HMA Compaction Study: Two Different Approaches

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ABSTRACT: Hot-mix asphalt compaction is indispensable to ensure asphalt pavements durability, as has been shown by many studies in the past. Several types of rollers, mixtures and atmospheric conditions create a complex phenomenon for which there is not enough scientific and technical information. In this paper two different approaches to study this matter are assessed, with focus on its application field and advantages/disadvantages.
The first approach consists in carrying out large field tests, where it is evaluated the influence of some variables in the compaction degree.
The alternative approach consists in the up to date numerical modelling. In this study HMA is modelled in two dimensions and the material components (aggregate and bituminous mastic) are represented by circular rigid particles that interact with each other at soft contact points based on the Distinct Element Method.

KEY WORDS: Asphalt mixtures, compaction, field tests, numerical models.

1 INTRODUCTION

Compaction increases asphalt mixtures density (lower volume) and particles become more closely packed with a higher number of contacts. This process gives the material the aptitude to support the expected traffic loads without rutting or other type of premature failure. In Portugal as in other countries, road authorities only specify one goal – final compaction degree higher than 97%. The lay-out of the construction (paver, type of rollers and sequence, etc.) is entirely decided by the constructor. In opposition to granular materials, asphalt mixtures have a limited compaction period (equal to the cooling time). Therefore it seems very important to know how every roller should be used to achieve compaction within the minimum execution time.

In this study it was studied asphalt compaction, using two different methodologies. The first methodology was to carry out field tests, trying to evaluate the influence of several parameters in the layer compaction degree, within real construction environment. The alternative methodology was to use numerical models. In comparison to traditional studies at laboratory or at field, numerical modelling permits to perform a larger number of analyses in less time and with a small cost. The two methodologies application is described and discussed the ability to study/examine the complex process that is asphalt compaction.

2 FIELD TESTS

The tests are briefly described and the results statistically analyzed with regression models to find the influence of each test parameter in the layer compaction degree. Complete results can be found in (Micaelo 2009).

The experiment consisted on measuring the compaction degree in a real construction environment for a variety of compaction conditions. It was varied the asphalt temperature, the roller weight, the roller compaction mode, the roller dynamic parameters and the number of roller passes. The tests were carried out during paving of two pavement layers with different asphalt mixtures. The tests were executed in a parking area around the factory of HAMM AG, roller manufacturer, in Tirshenreuth, Germany, on 1st to 5th August 2005. The area, with approximately 7200 m^2, was divided in 72 test sections which were then subdivided in 6 parts according to the number of roller passes.

The pavement was designed with two granular layers and two asphalt layers. For the asphalt base layer, with 14 cm, was used a continuously graded mixture 0-32 mm with unmodified 50/70dmm bitumen. For the wearing layer, with 3.5 cm, was used the Stone Matrix Asphalt, with aggregate gradation 0-11 mm, polymer modified bitumen Styrell PmB 45A and cellulose fibers.

The compaction was carried out with two HAMM steel-wheel rollers, the DV70VO and the DV90VO. The first has a static linear load of 26.5 and 26.0 kg/cm, respectively in front and rear drums, and the second roller 28.9 and 27.1 kg/cm. Both rollers can be used in four different compaction modes, depending on the selection of the static or the dynamic mode in each drum (vibration or oscillation): “S-S” static-static; “V-S” vibration-static; “S-O” static-oscillation; “V-O” vibration-oscillation. The “V-S”, “S-O” and “V-O” modes are classified as dynamic compaction modes. It was defined an additional compaction mode with the combination of the static mode “S-S” and one dynamic mode, where after the dynamic passes the roller did 4 extra passes in the static mode.

The dynamic action of the drum is defined by the dynamic principle (vibration or oscillation) and its characteristics (frequency and amplitude). In the oscillatory drums the amplitude (tangential) is fixed (1.30 mm – DV70 and 1.37 mm – DV90) while in the vibratory drums is possible to select two amplitude (vertical) values. It was selected the maximum amplitude for the compaction of the base layer and the lowest for the wearing layer. For both dynamic modes it is possible to change the frequency in a predefined range. It was defined three frequency levels (high, medium and low) for each mode (oscillation and vibration). The tests were carried out for the three levels in “V-S” and “S-O” modes while for “V-O” mode it was selected just both maximum values and both minimum values.

