# EVALUATION OF COMPACTION BEHAVIOUR OF HOT MIX ASPHALT BY MEANS OF FINITE ELEMENT MODEL

*Rampini R.*
*PhD – Polytechnic of Milan – riccardo.rampini@polimi.it*
*Fiori F.*
*PhD – Polytechnic of Milan – federico.fiori@polimi.it*
*Bacchi M.*
*PhD Student – Polytechnic of Milan – matteo.bacchi@polimi.it*

## ABSTRACT

The behaviour of hot asphalt mix still represents a relevant question in road engineering from which depends the understanding of compaction phenomenon and the quality of the paving job.

The use of finite element models can provide a valuable tool to predict the response of the bituminous material when compacted under high temperatures, but due to a remaining lack of understanding, the definition of the constitutive parameters of the model still results to be too approximated.

This paper presents the results of a compaction simulation of hot asphalt mix by means of a finite element model. The compaction phenomenon has been modelled considering the elasto-plasticity of the bituminous material and the dynamics of the rolling procedures for each single pass.

Differently from ordinary algorithms, the developed model lays the basis on an experimental compaction model already obtained by one of the Authors through real-scale tests. The calculus parameters, then, could be consequently refined for better describing the real phenomenon.

The model has been finally validated by means of a direct measure of the Elastic Modulus of the material at final compaction temperature, using the indirect tensile test by means of the Nottingham Asphalt Tester (N.A.T.).

The model thus created provides a more refined definition of the computation parameters usually assumed in hot asphalt finite element models, representing at the same time a useful tool for simulating the compaction phenomenon of hot asphalt mixes.

*Keywords: hot asphalt compaction, finite element model*

# 1. INTRODUCTION

Physical and mechanical characteristics of hot asphalts mix vary considerably during the compaction process. The gradual increase in density generated by the roller passes and the continuous cooling of the mix produce, in fact, a sensible reduction of the plastic properties of the material in favour of an increment of elasticity (Ter Huerne, 2004).

At the present, the behaviour of asphalt concrete at high temperatures (> 60°C) is not fully understood, essentially because of the unsuitability of the hot soft material to be subjected to load test measures. For this reason the use of a simulation tool based on a finite element model analysis (F.E.M.) certainly represents a useful method for determining the constitutive bonds that characterize hot asphalt concrete during the compaction process.

The conventional finite element modelling techniques normally require the definition of the constitutive laws of the material to allow the construction of the model; then, after the application of the stress, tensional and deformative responses can be measured.

Concerning this study, the constitutive laws of the hot asphalt concrete are unknown and represent the object of the analysis. On the opposite, the results of the compaction procedure in terms of degree of compaction could be calculated applying the results of a recent experimental analysis conducted by one of the Authors (Rampini, 2007; Crispino, Rampini, Pozzi, 2007).

By means of a backward procedure it's been possible to determine the stress-strain behaviour of the material during each phase of the compacting procedure.

# 2. BACKGROUND

Recent experimental analysis (Rampini, 2007) allowed to determine the correlation between the obtainable degree of compaction and the applied Total Equivalent Static Load (TeSL). The TeSL corresponds to the sum of all the Static Linear Loads transferred over a pavement section, corrected by a dynamic coefficient in case of vibratory pass (where the Static Linear Load represents the ratio between the load transmitted to the ground by each roller drum and its width, expressed in daN/cm [1]).

The model has been created considering a layer of Asphalt Base mix with a thickness of 45 mm. The main characteristics of the mix are summarized in Table 1.

**Table 1 Main characteristics of the asphalt mix**

| Asphalt Mix | Layer Thickness [mm] | Bitumen Penetration Index | Sieve Diameter [mm] | Passing [%] | |
|---|---|---|---|---|---|
| Asphalt Base | 45 | 160/220 | 22.4 | 100 | 100 |
| | | | 16 | 85 | 99 |
| | | | 11.2 | 58 | 88 |
| | | | 8 | 50 | 76 |
| | | | 5.6 | 41 | 67 |
| | | | 4 | 36 | 59 |
| | | | 2 | 26 | 47 |
| | | | 1 | 19 | 36 |
| | | | 0.5 | 13 | 26 |
| | | | 0.25 | 8 | 18 |
| | | | 0.125 | 4 | 12 |
| | | | 0.075 | 2 | 7 |
| | | | 0.063 | 2 | 6 |

