibrations and the wind, we computed the resistive effort for the 'there and back' trajectory. Figure 5 shows the resistive effort for each ‘there and back’ of the compactor, with a logarithmic x-axis. We can see that the resistive effort is decreasing until the 3rd ‘there and back’ , stay constant until the 7th and seems to increased after.

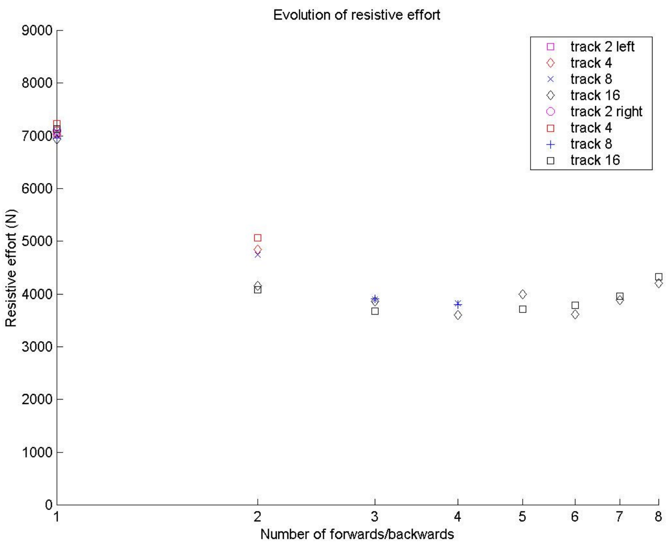

Figure 5: Average resistive effort calculated on 'there and back'

The computation of the resistive effort on 'there and back' has the advantage to eliminate the influence of the gravity.

5. Relationship compacity/resistive effort

Previous section presented the compacity and the resistive effort results. Figure 6 (next page) represents the compacities of each track versus the resistive effort calculated for the last ‘there and back’ trajectory on this track. The compacity is represented with its standard deviation.

It was obvious that the relationship between compacity and resistive effort for both left and right axis is linear for the first three tracks so we draw the regression lines between 2 and 8 passes. The correlation coefficients of the regressions are respectively 0.9996 and 0.9975 on the right and left axis ; the slopes of these relations are very closed from each other. The points corresponding to the track 16 have not been used to make the regression.

In the section 4.6.2 we noticed that for the last passes on the track 16 the resistive effort was increasing. In the section 4.5. we made an other observation: after 95% of compacity the behaviour of the asphalt is changing, i.e., the asphalt is no more in its logarithmic law of compaction. These two remarks can be linked because the compacity measured on the track 16 is 95%. We deduce from these remarks that the change in the evolution of the resistive effort is linked with a change in the law of compaction.

For this asphalt and in the conditions of the experiment previously described, the relationship Compacity / Resistive Effort :

- is linear until the compacity rate of 94% (which is equivalent to 8 passes),
  (it corresponds for the gyratory shear compacting press test to the domain where the asphalt is compacted in its logarithmic law.)
- can not be defined after 94% of compaction
  (it corresponds, for the gyratory shear compacting press test, to the domain where the asphalt is no longer compacted in its logarithmic law.)

Thanks to Figure 6, we can define a precision on the resistive effort assuming that the resistive efforts have to be the same when the compacities are the same. For track 2 and, to a smaller extend for track 8, the compacities can be compared on the left and right axis, we notice a deviation between the resistive efforts of less than 50N. For track 4, the compacities are not equals and we have a difference between the resistive efforts.

Associated to the standard deviation of about 50N.m on the resistive effort, we have a precision on the estimation of the compacity of about 0.1%. So, if we assume that the accuracy on the estimation is given by twice the standard deviation, the accuracy on the measurement of compacity by the resistive effort is +/- 0.2%.

6. Conclusions and perspectives

We proposed in this article a new method of control of the compaction rate during the process. This method consists in the calculation of the resistive effort, due to the asphalt, by using proprioceptives sensors embedded on the compactor.

The evolution of the compacting rate is linked with the evolution of the resistive effort. We could make this study helping with the modelling of the compactor moving along a straight line and with a full scale experiment, presented in the beginning. The data analysis presented leads to the study of the relationship compacity/ resistive effort. This study shows that, in the conditions of the experiment:

for a compacting rate between 89% and 94%, the calculation of the resistive effort makes possible the estimation of the compacity with an accuracy of +/- 0.2%.

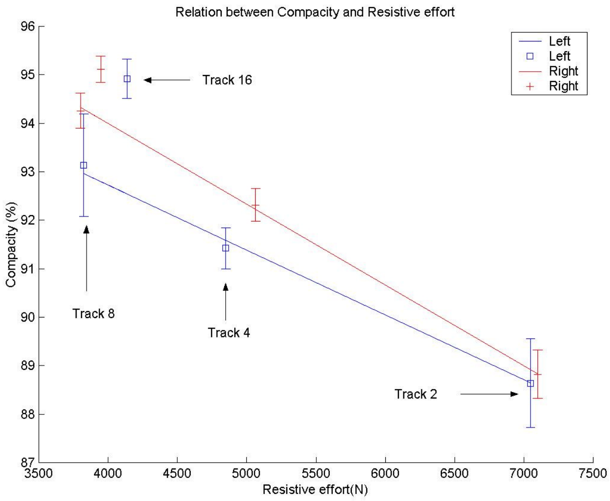

Figure 6: Relationship compacity/resistive effort.

Having developed the computations tools, the estimation of the compacting rate is possible in 'real time' with a few equipment. This minimum equipment required is represented Figure 7.

- 2 pressure sensors to calculate the motors torques,
- 2 encoders, one for each drum, to calculate the rotations speed,
- An onboard computer to record the data and to compute the resistive effort.

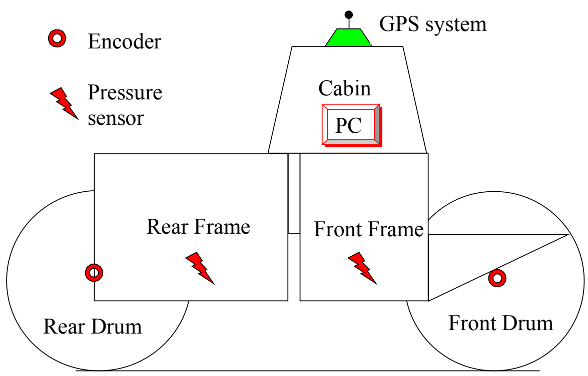

Figure 7: Minimum equipment required.

In the case of a calculation only on the 'there and back' trajectories it has to be notice that the declivity does not have to be calculated. Then the GPS system which is an expensive equipment is not required.

The identification is an essential step to compute the resistive effort. This step can be made with the same equipment embedded on the compactor to estimate the compacting rate. The identification requires :

- to move the compactor on a 'there and back' trajectory,
- to put the compactor on support.

Some methods that permit to identify the parameters more directly and more simply may be investigated to reduce the cost.

Even if we obtain good results, we are not able yet to propose a global tool to estimate the compacting rate for all the materials.

It would be of interest to make other experiments to have a bigger set of results. We can imagine to change the thickness of the asphalt, the initial temperature, the declivity or the weather conditions. Obviously, it would be of higher interest to study different kinds of asphalt. But the cost of each experiment is very high because it requires many people and the laying of the asphalt is expensive. An idea is to use a compactor fully equipped and to use it to make measurements on real roads sites in order to build a data base.

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