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HOT-MIX ASPHALT COMPACTION EVALUATION WITH FIELD TESTS

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Abstract. The objective of this study is to determine the influence of field compaction conditions on hot-mix asphalt layers compaction. A large field test was carried out to assess the compaction degree variation under field conditions such as the type of layer, the temperature and the roller (weight and compaction mode). Compaction evolution with roller passes of two asphalt layers was assessed *in-situ* with a nuclear and a non-nuclear measurement device. The analysis of the compaction results with regression models showed that the temperature, the roller weight and the asphalt mixture are the most influential and that the frequency, for all dynamic compaction modes, is not relevant. Finishing compaction increases layer's compaction degree up to 2%. The two different density gauges used in this study measured different compaction degree values.

Keywords: hot-mix asphalt, compaction, roller, field tests, nuclear density gauge, Pavement Quality Indicator.

1. Introduction

During hot-mix asphalt compaction, bitumen and aggregate particles are moved until attaining stable positions and major air voids are expelled resulting in bulk volume reduction. This "structural modification" determines the ability of asphalt mixtures to support expected loads during life cycle as designed, i.e., without premature rutting, fatigue cracking, etc. In most cases road authorities only specify one goal for constructed pavements – to obtain a compaction degree at the end higher than a certain value (usually 97% – relative to design density). The layout of construction is entirely decided by the constructor.

In spite of the recognized importance by all key players of the construction process (contractors, designers and road authorities), there is not enough scientific and technical information about asphalt behaviour during the compaction process (Huerne *et al.* 2008; Masad *et al.* 2014). The list of papers in conferences and scientific journals show clearly that asphalt mixtures characterization and design have had much attention while "how to construct", which provides or not as designed characteristics to the in-service material, has not attracted as much research.

The paving process is carried out in two phases. First, the asphalt mixture is spread continuously by the paver in a layer with predefined width and thickness, and with a compaction degree of 80–85% (Micaelo 2009). Second, the roller(s) make passes over the layer in a certain predefined sequence (breakdown, intermediate, finishing) to attain the required compaction degree. Different types of rollers and action modes are used in each sequence period, depending on the layer characteristics and each country practice tradition. The two main types of rollers (steel-wheeled and pneumatic) achieve compaction by applying static and/or dynamic loads. Dynamic loading is originated by the introduction of eccentric masses inside drums which rotate at high velocity making the roller drums to exhibit a low oscillatory movement while rolling. The most common is the vibration mode, developed during the 1950's and implemented by all roller manufacturers, which applies a vertical oscillatory movement. Other dynamic loading types are patent protected as the "oscillation" (HAMM AG, Germany) and the "variocontrol" (BOMAG GmbH&Co, Germany). In the "oscillation" technology the eccentric masses rotation creates a continuous back-front rotating movement while in the "variocontrol" the eccentric masses relative position varies so that the oscillatory direction is changed between vertical and horizontal directions (Kearney 2006; Mooney *et al.* 2010). Fig. 1 shows the principles of vibration and oscillation modes, which were tested in field, namely the eccentric masses movement and position that originates drum oscillatory movement while rolling.

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The dynamic movement/action is characterized by two parameters: amplitude and frequency. The frequency is the number of movements/impacts per second and is defined by the eccentric masses mounted shaft rotation velocity. The amplitude is the max movement from static position, which depends on the dynamic mode. In the vibration mode the amplitude is defined as the vertical movement of the drum's centre while for the oscillation mode is defined as the horizontal movement at the drum-layer contact point. However, true dynamic behaviour depends on the roller characteristics (manufacturer defined) and field conditions (layer characteristics, foundation stiffness), which are hardly predicted (Facas *et al.* 2010). According to Dietmar Adam (Mooney *et al.* 2010), the drum experiences five different operating conditions in the vibration mode (continuous contact, partial uplift, double jump, rocking motion, chaotic motion) which are identified with frequency spectrum analysis. Anderegg *et al.* (2006) states that the most common condition during hot-mix asphalt compaction is "continuous contact" where the drum though the vertical oscillatory movement never loses the contact with the compacting layer. In opposition, in a field test (Micaelo 2009) where a vibratory roller was monitored with accelerometers mounted on the drum, the frequency spectrum (Fig. 2) showed peaks at integral multiples of the excitation frequency (e.g. peak at $f \approx 106$ Hz) during all passes, and for the selected frequency range. This behaviour corresponds to the "partial uplift" operating condition (Adam's classification) that is characterized by a period of time in every cycle where the drum looses contact with the layer.

During the 1970's and the first half of the 1980's many field studies were carried out with vibratory rollers by Machet, Quibel, Froumentin, among other researchers, in France (Micaelo 2009; Ruban 2002). These studies concluded that: (1) vibratory rollers are more effective than static rollers, i.e., vibratory rollers achieve equal compaction with less roller passes; (2) the compaction effort depends on static linear load, frequency, amplitude, velocity and number of vibratory drums; (3) the compaction force is not proportional to the centrifugal force (force generated by the rotating eccentric masses); (4) the frequency influence is large around layer-drum resonant frequency and small above that (common used frequencies); (5) compaction effort increases with the theoretical amplitude (eccentric momentum of unbalanced masses); (6) compaction effort varies in opposition with the roller velocity. Since that time rollers have been modified by manufacturers, exhibiting today in general lower weight and different vibration characteristics (higher frequency and lower amplitude). No independent studies were found regarding asphalt compaction with other dynamic type rollers.

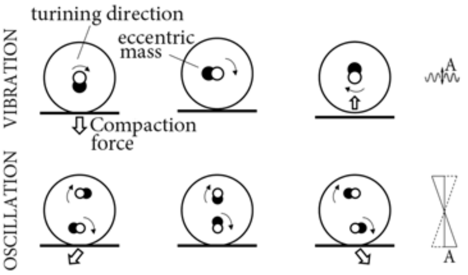

Fig. 1. Vibration and oscillation principles – adapted from Mooney *et al.* (2010) and Kearney (2006)

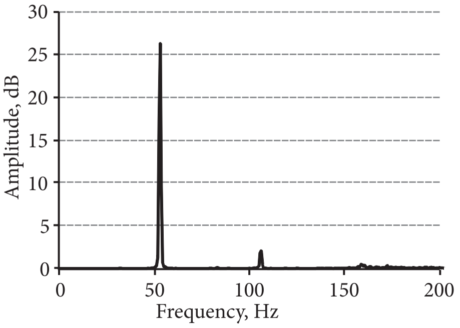

Fig. 2. Frequency spectrum of the vibratory drum during hot-mix asphalt compaction (Micaelo 2009)