This type of asphalt mix corresponds to one of those examined during the experimental study (Rampini, 2007; Crispino, Rampini, Pozzi, 2007) and it's characterized by a fairly small thickness, which allows a more handy elaboration and a reliable equation for the prediction of the degree of compaction. The results obtained for the case of the Asphalt Base mix with a thickness of 45 mm present the following equation, which correlates the degree of compaction (DoC) with the Total Equivalent Static Load (TeSL):

$$DoC = 2.87 \cdot \ln(1 + TeSL) + 82 \qquad \text{(Eq. 1)}$$

where:

$$TeSL = \sum_{i=1}^{n} \left( k_i^f \cdot SLL_i^f + k_i^r \cdot SLL_i^r \right)$$

and

$n$ = number of passes;
$k$ = dynamic coefficient (k=1, static);
$SLL^f$ = Static Linear Load (front drum);
$SLL^r$ = Static Linear Load (rear drum).

## 3. MODEL CHARACTERIZATION

During the entire analysis, the asphalt concrete has been considered as an elasto-plastic material. Due to the rapidity of application of the load, the viscous component was considered to be legitimately ignored.

The utilization of the Total Equivalent Static Load in the analysis potentially allowed to make use of any type and number of rollers, performing a variable number of passes. For easiness of elaboration the simulation of the compaction process has been carried out using only one “virtual” roller. Its characteristics are the same of one of the rollers actually used during the real-scale experimentation, and are shown in Table 2.

**Table 2 Main characteristics of the roller used in the simulation**

| Roller Abbrev. | Operating Weight [kg] | Static Linear Load [kg/cm] | | Amplitude Hi/Low [mm] | | Frequency Low/Hi [Hz] | | Drum Diameter [mm] | Drum Width [mm] |
|---|---|---|---|---|---|---|---|---|---|
| | | Front | Rear | Front | Rear | Front | Rear | | |
| R1 | 10400 | 30.7 | 31.2 | 0.7/0.3 | 0.7/0.3 | 50/62 | 50/62 | 1300 | 1680 |

The compaction process consists of 7 consecutive passes executed with vibration at low amplitude; the dynamic coefficient *k* results equal to 1.22 [Rampini, 2007].

## 3.1 Development of the model

The entire compaction process makes use of the software Ansys Multiphysics© 10.0. The model has been created using SOLID45 elements, embedded at the base; the application of the loads was possible by means of a plain surface made of squared SURF153 elements of 1 cm of width each. The meshing and merging operations allowed to obtain a complete correspondence between the nodes.

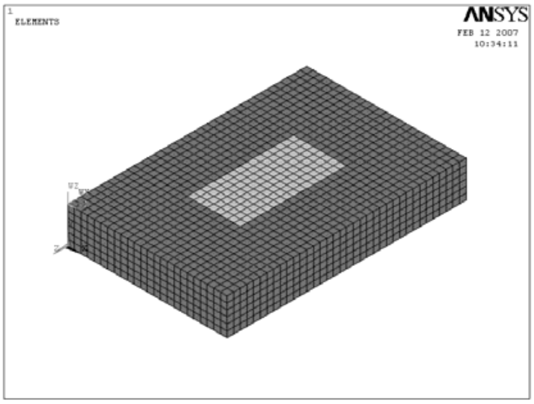


**Figure 1 Model structure with SURF153 elements**

The width of 1 cm for each SURF153 element allowed to apply the roller static linear load over a unitary area, with an equivalent pressure expressed in $daN/cm^2$.

## 3.2 Load application procedure

The load transmitted by each roller drum to the pavement has been distributed over a contact area whose dimensions vary in function of the degree of compaction of the material.

The pressure distribution has been imposed with reference to the typical diagram of the contact pressures transmitted to the pavement by a wheel in motion.

The total pressure transmitted by each drum corresponds to the value of static linear load applied over an area of unitary width; for the utilized roller equals 30.7 daN/cm$^2$ for the front drum and 31.2 daN/cm$^2$ for the rear one. The load has been discretized and distributed on the surfaces constituting the load area; the sum of the pressures on all surfaces equals the total pressure transmitted by the drum.

Figure 2 shows an example of pressure area of 8 cm of width; the variation of the load area dimension during compaction will be successively described.