Regarding the temperature influence on the compaction degree, the compaction modes were repeated with three different layer temperature levels: hot (160-130ºC), average (130-100ºC) and cold (100-70ºC). The temperature measurement was done with infrared thermometers before the first roller pass. The coolest sections were obtained by allowing the paved layer to cool to the defined temperatures.

The pavement structure, the foundation, the paver (Vögele Super 1800-1), the roller velocity (4 km/h) and the asphalt production facility were not changed. The weather conditions changed, with maximum temperatures between 13 and 21 ºC and minimum temperatures between 7 and 12ºC. There was slight intermittent rainfall during four days.

The compaction degree measurements were taken with two different in-situ measuring equipments, the nuclear density gauge (Troxler manufacturer) and the Pavement Quality Indicator (PQI). It was not possible to take cores to measure the density at lab.

Figure 1 shows the field test results, according to the layer type and the measurement equipment. The bulk results show that:

- As expected the compaction degree increases with the number of roller passes, with a high value for just one pass;
- The results variability for a number of accumulated roller passes is larger for the Troxler measurements and the base layer;
- For the same accumulated roller passes the compaction degree is lower in the base layer than in the wearing layer.

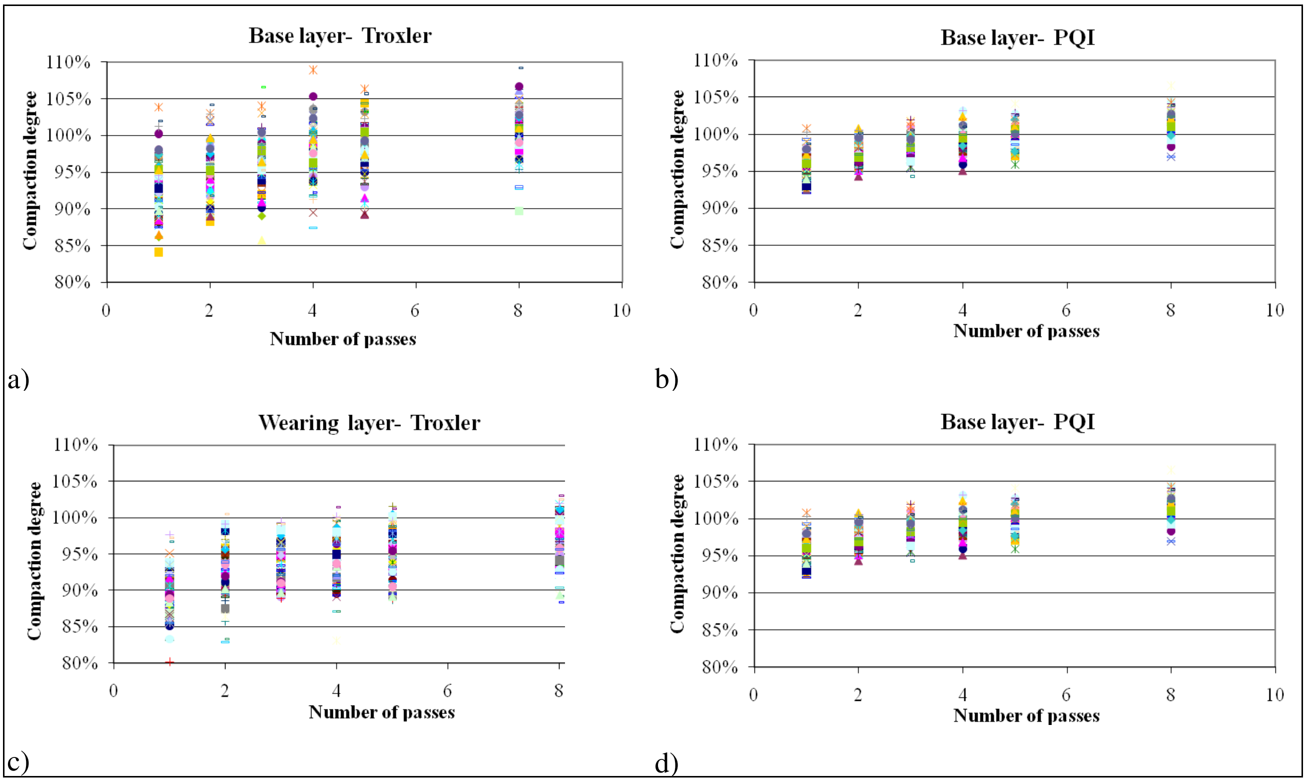

Figure1: Compaction degree measurements for the two asphalt layers.

As it was not possible to measure the compaction degree with an accurate procedure (water displacement lab procedure) it can not be evaluated the accuracy of the two in-situ measuring equipments. The average measured compaction degree in the base layer is higher than in the wearing layer, for any number of roller passes, with both measuring equipments. On average, for the wearing layer it was not possible to obtain the minimum compaction degree (97%) with 8 roller passes while for the base layer it was enough 3 or 4 passes.

As during the tests many variables were varied the results were studied statistically with regression models to evaluate the influence of each in the compaction degree. A regression model (mathematical equation that relates one or more variables with a certain error) is a statistical technique, descriptive and inferential, that can helps to evaluate the relation between a group of independent variables and a dependent variable. In this study the dependent variable is the compaction degree (Gc) and the independent variables all the test variables that were changed during the test. Therefore it was used multiple regression models.