During the last two decades not many studies have been published about roller compaction and most were focused on granular medium compaction. The high costs, the unpredictable weather conditions and the required organization incentivised research to move from field to lab, where the ability of several types of laboratory compactors to reproduce field compaction has been tested. However, many studies concluded that none is able to reproduce all field asphalt characteristics (mechanical properties, voids volume and distribution, etc.) at the same time (Hunter *et al.* 2009; Wistuba, Mollenhauer 2013). Lab compaction studies focused on the reproduction in lab of field samples and the measurement of asphalt mixtures' compactability, i.e., "…the relation between its density or void content and the compaction energy applied to it…" as defined in *EN 12697-10:2001 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 10: Compactability*. It was concluded that compaction effort increases in presence of the following asphalt mixture characteristics (Breakah *et al.* 2011; Micaelo 2009; Renken 2004, 2005; West *et al.* 2010; Çelik, Atiş 2008): (1) discontinuous aggregate gradation; (2) higher crushed aggregate content and aggregate particles angularity; (3) higher aggregate particles max dimension to layer thickness ratio; (4) lower bitumen content; (5) higher bitumen viscosity or lower compaction temperature.

Nowadays, due to very high motorization rate in urban areas, road pavement maintenance faces important time and spatial constrains. Repaving is commonly carried out at night or under restricted time frame, i.e. under adverse weather and working conditions. Given the fact that in opposition to granular materials, asphalt mixtures have a limited compaction period (equal to the cooling time), it is very important to know how every roller is to be used to achieve the required compaction within the minimum period of time.

This study concerns the hot-mix asphalt compaction process. A large field test was developed with the goal of evaluating the influence of known key factors on layer's compaction degree. The roller compaction of two hot-mix asphalt layers was carried out at varied conditions and the layer's density assessed in situ with two different density gauges. Regression models were developed with data from the two devices to quantify each factor's importance magnitude on final layer's density.

2. Experimental program

The experimental program consisted of a field test where it was measured *in situ* the compaction degree of two asphalt layers, using two different density gauges, for a variety of compaction conditions in a real construction environment. Different compaction conditions were obtained by changing the following factors' values/conditions: (1) layer temperature; (2) roller weight; (3) roller compaction mode; (4) roller dynamic parameters; (5) number of roller passes.

The tests were carried out during the paving operation of two hot-mix asphalt layers, with different asphalt mixtures, in a parking area around the factory building of HAMM AG, Tirshenreuth, Germany. The area, with approximately 7200 m^2, was divided in 72 test sections in accordance with the different compaction conditions.

The pavement was designed with one granular layer (200 mm) and two asphalt layers (base and surface courses). For the base course, 140 mm thick, a continuously graded aggregate mixture 0/32 mm was used with unmodified bitumen 50/70 (AC 32 base 50/70 – *EN 13108-1:2006 Bituminous Mixtures – Materials Specifications – Part 1: Asphalt Concrete*). For the surface course, 35 mm thick, the Stone Mastic Asphalt was used, with discontinuously aggregate gradation 0/11 mm, polymer modified bitumen *Styrell PmB 45A* and cellulose fibbers (SMA 11 PmB45 – *EN 13108-5:2006 Bituminous Mixtures – Materials Specifications – Part 5: Stone Mastic Asphalt*). Fig. 3 and Table 1 present the volumetric and aggregate characteristics of the two asphalt mixtures.

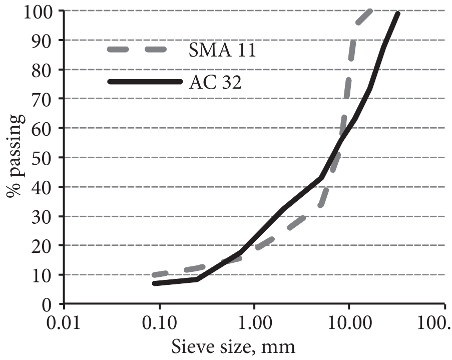

Fig. 3. Asphalt mixtures aggregate gradation

Table 1. Asphalt mixtures design properties

Bituminous mixtures	Unit	SMA 11 PmB45	AC 32 50/70
Binder content, *B*	$\%_{Mass}/\%_{Vol}$	6.4/16.3	4.0/8.8
Bulk density, ρ_b	kg/m^3	2606	2244
Max density, ρ_{mv}	kg/m^3	2698	2474
Air voids content, V_m	%	3.4	9.3
Voids in mineral aggregate, *VMA*	%	19.7	18.1
Voids filled with bitumen, *VFB*	%	82.7	48.6

Compaction degree measurements were carried out *in situ* with two non-destructive measurement instruments based on different technologies, the Nuclear Density Gauge – *NDG* (TROXLER Model 4640-B) and the Pavement Quality Indicator^{TM} – *PQI* (TRANSTECH Model 301). The first instrument measurement technology principle is gamma rays propagation, powered by a Cesium 137 radioactive isotope source, and the Compton scattering mechanism. The collision of gamma rays photons and material electrons cause energy loss and change of propagation direction. As the material density increases the number of photons scattered back to the instrument reduces. With proper calibration, photon count during a defined measuring period (30 s to 240 s) is related to the layer density (Kvasnak 2007). The method is simple and non-destructive, being used for some decades for this purpose. Pointed drawbacks concern radiation and requested procedures with license (country dependent), maintenance and control. The second instrument is more recent (from 1998); it develops an electro-magnetic field and determines density by measuring dielectric properties (dielectric constant) of surface material that change in the same way as density. Aggregates, bitumen and air have different dielectric constants, which makes the layer property to change as air is expelled with compaction (Kvasnak 2007). This instrument does not request licensing and safety control procedures in opposition to the nuclear instrument; it is easier to transport (7.5 kg) and provides instantaneous measurements (3 s) (Karlsson 2002).

The extraction of cores from pavement for density measurements at laboratory was not permitted. In the paper, the Compaction Degree (*CD*) is $\frac{\rho_b}{\rho_{mv}}$, where ρ_b is the layer's density and ρ_{mv} is the asphalt mixture design density (impact compaction – *EN 12697-30:2004 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 30: Specimen Preparation by Impact Compactor*).