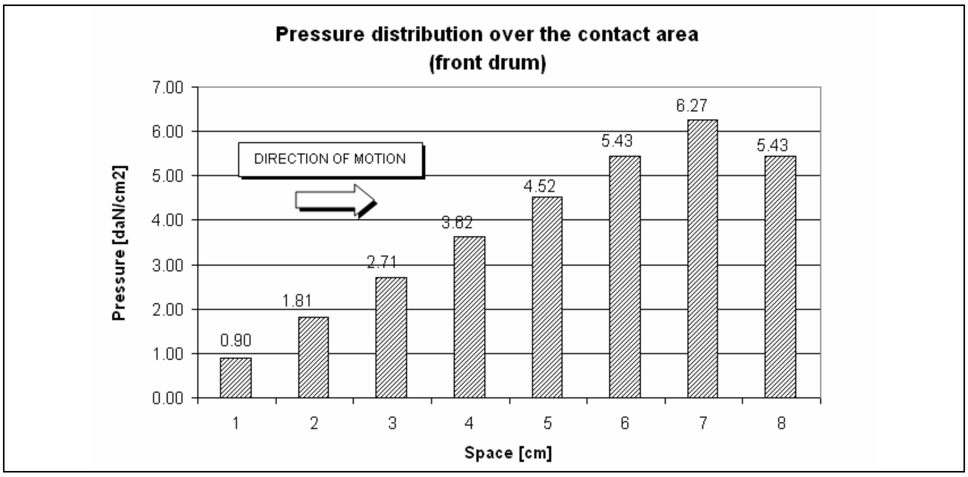


**Figure 2 Example of pressure distribution over a contact area of 8 cm of width**

The simulation of the roller drum transit has been accomplished applying the different pressures gradually and in progression, for a duration of time corresponding to a rolling speed of 5 km/h, and considering the inversion of motion of the roller at each pass. This computation has been carried out using the Transient Dynamic Analysis.

## 3.3 Definition of the material characteristics

Considering the hypothesis of elasto-plastic material, the input data requested by the software result to be:

- elastic modulus E;
- Poisson ratio υ;
- yield stress;
- slope of the plastic branch (Tang Mod);

- density of the material.

The density of the material could be easily obtained from the Equation 1, while the Poisson ratio was fixed equal to 0.2 [Ter Huerne, 2004].

The unknown parameters, then, are represented by the elastic modulus, the yield stress and the slope of the plastic branch, whose values vary continuously during the compaction process.

## 4. PRELIMINARY CALCULATION

The determination of the unknown parameters has been achieved analysing the thickness reduction produced by each pass of each roller drum. The output values from the software computation have been compared to those calculated by means of the application of the Equation 1. Reiterating the process it's been possible to determine the unknown parameters for each load step.

In Table 3 are shown the results in terms degree of compaction and relative thickness reduction obtained from the Equation 1; the elaboration has been arrested at the seventh pass corresponding to a degree of compaction of 100%.

**Table 3 Determination of thickness variation by means of the DoC equation**

| N° of Roller Pass | Drum Pass | TeSL [daN/cm] | DoC [%] | Δ thickness [%] | Thickness before pass [cm] | Δ thickness [cm] | Thickness after pass [cm] |
|---|---|---|---|---|---|---|---|
| 1 | Front | 37.45 | 92.5 | 10.47 | 5.50 | 0.58 | 4.92 |
| | Rear | 75.52 | 94.4 | 1.97 | 4.92 | 0.11 | 4.82 |
| 2 | Rear | 113.58 | 95.6 | 1.16 | 4.82 | 0.06 | 4.75 |
| | Front | 151.04 | 96.4 | 0.81 | 4.75 | 0.04 | 4.71 |
| 3 | Front | 188.49 | 97.1 | 0.63 | 4.71 | 0.03 | 4.67 |
| | Rear | 226.55 | 97.6 | 0.53 | 4.67 | 0.03 | 4.64 |
| 4 | Rear | 264.62 | 98.0 | 0.44 | 4.64 | 0.02 | 4.62 |
| | Front | 302.07 | 98.4 | 0.38 | 4.62 | 0.02 | 4.60 |
| 5 | Front | 339.53 | 98.7 | 0.33 | 4.60 | 0.02 | 4.58 |
| | Rear | 377.59 | 99.0 | 0.30 | 4.58 | 0.02 | 4.56 |
| 6 | Rear | 415.65 | 99.3 | 0.27 | 4.56 | 0.02 | 4.55 |
| | Front | 453.11 | 99.6 | 0.25 | 4.55 | 0.01 | 4.53 |
| 7 | Front | 490.56 | 99.8 | 0.23 | 4.53 | 0.01 | 4.52 |
| | Rear | 528.63 | 100.0 | 0.21 | 4.52 | 0.01 | 4.51 |

It can be noticed that starting from an initial thickness of 5.5 cm, at the end of the process a final thickness of 4.5 mm was obtained.