At the beginning, the following independent variables were selected: type of layer; roller; layer temperature; compaction mode (S-S, V-S, S-O, V-O); dynamic mode frequency; number of roller passes. Different regression models were determined for the test results obtained with the two measuring equipments. Different math functions were tested, with the exponential function showing the best results. Table 1 shows the coefficient of determination (R^2) and the Beta standardized coefficients, which quantify the influence of each variable on the dependent variable (Gc), for the determined regression models. A higher Beta standardized coefficient means that the independent variable value change influences more the dependent variable value.

Table 1: Coefficient of determination and Beta standardized coefficients

Data	R^2	Beta standardized coefficients							
		Layer	Roller mass	Layer Temperature	Static roller passes	Vibration frequency	Oscillation frequency	Frequency V-O	Nº of roller passes
"Troxler"	0.723	-0.370	0.202	0.363	0.275	0.100	0.125	0.252	0.533
"PQI"	0.909	-0.822	0.035	0.227	0.146	0.124	0.146	0.177	0.389

The regression model "PQI" shows a very good adjustment to the test results while for "Troxler" is fair. In both models it was included the same variables but not all that were previously selected. The compaction mode and the dynamic mode frequency variables failed in the multicollinearity statistics tests and the significance tests to the regression coefficients. Therefore it was included just one type of the two kinds of variables, modes or frequencies. A positive beta coefficient value means that the dependent variable varies in the same way as the independent variable.

Regarding the influence of the variables on the compaction degree, the two regressions agree about the three variables with higher influence but determine different influence levels. For the "Troxler" regression, the number of roller passes is the most influent while for the "PQI" it is the type of layer. For the "Troxler" the influence levels of these variables are nearer than for the "PQI" regression. The roller mass can be considered influent for the "Troxler" regression while for "PQI" is null. The static roller passes at the end have more influence in "Troxler" regression, which in this situation can be quantified as 2.8% increase in the compaction degree. About the compaction modes, the dynamic modes have higher performance than the static mode (all beta coefficients are positive). For both regressions the performance grows in the following order: "V-S", "S-O" and "V-O". The first two modes have similar performances. The use of "V-S" instead of the "S-S" increases 1.3% on average the compaction degree. The performance of "V-O" is not consensual, with a higher influence level determined by the "Troxler" regression.

The two measuring equipments measured different field compaction degrees. PQI could have been influenced by the superficial moisture during base layer paving and the SMA superficial texture, while Troxler could have been influenced by the layers thickness and the short measuring time (only 30 sec.).