For the paving operation a track paver was used, model VÖGELE Super 1800-1, with a screed that compacts using vibration and one tamping bar. Compaction was carried out with two different steel-wheeled rollers, HAMM models DV70VO and DV90VO. Only one roller was used in each test section. The rollers are referred in the paper from this point forward, respectively, as DV70 and DV90. The first roller has a static linear load of 2.70 N/m and 2.65 N/m, respectively in front and rear drums, and the second roller 2.95 N/m and 2.77 N/m. Both rollers have four different compaction modes, depending on the selection of the static or the dynamic mode in each drum (vibration or oscillation). Vibration is only activated in front drum and oscillation in rear drum. According to this, four different roller compaction modes were established: static-static "S-S"; vibration-static "V-S"; static-oscillation "S-O"; vibration-oscillation "V-O". The "V-S", "S-O" and "V-O" modes are classified as dynamic compaction modes.

Dynamic roller behaviour is dependent on working drum's amplitude and frequency. Regarding the amplitude, in the oscillation mode the amplitude (horizontal) is fixed, 1.30 mm for DV70 and 1.37 mm for DV90, while in the vibration mode both rollers work with two different amplitudes. Following the recommendations of several studies (Micaelo 2009; Scherocman 2006), the max vibration amplitude (0.61 mm for DV70 and 0.62 mm for DV90) was assigned for base course compaction and the minimum (0.42 mm for DV70 and 0.41 mm for DV90) for surface course compaction. The frequency of both dynamic compaction modes is usually selected over a range of 10 to 20 Hz (V/O). Three frequency levels were defined for each roller and compaction mode. The 3 frequency levels were used with "S-V" and "S-O" modes while for "V-O" mode only both minimums and maximums levels were tested. Table 2 shows the compaction frequencies used in the field test.

The influence of the number of roller passes was assessed by measuring layer's compaction after several number of roller passes being carried out (1, 2, 3, 4, 5 and 8). One roller pass is considered as the roller movement from one side to the other side of the test section in only one direction. Each layer test section (72 in each layer) was approximately $2.5\times43\ \mathrm{m}^2$, which was divided in 12 parts. Half were assigned to density measurements and the others for stopping/inversion of roller movement. Fig. 4 shows the paving and roller compaction scheme that was implemented, the test section dimensions and each number of roller passes measurement position. Inside each measuring part 3 points were chosen for compaction measurement with *NDG* and *PQI*. At the beginning of field tests there were available 3 *NDG* and 1 *PQI*. As *NDG* takes more time to make measurements, each point measurement was made with a different *NDG*. However at the beginning of surface course compaction it was noticed that 2 *NDG* were not functioning properly and so only 1 measurement was taken with *NDG* in each test section part. In the results analysis, for each test section compaction conditions, the compaction degree after *N* passes is the average of each equipment measurements. The roller velocity was set to 4 km/h, automatically controlled.

Additionally, in order to determine the influence of static roller passes at the end of compaction (commonly designated as finishing) the effect of 4 additional roller passes was assessed after dynamic compaction. This test variable was not evaluated for all compaction conditions due to test area limitation.

The influence of asphalt layers temperature was assessed by carrying out compaction at three different temperature ranges: Hot/*TH (*160 °C to 130 °C), Warm/*TW* (130 °C to 100 °C) and Cold/*TC* (100 °C to 70 °C). The layers temperature was measured with an infrared thermometer before compaction started. In order to achieve lower temperatures, paved sections were allowed to cool down until the desired temperature range was attained.

Table 3 summarizes all variations implemented in the field test.

Table 2. Dynamic modes frequencies for each roller, compaction mode and course in Hz

Frequency level	Base course				Surface course			
	DV70		DV90		DV70		DV90	
	V	O	V	O	V	O	V	O
Low (*FL*)	35	30	35	32	40	30	45	32
Intermediate (*FM*)	38	33	37	37	45	33	50	37
High (*FH*)	42	36	42	42	50	36	55	42

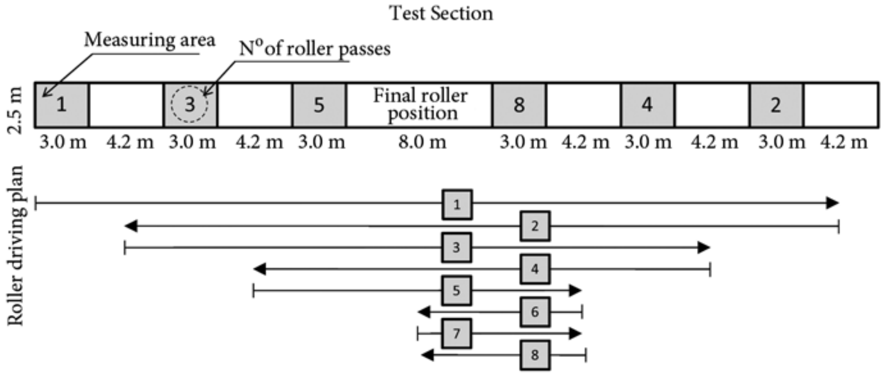

Fig. 4. Paving and roller compaction scheme

Regarding weather conditions, air temperature varied between 11 °C to 21 °C and during 3 days there was a small rainfall.

3. Results

The aim of this research was to quantify the influence of several field compaction factors on asphalt layer's density (or *CD*). The output of the experimental program is 5184 density values measured in field (*NDG* and *PQI)* of two asphalt layers compacted at different conditions (rollers, temperature, number of passes, compaction mode and drum's frequency).

Table 3. Field test factors variation list

Factors	Variation
Layer	AC 32 base 50/70 – 140 mm SMA 11 PmB45 – 35 mm
Roller	DV70, DV90
Number of roller passes	1, 2, 3, 4, 5, 8
Compaction modes and frequencies	S-S S-V (FL, FM, FH) S-O (FL, FM, FH) V-O (FL, FH)
Layer temperature	TH, TW, TC
Static passes at end	4 additional passes for: DV70, DV90 S-V, S-O, V-O TH-FH, TW-FL, TC-FH

The analysis of field test results is presented in two parts. First, in the section 3.1, compaction results are presented and analysed in general terms. Following this, the section 3.2 presents the implementation of regression models in order to quantify the influence of each variable on compaction degree.