The density of the material then has been calculated (Table 4) applying once again the Equation 1 and considering a final density of the material equal to 2,350 kg/m$^3$ in correspondence of a degree of compaction of 100% [Dynapac, 2000].

**Table 4 Density variation of the material during compaction**

| N° of Roller Pass | Drum Pass | DoC [%] | Density [kg/m$^3$] |
|---|---|---|---|
| Paver pre-compaction | | 82.0 | 1927 |
| 1 | Front | 92.5 | 2173 |
| | Rear | 94.5 | 2220 |
| 2 | Rear | 95.6 | 2247 |
| | Front | 96.4 | 2266 |
| 3 | Front | 97.1 | 2281 |
| | Rear | 97.6 | 2293 |
| 4 | Rear | 98.0 | 2303 |
| | Front | 98.4 | 2312 |
| 5 | Front | 98.7 | 2320 |
| | Rear | 99.0 | 2327 |
| 6 | Rear | 99.3 | 2334 |
| | Front | 99.6 | 2340 |
| 7 | Front | 99.8 | 2345 |
| | Rear | 100.0 | 2350 |

## 4.1 Determination of the contact area dimensions

Because of the continuous increase of density of the material, the contact area of each roller drum reduces considerably during the compaction process, with a consequent increase of the contact pressures transmitted to the pavement. Some simple geometric considerations allowed to calculate the value of the contact area of the drum in relation to the relative decrease in thickness produced by the drum pass. It must be underlined that the considered thickness reduction only refers to the plastic permanent deformation, while the elastic component could not be quantified. For the successive computation of the contact areas, the elastic contribution, which increases with the compaction progress, has been taken into consideration as well.

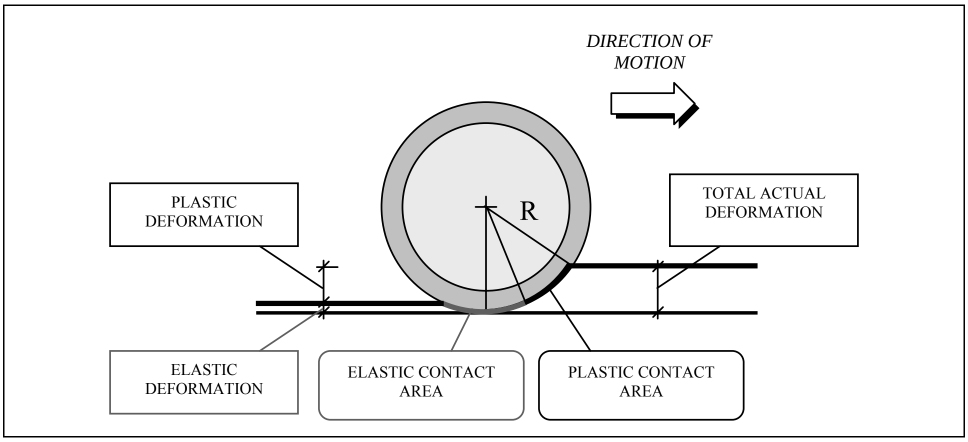


**Figure 3 Decomposition of the contact area in its elastic and plastic component**

The obtained values of the contact area width are shown in Table 5.