This methodology allowed to study the process in a real construction environment but the cost was very high, it was difficult to manage paving and measurements (workers and equipments) and the weather forecast is only accurate for some days ahead. The available in-situ measuring equipments measure different values. Finally, the number of key variables is so large that is not possible to carry out experiments where all variables influence is analyzed. In this study each layer includes many other variables whose influence should also be quantified as the thickness, the aggregate (gradation, angularity, etc.) and the bitumen (type, content, etc.).

3 NUMERICAL MODELLING

Numerical models are traditionally divided in two groups: discrete and continuous. Discrete methods (also named micromechanical methods) intend to predict the materials macroscopic behaviour by simulating the interaction of the different elements that compose the material, while continuum-based methods use in general macroscopic stress/strain phenomenological laws.

Asphalt mixtures are complex materials composed of bitumen, aggregates, filler and voids. A range of asphalt mixtures can be produced depending on the proportions of these components and the aggregate gradation. During compaction, aggregate and mastic (bitumen plus fine aggregate) are displaced until getting stable positions. Some researchers (Collop et. al 2004), among others, refer that the asphalt complex behaviour is originated by the interaction of the different elements and therefore it can not be studied by the traditional continuous methods. Different numerical models, for example Finite Element Method – FEM, Distinct Element Method – DEM and Lattice Network Model – LNM may be adopted for discrete modelling purposes.

In the last decade, some studies were published about the implementation of discrete models to the analysis of asphalt mixtures. However, until now micromechanical methods had not been used to study asphalt compaction. On the other hand, some applications to the powders compaction study could be found (Ransing et al. 2000). The powders compaction, like asphalt, consists in creating contacts through reorientation and distortion of the particles.

In this paper, it is described the implementation of a 2D DEM model to study HMA compaction.

3.1 DEM - Distinct Element Method

The Distinct Element Method was first introduced by (Cundall 1971) for blocky rock systems studies and then successively adapted over the years to a variety of engineering problems. The materials are discretized in small rigid particles that interact at soft contacts allowing the contacts to be created and broken during the simulation course.

The DEM is based on two main principles:

- Force – Displacement law: the contact force acting on two entities in contact is derived from the relative displacement between the entities;
- Law of motion: the motion of a rigid particle is determined by the resultant force and moment vectors acting upon it (Newton's second law).

The two principles are applied consecutively in the calculation cycle. The general DEM calculation cycle is based on an explicit local equilibrium scheme whereby the motion of each particle is defined using the sum of the forces at its contacts. The dynamic behaviour is numerically represented by an algorithm with explicit timestep that uses central differentiation scheme for velocities and accelerations. The adopted timestep is limited so that during a single timestep the disturbances can only propagate to its immediate neighbours. At every step the forces acting upon a particle are exclusively determined by its interaction with other particles at its contacts. During the simulation process the DEM calculation cycle is usually applied thousands or even millions of times.

The method can model a static problem or a dynamic problem. The implemented method models the system in two-dimensions, only two force components and one moment component are determined in opposition to the three force components and moment components that exist in a three-dimension assembly. The modelled assembly can be seen as a collection of variable-radius cylinders or alternatively as a collection of variable-radius spheres whose centroids all lie upon the same vertical plane. The force-displacement law is applied, in every cycle, to determine the normal and shear forces acting in all contacts based on contacts stiffness and relative displacements. The normal and shear stiffnesses are defined by the adopted contact model. In the present work it was used the Linear Elastic and the Burger's Viscoelastic contact models. The Burger's model is used to simulate time-dependent behaviour and for some conditions the visco-elastic-plastic behaviour exhibited by asphalt mixtures. The model considers the association of Maxwell's model and Kelvin's model in series.

A Bonding Model and the Mohr-Coulomb Model are adopted for the failure contact modelling. The Bonding Model is adopted just for particle-particle contacts and it specifies maximum tension/shear strength. When the contact force is exceeded the contact is considered to fail. The Mohr-Coulomb Model defines the maximum shear contact strength as a function of the normal contact force and the contact friction coefficient. It is only active when the Bonding Model is not considered or the contact has previously failed.