3.1. Global analysis

Fig. 5 presents *CD* evolution with roller passes per layer and per measurement device. In each plot 432 points are represented, corresponding to 72 different test sections times 6 different number of carried out roller passes (1, 2, 3, 4, 5 and 8). It is concluded that *NDG* and *PQI* measured different compaction behaviours; *CD* value and evolution is highly influenced by layer's type. Table 4 lists *CD* mean (μ) and standard deviation (σ) values for the data measured with the two methods (Fig. 5), for the different number of roller passes and layer type. For the same number of roller passes carried out, *CD* mean is always higher for the base course. On average, for the surface course it is not possible to achieve minimum required *CD* (97%), CD_{min}, with 8 roller passes while for the base course it is only required 2 to 4 passes, depending on considered measurements (*NDG* or *PQI*). Compaction conditions influence on compaction degree is expressed by *CD* standard deviation. For all number of roller passes, *NDG* data variability is higher (σ_{NDG} > 3%), near twice for the base course (σ_{PQI} < 1.8%), which is likely to be due to higher sensitivity to low *CD* variations or higher measurements variation. According to *NDG* data, compaction conditions have the same influence magnitude on base and surface courses

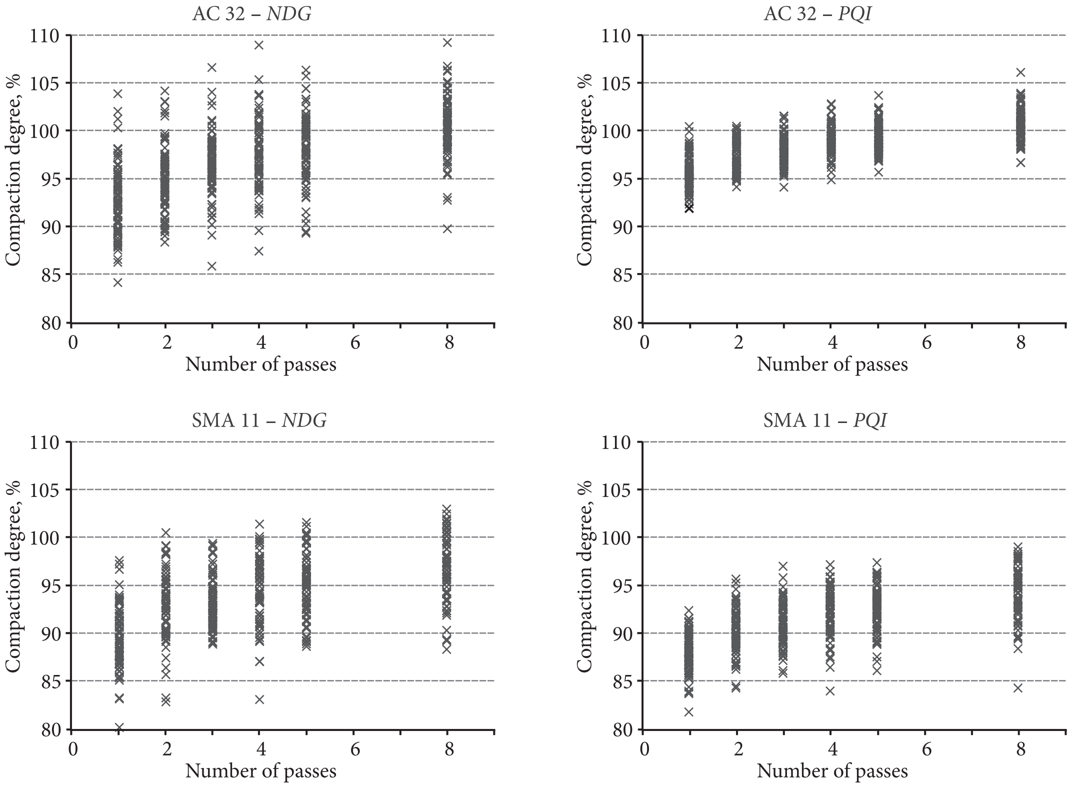

Fig. 5. Compaction degree evolution with roller passes per layer and measurement equipment

attained compaction degree while according to *PQI* data the surface course is more influenced by the compaction process (1.5–1.8% to 2.2–2.8%). It is not identified a variability variation trend with roller passes.

Table 5 shows average standard deviation of *CD* measurements among the 3 points of each test section measuring part. There is no data for surface course *NDG* measurements as only one measurement was taken. For the base course, *NDG* values are around three times higher, which explain part of higher σ values showed in Table 4. Karlsson (2002) states that *NDG* measurements repeatability is lower than of *PQI* because gamma radiation emitted by the isotopes is not constant, which is minimized if long measuring periods (4 min) are used. It was considered in the field test a measuring period of 30 s. *PQI* measurements variation increases to almost the double from base to surface course which explain part of the CD variability increase showed in Table 4 (1.5–1.8% to 2.2–2.8%).

Table 4. Mean (μ) and standard deviation (σ) of *CD* after *N* roller passes, per layer type and measurement equipment

			Number of roller passes					
			1	2	3	4	5	8
Base course	*NDG*	μ	92.8%	95.0%	96.5%	97.5%	98.1%	100.5%
		σ	3.7%	3.4%	3.3%	3.6%	3.6%	3.4%
	PQI	μ	95.9%	97.4%	98.3%	99.3%	99.5%	101.0%
		σ	1.8%	1.6%	1.5%	1.6%	1.6%	1.7%
Surface course	*NDG*	μ	89.6%	92.9%	93.5%	94.7%	95.0%	96.7%
		σ	3.3%	3.6%	2.7%	3.5%	3.2%	3.4%
	PQI	μ	87.8%	90.3%	90.8%	92.2%	92.5%	94.4%
		σ	2.2%	2.3%	2.2%	2.5%	2.4%	2.8%

Table 5. Average standard deviation (σ) of *CD* measurements in each test section measuring part

Layer	Equipment	Number of roller passes					
		1	2	3	4	5	8
AC 32	*NDG*	3.3%	3.2%	3.4%	2.9%	3.5%	2.8%
	PQI	1.3%	1.1%	1.0%	1.0%	1.1%	1.0%
SMA 11	*PQI*	2.0%	1.9%	1.7%	1.9%	1.9%	1.8%