**Table 5 Variation of the contact area width during compaction and corresponding approximated values**

| N° of Roller Pass | Drum Pass | Thickness before pass [cm] | Δ thickness [cm] | R–Δs [cm] | Angle [rad] | Width of contact area (calculated) [cm] | Width of contact area (approx.) [cm] |
|---|---|---|---|---|---|---|---|
| 1 | Front | 5.50 | 0.58 | 64.42 | 0.1332 | 8.66 | 8 |
| | Rear | 4.92 | 0.11 | 64.89 | 0.0578 | 3.76 | 4 |
| 2 | Rear | 4.82 | 0.06 | 64.94 | 0.0443 | 2.88 | 3 |
| | Front | 4.75 | 0.04 | 64.96 | 0.0371 | 2.41 | 3 |
| 3 | Front | 4.71 | 0.03 | 64.97 | 0.0327 | 2.13 | 2 |
| | Rear | 4.67 | 0.03 | 64.97 | 0.0298 | 1.94 | 2 |
| 4 | Rear | 4.64 | 0.02 | 64.98 | 0.0274 | 1.78 | 2 |
| | Front | 4.62 | 0.02 | 64.98 | 0.0253 | 1.65 | 2 |
| 5 | Front | 4.60 | 0.02 | 64.98 | 0.0238 | 1.55 | 2 |
| | Rear | 4.58 | 0.02 | 64.98 | 0.0227 | 1.47 | 2 |
| 6 | Rear | 4.56 | 0.02 | 64.98 | 0.0216 | 1.40 | 2 |
| | Front | 4.55 | 0.01 | 64.99 | 0.0204 | 1.33 | 2 |
| 7 | Front | 4.53 | 0.01 | 64.99 | 0.0196 | 1.28 | 2 |
| | Rear | 4.52 | 0.01 | 64.99 | 0.0190 | 1.24 | 2 |

It can be noticed that the contact area width changes considerably during the compaction process, consequently the corresponding variation of the pressure values transmitted by the roller to the pavement results definitely significant.

Since the model considers discrete surface elements, the contact areas used for the computation have been approximated to the integer, also considering the gradual increase of the elastic component of the deformation (Table 5).

Recalling that the load is equal to 30.7 daN/cm$^2$ for the front drum and 31.2 daN/cm$^2$ for the rear one, the simulation of the compaction process has taken place executing 7 roller passes (14 drum passes), also considering the inversion of motion of the roller in correspondence to each pass.

## 4.2 Determination of the stress-deformation curve

Once determined the stress transmitted by the roller at each pass and its relative deformations in terms of thickness, it's been possible to obtain the stress-deformation curve, which provides the basic information about the variation of the plastic characteristics of the material during the compaction process.

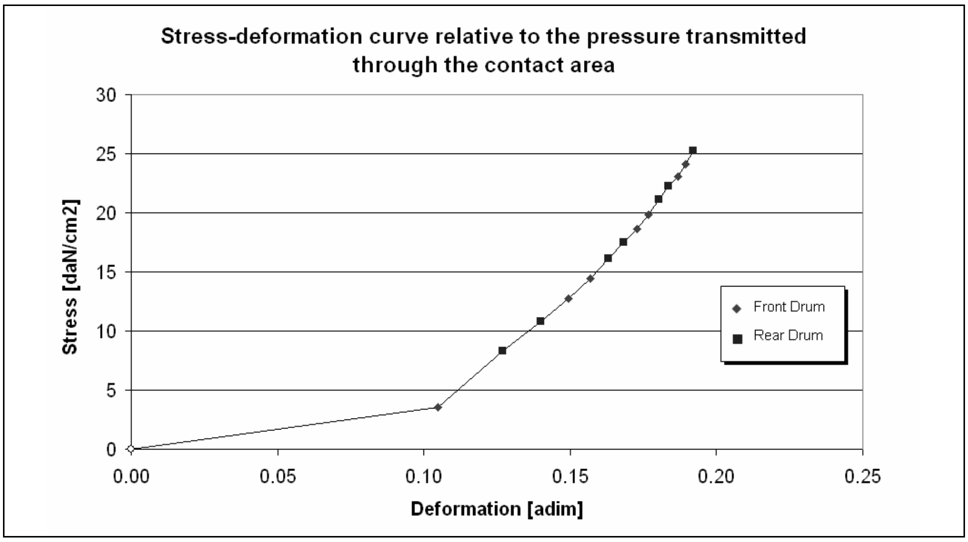


**Figure 4 Stress-deformation curve relative to the vertical contact pressures transmitted by the roller drums to the asphalt surface**

The curve was determined considering the stresses generated by the roller to the asphalt surface and the deformations calculated as the ratio between the variation of layer thickness caused by each drum pass and the layer thickness before each pass.

The curve shown in Figure 4 has been plotted considering each roller drum pass; in particular 14 points have been determined, 7 relative to the front drum and 7 for the rear drum.

# 5. RESULTS OF THE F.E.M. ANALYSIS

Reiterating the computation algorithm previously described, it's been possible to univocally determine the fundamental parameters that describe the constitutive bonds of the asphalt mix during compaction; the results are shown in Table 6.