The simulation process has several steps. Figure 2 shows the steps and its execution order. First, assembly generation, the particles are positioned in a specific location and the contacts are created; second, it is defined the contact models, the boundary conditions (e.g. areas of restricted particles movements and assembly stresses) and the loads (active loads with forces acting on particles gravity centre and imposed wall movements or passive loads with imposed disturbances in the assembly); third, calculation, defined by the total number of calculation cycles and the timestep; finally, the results analysis, which determines if the simulation is valid, if the parameters values are as expected, the errors to avoid in the future, etc. A discerning analysis may reduce the number of simulations and increase the software skills.

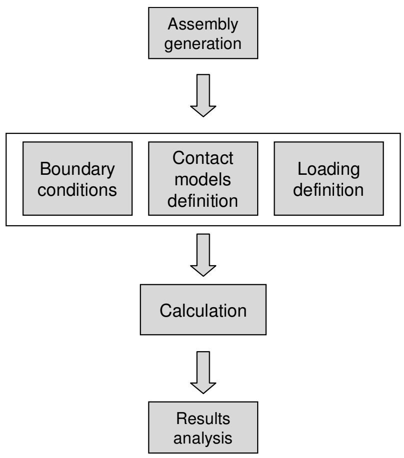

Figure 2: Sequence of the simulation steps.

Before the study described in this paper it was analyzed the potential of a 2D DEM model to study asphalt compaction (Micaelo 2009). The validation process consisted in the simulation of a simple lab compaction procedure, and it showed that it is possible to numerically reproduce the force evolution during the compaction process, with the right chosen contact models and parameters, but it is not possible to reproduce the porosity evolution because of the 2D limitations in the materials representation. After the promising simulation of the laboratory static compaction test it was decided to wide the research to field compaction (roller compaction).

3.2 Field Experiment

A small field test, with approximately 50 m long and 2.5 m wide, was carried out and controlled to acquire the necessary data for the simulations. The compaction test consisted in paving and compacting an AC 0/16 layer on top of another asphalt layer. It was selected one of the mixtures used before in the validation modelling procedures, described in Figure 3 and Table 1. The layer was pretended to be 70 mm thickness before the roller passes. Two different roller (HAMM HD75) compaction modes were used: static and vibratory. Figure 4 presents the cross-section and plan of each compaction mode of the test. During compaction it was monitorized the evolution of layer thickness (level and rod), the temperature (inside the layer and superficial by IF thermometer), the compaction times and the accelerations of the drum in the vibration mode, Table 2. After the test, cores were drilled to measure the final density and height (layer thickness). A roller pass represents the course of the roller from one side of the test section to another in one way. Figure 5 compares the thickness data acquired in the test and estimated statistically. It can be seen that the average layer thickness, before compaction, was lower in the vibratory test section. The thickness reduction for the vibratory mode is unlike because in the first passes there is a reduced compaction evolution as it can be seen by the comparison to the predicted by (FGSV 2004). Therefore it was used the predicted thickness evolution in the simulations of the vibratory mode compaction.

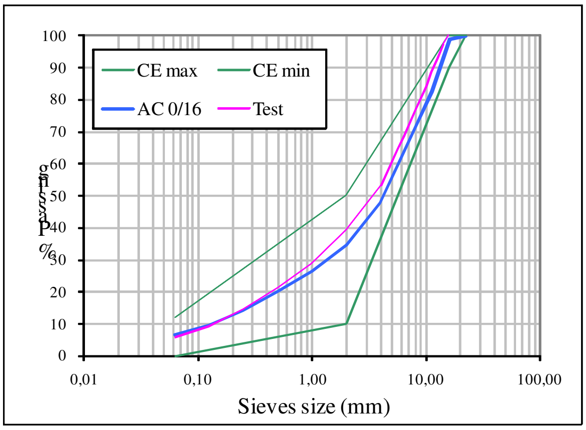

Figure 3: Gradation of AC 0/16.