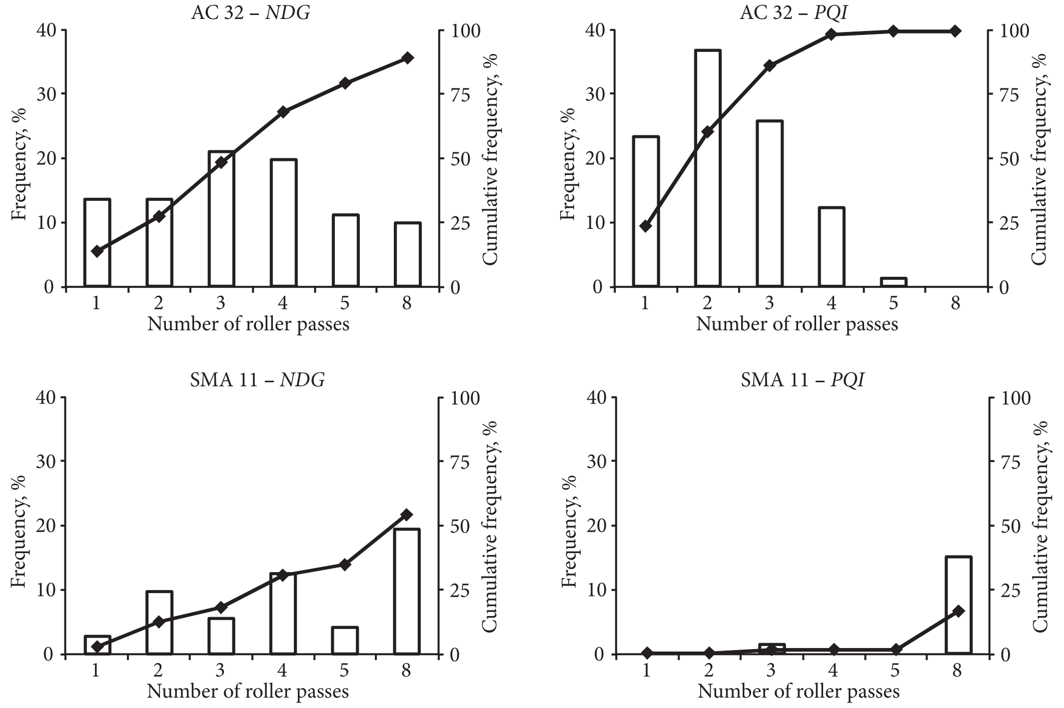

Fig. 6. Histogram of the number of roller passes needed to achieve CD_{min}

Fig. 6 shows the histogram of the number of roller passes needed to achieve $CD_{\min}$ in the 72 test sections. The frequency for N number of roller passes is the number of test sections that needed N passes to achieve the $CD_{\min}$. For the base course, 8 roller passes were sufficient to achieve $CD_{\min}$ in almost compaction conditions. In opposition, only in 20% to 50% of surface course test sections, depending on the considered measurements, was achieved $CD_{\min}$ with 8 roller passes.

Renken (2005) measured the compactability of some asphalt mixtures, in lab with the impact method (Marshall compactor) according to *EN 12697-10:2001*, and on field by measuring compaction evolution with roller passes on diverse compaction conditions. Analytical expressions were determined using experimental data, relating compaction resistance and number of roller passes needed to achieve $CD_{\min}$ with asphalt volumetric properties, compaction temperature, roller weight and compaction mode (static or vibration). Considering the expression for SMA mixtures, for the field test carried out it is predicted 10 to 26 roller passes to achieve compaction. The lower value (10 passes) is predicted when the layer temperature is the highest (TH-145 °C) and it is used DV90 in vibration mode, while the largest (26 passes) is for the lowest considered temperature (TC-90 °C) and it is used DV70 in static mode. When compared with field test results (Table 4), it is concluded that the expressions give conservative values since it was possible to achieve $CD_{\min}$ in many more compaction situations but confirms that SMA has high compaction resistance.

It is possible that the low *CD* values measured in the surface course are related to the measurement methods. Several studies concluded that the asphalt mixtures characteristics, the layer thickness and the environmental conditions affect measurements with nuclear and non-nuclear devices (Kvasnak 2007). Base course's asphalt mixture was produced with granitic aggregates and design density was 2244 kg/m^3, while the surface course's asphalt mixture was produced with basaltic aggregates and design density was 2606 kg/m^3. This large design density difference, associated with the small layer thickness (35 mm), makes it possible that the devices measured over a "thicker layer" resulting in lower measurement values than in reality were. Another identified factor is layer's surface characteristics. SMA surface texture is open while AC is closed. As air dielectric constant (1) is lower than of asphalt mixtures (5–6), the *PQI* density measurements are lower when there is air between the equipment plate and the asphalt surface.

3.2. Regression models

In the field test, 6 factors were changed with the purpose of evaluating their influence on the compaction process. The previous analysis methodology made it possible to take only general conclusions about the process. Therefore, field test results (*CD*) were studied with regression models. A regression is a mathematical relation between two or more variables, with specific deviation aiming to relate the dependent or output variable (compaction degree) with all independent or input variables (test factors), as:

$$Y = B_0 + B_1 X_1 + \ldots + B_k X_k + \varepsilon_i, \quad (1)$$

where Y – the dependent variable; X_i – the independent variable i (1, 2, …, n); B_i – the regression coefficient of variable i; ε_i – the residual random variable which quantifies the effects on Y not explained by X_i.

Other types of multiple regressions were also tested, namely, exponential and polynomials. The exponential and polynomials are applied as linear regressions if the expressions and variables are linearized.

The statistical software SPSS was used to perform the statistical analysis and to determine the regression coefficients based on the Least Square Method.

In agreement with the field test layout, the following variables were chosen as the most likely to influence the dependent variable (*CD*): (1) asphalt mixture/layer; (2) roller; (3) HMA temperature; (4) compaction mode (S-S, S-V, S-O e V-O); (5) dynamic mode frequency; (6) number of roller passes.

According to Pestana and Gageiro (2008), variables are classified into two scale groups: quantitative and qualitative. Quantitative variables are measured in numeric or quantitative scale while qualitative variables are measured in categorical scale. The compaction degrees, the number of roller passes, the temperature and the frequencies are classified as ratio quantitative while the rest as nominal qualitative. Qualitative variables were converted to quantitative to be included in the regression models. The roller type was substituted by the sum of the two drums static linear load. The compaction mode was divided in 4 variables where each represents one compaction mode, with two possible values, 1 if it is acting and 0 if it is not. This procedure was also applied to the layer type (0-base and 1-surface).

Fig. 7 shows the variation of the compaction degree (NDG data) with each variable in separate. For all variables it is not possible to exclude the possibility of linear relation between *CD* and each independent variable. However, for the number of roller passes variable the logarithm has a slightly better agreement with data ($R^2 = 0.2754$). In the regression model calculus, log-transformed variables were introduced as well as other variables created by mathematical manipulation (power law, combination of variables, etc.) of the ones formerly presented.

Since the two instruments measured different density values, data gathered with *NDG* and *PQI* was analysed in separate. Each equipment data is composed of 918 values, which according to Pestana and Gageiro (2008) is considered a large sample and adequate to regression model studies with up to 30 independent variables.