**Table 6 Results of the F.E.M. analysis**

| N° of Roller Pass | Drum Pass | E [daN/cm$^2$] | Yield Stress [daN/cm$^2$] | Tang Mod [daN/cm$^2$] | Thickness before pass [cm] | Δ thickness [cm] | Thickness after pass [cm] |
|---|---|---|---|---|---|---|---|
| 1 | Front | 30 | 0.1 | 1 | 5.33 | 0.41 | 4.92 |
| | Rear | 500 | 3.0 | 45 | 4.92 | 0.11 | 4.81 |
| 2 | Rear | 600 | 6.3 | 85 | 4.81 | 0.06 | 4.74 |
| | Front | 700 | 7.2 | 90 | 4.74 | 0.04 | 4.70 |
| 3 | Front | 800 | 10.4 | 114 | 4.70 | 0.03 | 4.66 |
| | Rear | 930 | 11.2 | 120 | 4.66 | 0.03 | 4.63 |
| 4 | Rear | 1070 | 12.5 | 130 | 4.63 | 0.02 | 4.61 |
| | Front | 1180 | 13.4 | 135 | 4.61 | 0.02 | 4.59 |
| 5 | Front | 1280 | 13.5 | 140 | 4.59 | 0.02 | 4.57 |
| | Rear | 1370 | 13.6 | 140 | 4.57 | 0.02 | 4.55 |
| 6 | Rear | 1430 | 13.7 | 140 | 4.55 | 0.02 | 4.54 |
| | Front | 1500 | 13.8 | 140 | 4.54 | 0.01 | 4.53 |
| 7 | Front | 1600 | 13.9 | 140 | 4.53 | 0.01 | 4.51 |
| | Rear | 1680 | 14.0 | 140 | 4.51 | 0.01 | 4.50 |

The results in terms of thickness reduction obtained by the F.E.M. computation exactly match those calculated by the Equation 1 [2].

## 5.1 Determination of the constitutive bonds

Once calculated the fundamental parameters characterising the asphalt mix, it's been possible to determine the constitutive bonds of the material referred to each phase of the compaction.

In Figure 5 it is shown the progression of the stress-strain bond during the entire compaction process; each drum pass corresponds to a load-unload cycle.

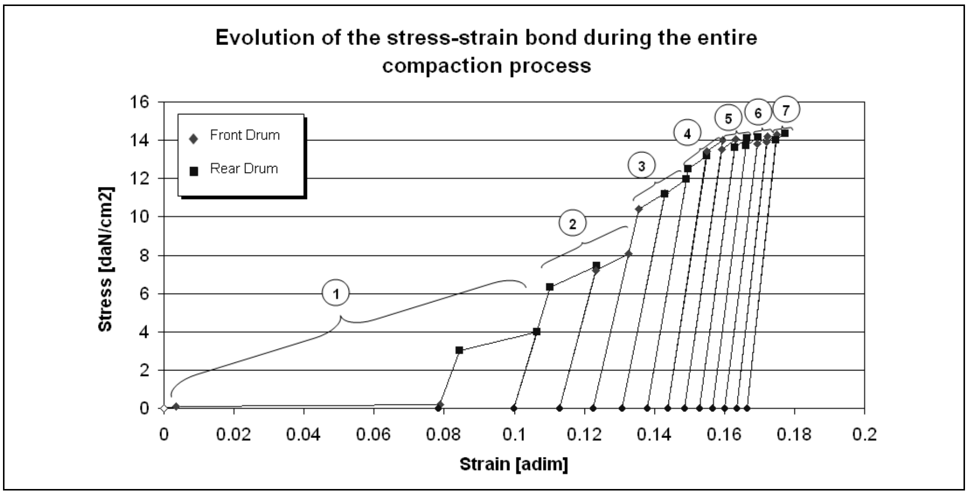


**Figure 5 Evolution of the stress-strain bond during the entire compaction process (7 roller passes)**

It can be noticed that, at the beginning of the compaction process, the asphalt mix is characterised by a very low stiffness, proved by the high deformation produced during the first pass. During the progression of the compaction the material becomes stiffer and the permanent deformation reduces its value showing a less effective compaction effect of the roller, which can be considered negligible right after the fourth roller pass. These considerations are confirmed by experience and are coherent with the initial hypotheses. Analysing the variation of the material behaviour in correspondence of each drum pass it can be observed that during the compaction the elastic branch of each curve increases in extension and slope, becoming stable during the last passes. Particularly, the variation of the single parameters could be analysed (Figs. 6, 7 and 8).