Table 1: AC 0/16 properties.

	AC 0/16
Bitumen content (% by total mass)	5.3
Density (g/cm^3)	2.4
Max. Density (g/cm^3)	2.5
Porosity (%)	3.9
Bitumen content (% by total volume)	12.1
VMA (%)	16.1
Voids filled with bitumen (%)	75.0

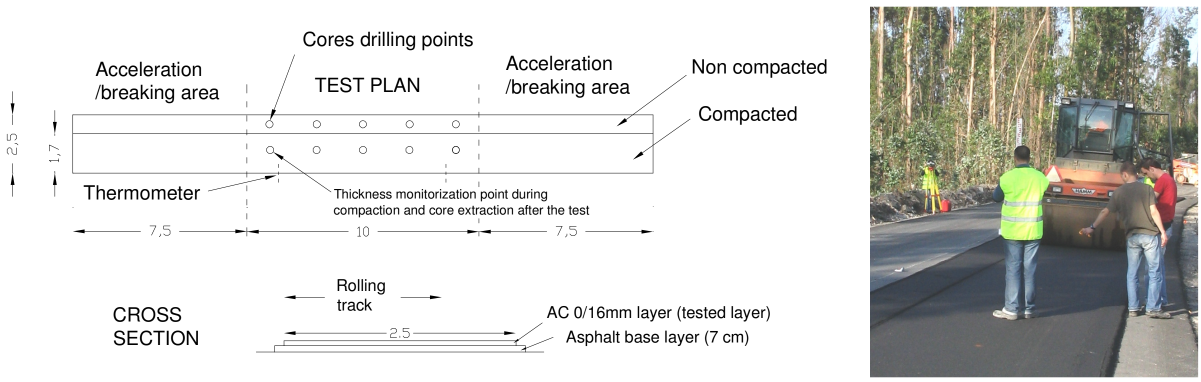

Figure 4: The cross-section and plan of the compaction test (left); work in progress photo (right).

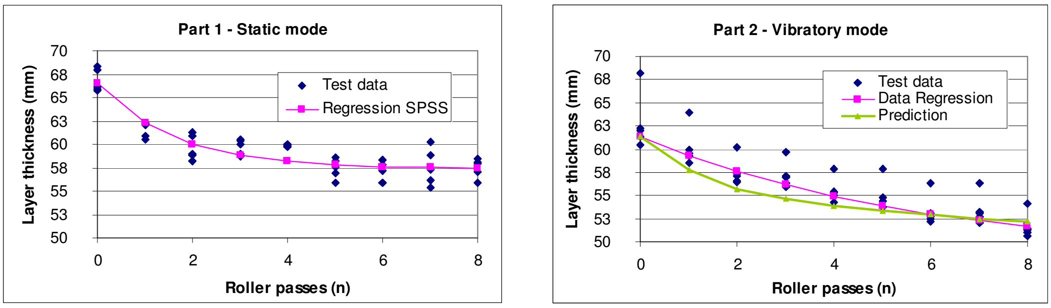

Figure 5: The thickness data measured and estimated for the static and vibratory compaction modes.

Table 2: Roller drum vibration data.

	Fo	Accelerations		Amplitudes	
		max	min	max	min
Pass	(Hz)	(m/s2)	(m/s2)	(mm)	(mm)
1	53.0	62.2	-57.9	0.51	-0.52
2	55.6	63.5	-59.7	0.49	-0.50
3					
4	55.4	64.9	-62.1	0.50	-0.51
5	55.1	66.1	-63.7	0.52	-0.52
6	55.5	67.2	-63.7	0.51	-0.52
7	55.0	65.1	-63.4	0.51	-0.52
8					

3.2 Simulations

As referred before the simulation process starts with the assembly generation. The assembly is composed of two kinds of particles, aggregate and mastic. The mastic includes the bitumen and the fine aggregate (less than 2 mm). As a DEM model increases the computational requirements as more particles are added to the assembly, the mastic particles were defined with 1 mm diameter while the coarse aggregate particle diameters were defined according to the grading sieves. The sieve generation technique is used to determine the number of particles for each sieve dimension, considering that there is equal ratio of the elements volume in the specimen and the elements area in the cross section used in the simulation. The particles are generated in a random position without contacts and then the contacts are imposed by other technique that combines sequentially the multi-layer generation and gravity action procedures. In the multi-layer technique, first it is generated a layer of particles and then compacted by wall movement until the desired porosity or stresses are reached. Following the gravity action technique is applied, which consists in letting the particles to settle by the gravity action like it was rain. Figure 6 shows the assembly that was used in the static mode compaction simulation. It is 305x67mm^2 and contains 11008 particles.