Exponential regressions with log-transformed variables showed the best agreement with data for the two groups (*NDG* and *PQI*). 40 and 46 values (over a total of

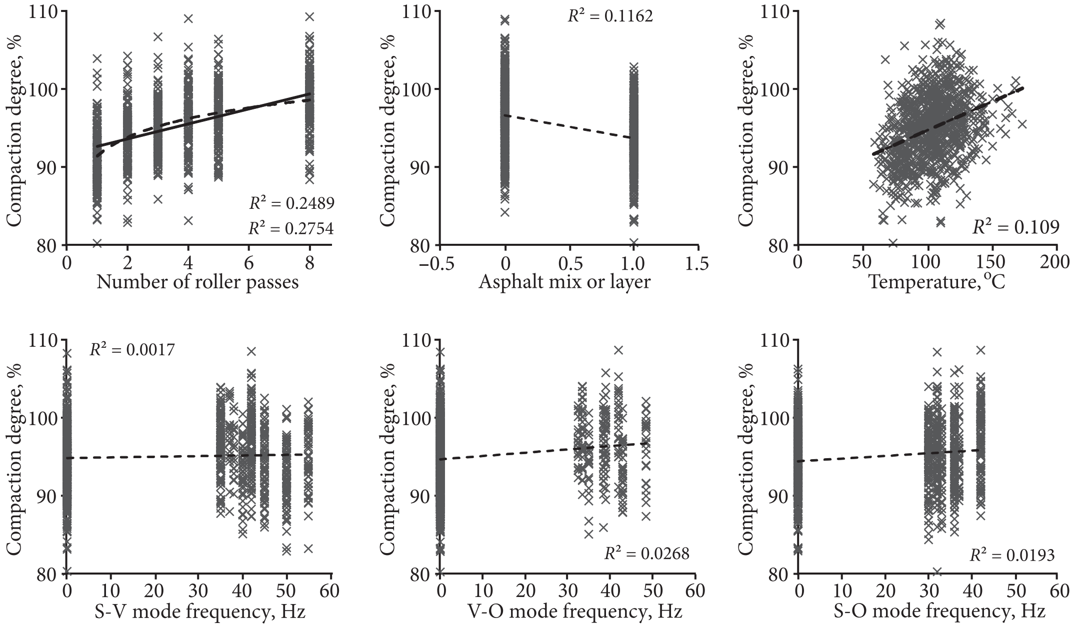

Fig. 7. Scattering diagrams of *CD* with all test variables (*NDG* data): roller passes; layer; temperature; V frequency; V-O frequency; O frequency

864 values) were identified as outliers for, respectively, *NDG* and *PQI*. Outliers are just 5% of all cases, what is considered acceptable. The regression models having better agreement with data are, respectively, for the *NDG* data (R^2 = 0.72).

$$CD = \exp\left[3.282 - 0.032 Layer + 0.271 \ln\left[\frac{\left(\frac{M}{L}\right)}{9.8}\right] + 0.039 \ln\left(T - 50\right) + 0.028 \cdot 4SP + 0.0025 \ln(Fv) + 0.0032 \ln(Fo) + 0.0070 \ln(Fo) + 0.035 \ln(N)\right], \quad (2)$$

and for the *PQI* data (R^2 = 0.91)

$$CD = \exp\left[4.239 - 0.078 Layer + 0.050 \ln\left[\frac{\left(\frac{M}{L}\right)}{9.8}\right] + 0.026 \ln\left(T - 50\right) + 0.016 \cdot 4SP + 0.0033 \ln(Fv) + 0.0040 \ln(Fo) + 0.0054 \ln(Fo) + 0.028 \ln(N)\right], \quad (3)$$

where *CD* – the compaction degree, %; *Layer* – as named (base 0 or surface 1); $\frac{M}{L}$ – the sum of static linear drum loads (DV70 – 5.35 N/m; DV90 – 5.72 N/m); *T* – the layer temperature; *4SP* – the static passes at end (Yes – 1; No – 0); *Fo* – the oscillation mode frequency, Hz; *Fv* – the vibration mode frequency, Hz; *Fvo* – the average frequency of V-O mode, Hz; *N* – the number of roller passes.

Table 6 and Table 7 summarize the statistical analysis of 2 regressions, namely the analysis of variance ANOVA, the *t*-Student test and the regression coefficients (unstandardized and standardized). The coefficient of determination (R^2) is a measure of the quality of the regression, i.e., the agreement with data, while the standardized coefficients express the importance of the independent variable to the dependent variable change. These coefficients are obtained with standardization of the regression coefficients (absolute), according to:

$$B_i' = B_i \cdot \frac{\sigma_{X_i}}{\sigma_Y}, \quad (4)$$

where B'_i – the standardized coefficient; B_i – the regression coefficient (unstandardized); σ_{X_i} – the standard deviation of X_i independent variable; σ_Y – the standard deviation of the dependent variable. The standardized coefficient weights the variation in the dependent variable of a unitary value change in independent variable. A positive value means that the dependent variable value varies in the same way as the independent variable.

The regression analysis shows that *CD* is adequately expressed as a function of field compaction conditions (high R^2 values), with better agreement to *PQI* data. This regression model has prediction ability as R^2 value is higher than 0.90. The ANOVA (Analysis of Variance) test to the regression models and the *t*-Student test to the regression coefficients show its significance with 99% reliability.

Regarding the independent variables included in the regression models, the same variables were recognized by both regression models as influential to the compaction process. The independent variables are the layer/asphalt mixture, the roller static linear load, the dynamic compaction mode frequencies and the number of roller passes. When the roller is acting on static mode, all frequency variables are set with the value of 1. Initially, the variables

Table 6. *NDG* data regression analysis

ANOVA – Analysis of Variance					
Model	Sum of squares	*df*	Mean square	*F*-Snedecor	
				F	*Sig*
Regression	1.188	8	0.148	284.215	0.000
Residual	0.454	869	0.001		
Total	1.642	877			

Regression coefficients analysis					
Model	Unstandardized coefficients		Standardized coefficients	*t*-Student test	
	B_i	Std. Error	B'_i	*t*	*Sig*
(*Constant*)	3.282	0.096		34.285	0.000
Layer	−0.032	0.002	−0.370	−20.700	0.000
ln (*M*/*l*)	0.271	0.024	0.202	11.289	0.000
ln(*T*)	0.039	0.002	0.363	20.275	0.000
4*SP*	0.028	0.002	0.275	15.120	0.000
ln(*Fv*)	0.002	0.001	0.100	3.024	0.003
ln(*Fo*)	0.003	0.001	0.125	3.763	0.000
ln(*Fvo*)	0.007	0.001	0.252	7.986	0.000
ln(*N*)	0.035	0.001	0.533	29.789	0.000

Note: df – the degrees of freedom; *F* and *t* – the tests' statistic; *Sig* – the significance level.