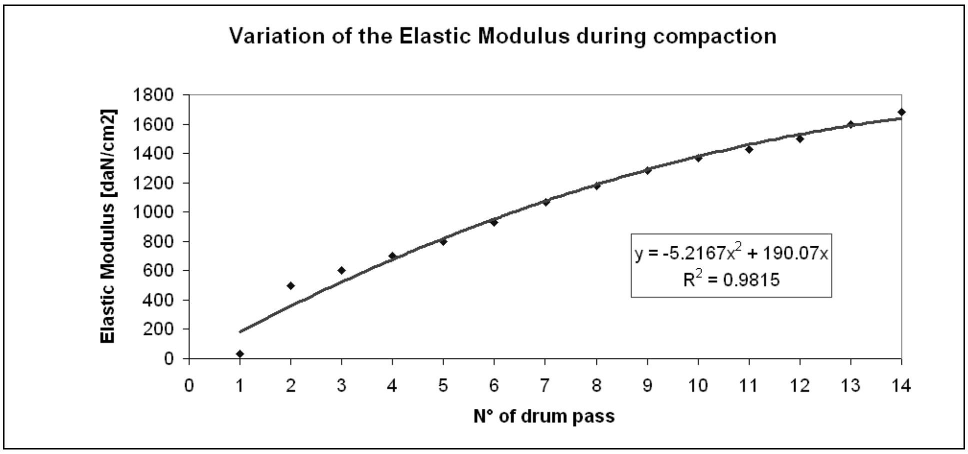


**Figure 6 Variation of the Elastic Modulus during compaction**

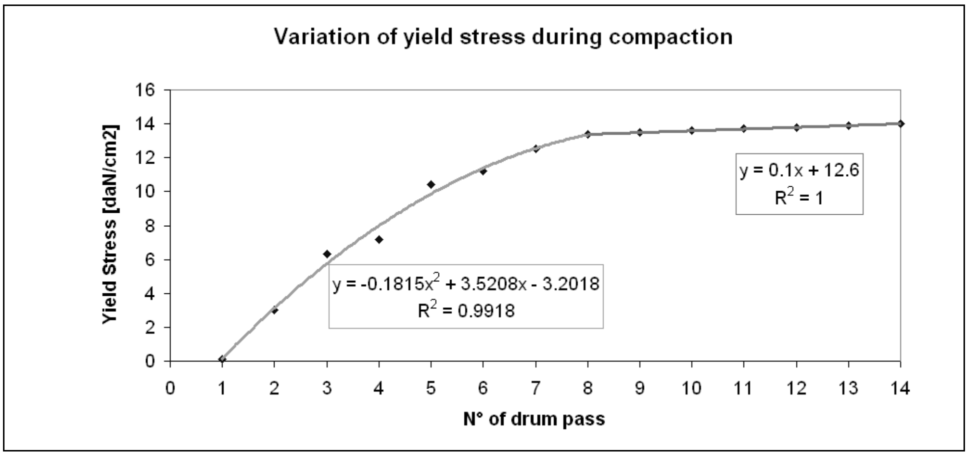


**Figure 7 Variation of the yield stress during compaction**

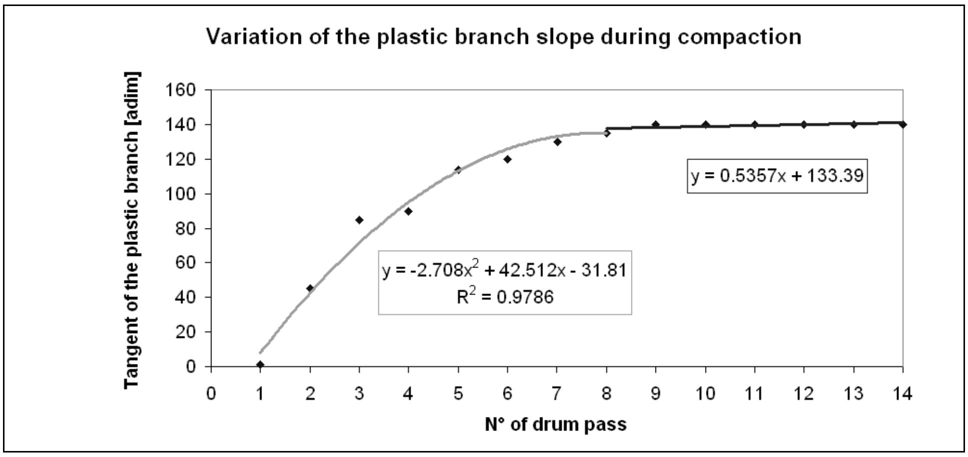


**Figure 8 Variation of the slope of the plastic branch during compaction**

## 6. VALIDATION OF THE MODEL

With the intention of finding an experimental confirmation of the obtained results, a measure of Elastic Modulus of the hot asphalt mix has been carried out, using the indirect tensile test by means of the Nottingham Asphalt Tester (N.A.T.) [Cooper, Brown, 1993]. The test has been carried out over 7 laboratory samples compacted with 75 strokes per face corresponding to the 100% of Marshall degree of compaction. The samples have been heated up to a temperature of 80°C, then tested with the N.A.T.. Tests at higher temperatures could not be executed because of the high deformability of the material that caused errors in the transducers measurements.

The average value of Elastic Modulus relatively to the 7 measures at 80°C is equal to 148 MPa, resulting of the same order of magnitude of the one obtained by the F.E.M. elaboration at the end of the compaction process (168 MPa).

## 7. CONCLUSION

For determining the behaviour of the hot asphalt concrete during the compaction process a F.E.M. analysis has been carried out. The model considered a layer of Asphalt Base-45 mm compacted with a tandem roller, vibrating at low amplitude and executing 7 passes. The F.E.M. analysis has been applied atypically, first considering the results obtained by a previous experimental analysis on compaction of asphalt mixes, then moving backwards to the determination of the stress-strain characteristics of the asphalt mix during the entire compaction process.

The model allowed to determine the actual pressures transmitted by each roller drum to the pavement at each phase of the compaction. The phenomenon has been also analysed in relation to the progressive reduction of sinking of the drum into the asphalt layer, with consequent reduction of the contact area and increase of the contact pressures.