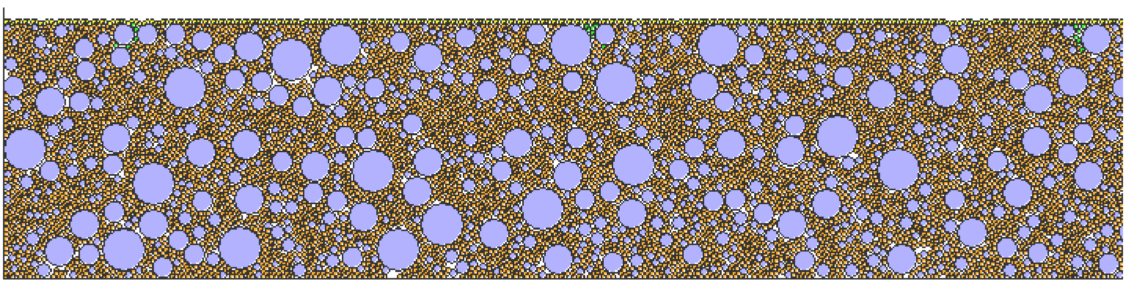

Figure 6: Static mode compaction assembly.

The roller compaction was simulated by reproducing the movement of the roller drum with a circular wall. In real roller compaction, displacements (layer thickness reduction) are not previously known. In the simulation the procedure works backwards as the final displacements are known and the forces not. The prescribed drum displacements are larger than the finals to account to the recoverable deformation. To find the correct displacements related to the contact characteristics an iterative procedure has been adopted. In the simulation each drum loads separately. First one drum does a pass followed by the other. Each roller pass displacement accounts for the pass of two drums so it was considered half imposed displacement by each drum.

Figure 7 shows the simulation of the drum pass and the forces arising of the roller-material interaction.

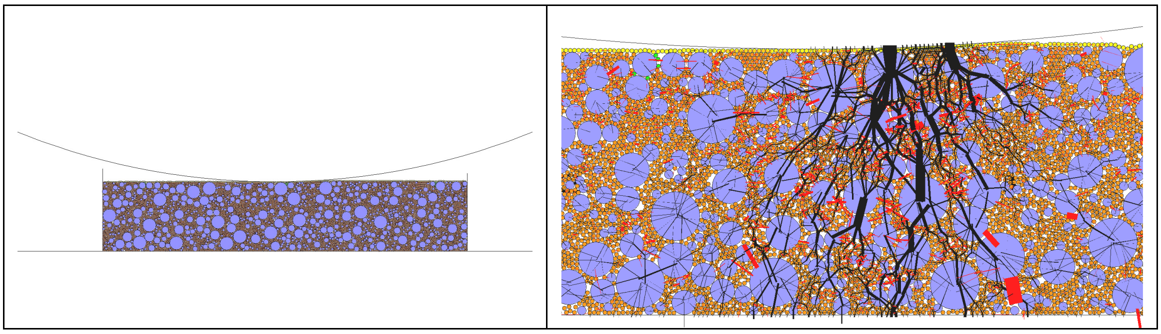

Figure 7: Static roller drum loading the assembly during the second pass (front drum), from left to the right. a) general view; b) zoom in of the centre area.