Table 7. *PQI* data regression analysis

ANOVA – Analysis of Variance					
Model	Sum of squares	*df*	Mean square	*F*-Snedecor	
				F	*Sig*
Regression	1.752	8	0.219	1075.700	0.000
Residual	0.176	863	0.000		
Total	1.927	871			

Regression coefficients analysis					
Model	Unstandardized coefficients		Standardized coefficients	*t*-Student test	
	B_i	Std. Error	B'_i	*t*	*Sig*
(*Constant*)	4.239	0.060		70.645	0.000
Layer	−0.078	0.001	−0.822	−79.767	0.000
ln (*M*/*l*)	0.050	0.015	0.035	3.363	0.001
ln(*T*)	0.026	0.001	0.227	21.903	0.000
4*SP*	0.016	0.001	0.146	13.873	0.000
ln(*Fv*)	0.003	0.000	0.124	6.735	0.000
ln(*Fo*)	0.004	0.001	0.146	7.878	0.000
ln(*Fvo*)	0.005	0.001	0.177	10.061	0.000
ln(*N*)	0.028	0.001	0.389	37.758	0.000

Note: df – the degrees of freedom; *F* and *t* – the tests' statistic; *Sig* – the significance level.

were included that represented the dynamic compaction modes action (on/off) and the variables that represented the frequencies in the regression models but for all tested situations (combination of variables) the regression models failed the multicollinearity tests, meaning that one variable is not important for the regression model when the other is present or the relation between variables is higher than the regression model R^2. Therefore, it was decided to keep the frequency variables instead of the mode variables. None of the variables created from two others were considered important.

The analysis of *Beta* standardized coefficients allows conclude that for both regression models the three most important variables are the type of layer, the number of roller passes and the layer temperature. However, the relative importance of these variables is not the same for the two regression models. For the *NDG* regression model the most important variable is the number of roller passes, followed by the layer and the temperature with equal importance, while for *PQI* regression model it is the layer with a large difference to the other two variables. Compaction increases with the number of roller passes and the temperature, and decreases with layer change from AC to SMA, which means that the surface course has higher compaction resistance. The roller static linear load is only influential to the *NDG* regression model, showing the lowest importance in the *PQI* regression model. It is related with the small difference of static linear load between the two rollers. The 4 roller passes at the end increases the *CD* in 1.6% to 2.8% for, respectively, *PQI* and *NDG* measurements.

Regarding the importance of the compaction modes, all frequency variables have positive coefficients which mean S-S mode is less efficient than dynamic modes as expected. The performance decreasing order is V-O, S-O and S-V. The difference of S-V and S-O is small and similar for both regression models. When the roller is acting on V-O mode, the *NDG* regression determines that the *CD* increases more than would be with S-V and S-O working at same time while for the *PQI* regression model it is just slightly more efficient than the other two dynamic modes. Figs 8 and 9 illustrate graphically the sensitivity of base course compaction evolution with temperature and roller (load, passes and compaction mode).

As stated before, the range of the *CD* variation predicted for the same input variables is larger for the *NDG* regression model. In the first simulated situation, Fig. 8, according to *NDG* the increase of layer temperature is equivalent to changing roller. In both cases it is very difficult to get $CD_{\min}$ within lower temperature range (*TC*). The compaction efficiency with roller passes is enhanced by using the roller at a dynamic compaction mode, especially V-O mode (Fig. 9).

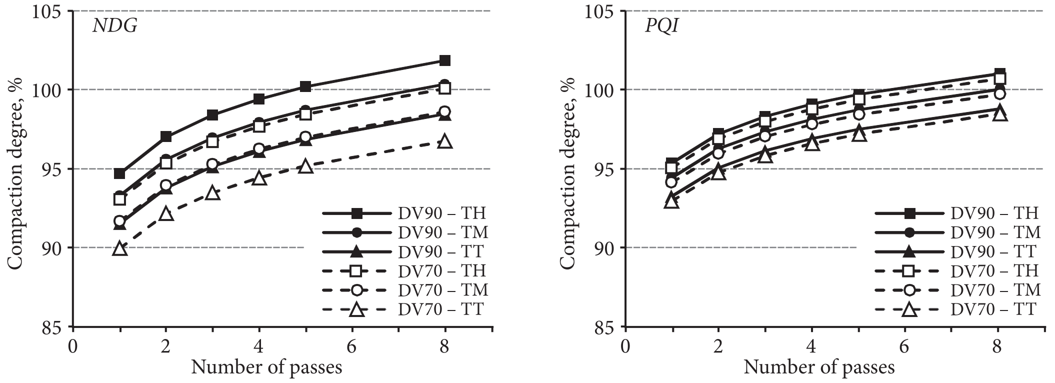

Fig. 8. Base course *CD* prediction, by *NDG* (a) and *PQI* (b) regression models, with number of roller passes in S-S mode for the two rollers and at different temperatures

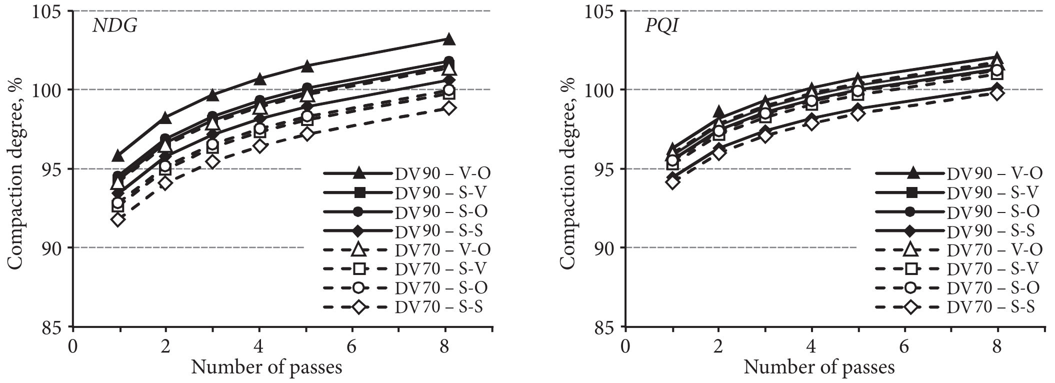

Fig. 9. Base course *CD* prediction, by *NDG* (a) and *PQI* (b) regression models, with number of roller passes for the two rollers working at different compaction modes and at intermediate layer temperature