The simulation by means of the F.E.M. analysis allowed to obtain the constitutive bonds characterising the hot asphalt concrete during the entire compaction process. Particularly the values of Elastic Modulus, Yield Stress and slope of the plastic branch in correspondence of each drum pass have been estimated. Finally their variation laws have been deduced.

The validation of the model has been carried out measuring the value of elastic modulus by means of the N.A.T. indirect tensile test. In spite of the difficulties connected to the high plasticity of the material, the obtained measures confirm the outputs of the analysis.

Through the present study the Authors wished to bring a significant contribution to the knowledge of the compaction phenomenon of hot asphalt mixes, aiming at a more comprehensive and rational approach to the design and maintenance of asphalt concrete pavements.

## ENDNOTES

[1] Note that the original definition of the SLL assumed the kilogram-force as unit; according to the S.I. notation, and for easiness of comparison, the daN is used in this dissertation.

[2] In correspondence of the first drum pass, the variation of layer thickness from 5.50 cm to 4.92 cm was possible considering E = 5 kg/cm$^2$; however, this very low value of E causes irregular deformations and generates errors in the simulation model. A correct behaviour of the first drum pass, causing the expected thickness reduction, was possible considering E = 30 kg/cm$^2$ and an initial layer thickness of 5.33 cm.

## REFERENCES

CRISPINO M., RAMPINI, R., POZZI, M., (2007) – "An experimental analysis of the effects of compaction on asphalt pavement macrotexture" – *Advanced Characterisation of Pavement and Soil Engineering Materials Conference*, Athens, Greece.

COOPER K.E, BROWN S.F., (1993) – "Assessment of the Mechanical Properties of Asphaltic Mixes on a Routine Basis Using a Simple Testing Equipment", Proceedings of the *5th Eurobitume Congress*, vol. 1B, Stockholm, Sweden.

DYNAPAC (2000) – *Compaction and Paving – Theory and Practice* – Svedala Dynapac Publication IHCCCAPEN1, Sweden.

RAMPINI, R. (2007) – *Sviluppo di una metodologia empirico-razionale per l'ottimizzazione delle tecniche di compattazione dei conglomerati bituminosi* – PhD Thesis, Politecnico di Milano, Milan, Italy.

TER HUERNE, H. L. (2004) – *Compaction of Asphalt Road Pavements* – PhD Thesis, CT&M Department, University of Twente, the Nederlands.