Huerne (Huerne 2004) states that according to the Critical State Theory compaction (volume reduction) only happens at stress states with low *q/p* ratio (lower than the critical ratio), where p = normal compressive stress and q = deviator stress. The higher is the *q/p* ratio the larger is the proportion of the shear deformation component to the total deformation. These stress parameters are given by:

$$p = \sigma_{oct} \tag{1}$$

$$q = \frac{3}{\sqrt{2}}\tau_{oct} \tag{2}$$

where σ_{oct} = octahedral normal stress and τ_{oct} = octahedral shear stress.

As stated the used model considers the system in two-dimensions, so the measured stress tensor (averaged for a specified area) is:

$$\begin{bmatrix} \sigma_x & \tau_{xy} \\ \tau_{yx} & \sigma_y \end{bmatrix} \tag{3}$$

where σ_x,σ_y = normal stresses and τ_{xy}, τ_{yx} = shear stresses.

Considering Plane Deformation State and linear behaviour, the out-of-plane normal stress is given by:

$$\sigma_z = \nu \times (\sigma_x + \sigma_y) \tag{4}$$

where ν = Poisson ratio. It was considered the same value used by Huerne ($\nu = 0.2$).

Figure 8 compares the stress paths, at two levels in the assembly, during one drum pass for the static and vibratory compaction modes. For the static mode the upper level “h4” experiences lower *q/p* ratios in opposition to the nearly constant *q/p* ratios at both levels for the vibratory mode. For the static mode the ratio varies between 2 and 5, and for the vibratory mode it varies between 2 and 3. Huerne obtained lower ratios, 1 to 2. As lower ratios mean higher proportion of volumetric deformation the vibratory mode is advantageous.

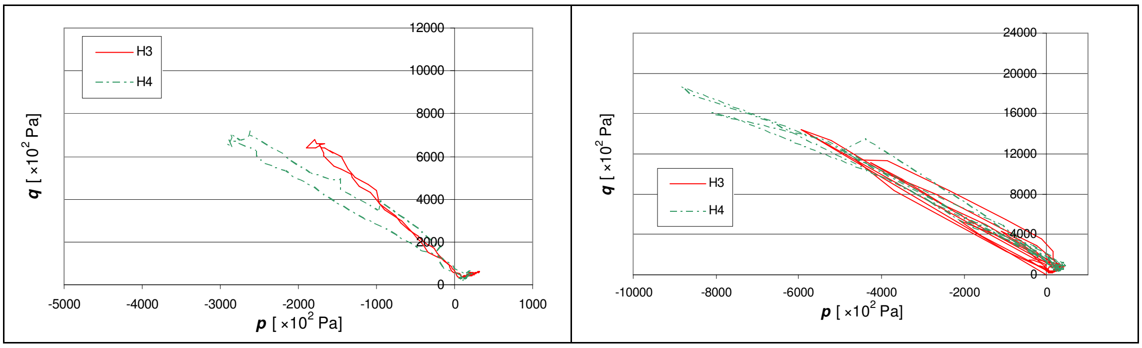

Figure 8: Normal compressive and deviator stresses at two levels inside the assembly during 3rd roller pass, in static mode (left) and vibratory mode (right).

4 CONCLUSIONS

This paper presents the study of HMA compaction with two different approaches. The first approach was to carry out field tests, where the paving conditions were varied to determine the influence in the final density. It was concluded that the type of layer, the number of roller passes and the temperature are the main variables but the two used measuring equipments do not agree about the influence level of each variable. The three dynamic compaction modes have different performances but all achieve higher densities than the static mode. This approach is useful but the previous pointed disadvantages do not advise many applications.

The second approach was to use a 2D DEM model to simulate field compaction, as the following step of the former studies. First, a test section was carefully constructed and monitored to obtain the required data (temperature evolution, thickness reduction with roller passes and vibratory drum behaviour). It was simulated the roller compaction in the static and vibratory compaction modes. The results agree reasonably well with the in field data and other available numerical data (Huerne 2004). According to the Critical State Theory the vibratory compaction mode is likely to create lower shear deformations during loading as compared to the static mode. Micromechanical models DEM were shown to be a capable tool to study a complex phenomenon like asphalt mixtures compaction at laboratory and at field, and in the future it should be extended to other mixtures and compaction conditions.

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