4. Conclusions

A large field compaction test was carried out in order to quantify the importance of several variables in asphalt layers compaction degree. Based on the test results and the analysis with regression models, it was determined that:

- the two density gauges measured different compaction values and the nuclear density gauge has higher measurement variability; the variability of the compaction degree with compaction conditions is similar for both layers (despite asphalt mixture and layer thickness differences) and it does not change with the number of accumulated roller passes;
- the surface course with gap-graded aggregate gradation and polymer modified bitumen proved to have large compaction resistance, though not as much as predicted by a model found in literature;
- it is possible to relate in situ measured compaction degree with the known variables of compaction process, showing that the adoption of correct compaction conditions is determinant to achieve desired compaction, especially when the layer temperature is low;
- the layer/asphalt mixture type, the layer temperature and the number of roller passes are the most influential variables but the two regression models do not agree on the relative importance;
- the dynamic compaction modes are more efficient than the static mode for the same number of roller passes and the Vibration-Oscillation mode have the highest performance; the Static-Vibration mode and the Static-Oscillation mode have similar performances; the frequencies of dynamic compaction modes proved not to be influential to the compaction process, at least in the tested range;
- finishing compaction (static roller passes at the end), a common field practice, increases compaction by up to 2%.

Field tests are a unique approach to evaluate compaction in a similar way to day-by-day construction conditions but on the other hand the cost is very high, it is affected by weather unpredictability and it is almost impossible to isolate each variable that influences the process.

Based on pointed conclusions, the relation between the layer/asphalt mixture characteristics and this factor coefficient in regression models is proposed for future research.

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References

Anderegg, R.; von Felten, D.; Kaufmann, K. 2006. Compaction Monitoring Using Intelligent Soil Compactors, in *Proc. of the GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*. February 26-March 1, 2006, Atlanta, USA. Reston: ASCE. http://dx.doi.org/10.1061/40803(187)41

Breakah, T. M.; Bausano, J. P.; Williams, R. C.; Vitton, S. 2011. The Impact of Fine Aggregate Characteristics on Asphalt Concrete Pavement Design Life, *International Journal of Pavement Engineering* 12(02): 101–109. http://dx.doi.org/10.1080/10298430903578937

Facas, N.; van Susante, P.; Mooney, M. 2010. Influence of Rocking Motion on Vibratory Roller-Based Measurement of Soil Stiffness, *Journal of Engineering Mechanics* 136(7): 898–905. http://dx.doi.org/10.1061/(ASCE)EM.1943-7889.0000132

Huerne ter, H.; Van Maarseveen, M.; Molenaar, A.; Van De Ven, M. 2008. Simulation of HMA Compaction by Using FEM, *International Journal of Pavement Engineering* 9(3): 153–163. http://dx.doi.org/10.1080/10298430701538091

Hunter, A.; McGreavy, L.; Airey, G. 2009. Effect of Compaction Mode on the Mechanical Performance and Variability of Asphalt Mixtures, *Journal of Transportation Engineering* 135(11): 839–851. http://dx.doi.org/10.1061/(ASCE)0733-947X(2009)135:11(839)

Karlsson, T. 2002. *Evaluation of the PQI – Pavement Quality Indicator*. Report No. 1040, Rockneby: SKANSKA. 10 p.

Kearney, E. 2006. Oscillatory Compaction of Hot-Mix Asphalt, in *Factors Affecting Compaction of Asphalt Pavements*. Transportation Research Circular E-C105. Washington: Transportation Research Board.

Kvasnak, A.; Williams, R.; Ceylan, H.; Gopalakrishnan, K. 2007. *Investigation of Electromagnetic Gauges for Determining in-Place HMA Density*. Report No. IHRB Project TR-547. Ames: Iowa State University. 71 p.

Masad, E.; Scarpas, A.; Rajagopal, K.; Kassem, E.; Koneru, S.; Kasbergen, C. 2014. Finite Element Modelling of Field Compaction of Hot Mix Asphalt. Part II: Applications, *International Journal of Pavement Engineering*. http://dx.doi.org/10.1080/10298436.2013.863310

Mooney, M.; Rinehart, R.; Facas, N.; Musimbi, O.; White, D.; Vennapusa, P. 2010. *Intelligent Soil Compaction Systems*. NCHRP Report 676. Washington: Transportation Research Board. 167 p.

Pestana, M. H.; Gageiro, J. N. 2008. *Análise de dados para ciências sociais, a complementaridade do SPSS* [Data Analysis for Social Sciences, the Complementarity of SPSS]. Lisboa: SÍLABO. ISBN 978-972-618-498-0.

Micaelo, R. 2009. *Compactação de misturas betuminosas – Ensaios de campo e modelação numérica* [Hot-Mix Asphalt Compaction – Field Tests and Numerical Modelling]. PhD Thesis. Universidade do Porto, Porto. 464 p.

Renken, P. 2004. The Compaction Resistance of Asphalt Mixes – a Comprehensive Performance Related Property, in *Proc. of the 3rd Euroasphalt & Eurobitume Congress*. May 12–14, 2004, Vienna, Austria. Breukelen: Foundation Eurasphalt, 2005–2015.

Renken, P. 2005. *Merkblatt für das Verdichten von Asphalt. Köln: Forschungsgesellschaft für Straßen- und Verkehrswesen*. 56 p. ISSN: 0039-2162.

Ruban, M. 2002. *Quality Control in Road Construction*. A. A. Balkema. 700 p. ISBN 90-5809-264-X.

Scherocman, J. 2006. Compaction of Stiff and Tender Asphalt Concrete Mixes, in *Factors Affecting Compaction of Asphalt Pavements*. Transportation Research Circular E-C105. Washington: Transportation Research Board.

West, R.; Watson, D.; Turner, P.; Casola, J. 2010. *Mixing and Compaction Temperatures of Asphalt Binders in Hot-Mix Asphalt*. NCHRP Report 648. Washington: Transportation Research Board. 157 p.

Wistuba, M.; Mollenhauer, K. 2013. Influence of Asphalt Compaction Procedure on 3D Deformation Properties, *International Journal of Pavement Engineering*. http://dx.doi.org/10.1080/10298436.2013.812213

Çelik, O. N.; Atiş, C. D. 2008. Compactibility of Hot Bituminous Mixtures Made with Crumb Rubber-Modified Binders, *Construction and Building Materials* 22(6): 1143–1147. http://dx.doi.org/10.1016/j.conbuildmat.2007.02.005

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