From gyratory data to field compacity – a numeric model

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ABSTRACT: The compaction of an asphalt mixture is a dynamic process influenced by various factors, including mixture properties, cooling rate and timing of the roller passes. At times, the target compacity may not be reached or achieved inefficiently. Laboratory compaction tests, done at constant temperature and energy level, often fall short in predicting real field compaction. To bridge the gap between laboratory and field compaction, a numerical model designated as Field Compacity Model (FCM) is proposed. The FCM is based on gyratory data and integrates field specificities by accounting for the mixture's cooling curve, roller types, number of passes and their timing. The objective of the FCM is to identify potential risks of field compaction issues at an early stage in an accessible and efficient manner. Following an initial verification stage, the model was used to estimate field compacity in three practical case studies, where it showed good predictive performance.

1 INTRODUCTION

1.1 *Background*

Regardless of the new technologies implemented in paving works, such as intelligent compaction (IC) and paver-mounted thermal profiling (PMTP), there remains some uncertainty regarding the final density of the compacted asphalt layer.

In the field, compaction depends on several factors, with the most important being compaction temperature, compaction energy, and the mixture properties. During compaction, the asphalt mixture undergoes a cooling process driven by several environmental conditions, including air temperature, wind, solar radiation and precipitation (Bijleveld et al. 2016). Regarding heat loss, the thickness of the layer being paved and the temperature of the layer beneath also have an influence (MultiCool 2024). The compaction energy will be a function of the type of roller, its configuration and the number of passes given. In fact, more important than the total number of passes is the timing (i.e. temperature compaction window) at which they occur.

In terms of mixture properties, due to the selected materials and composition, some mixtures will have better compactability than others (Francken & Leonard 2002, Margaritis et al. 2023). Ideally, this behavior should be identified in the laboratory beforehand. To evaluate compaction in the laboratory, the gyratory compactor (EN 12697-31 and ASTM D6925) is one of the most commonly used methods. This test provides a dataset that shows the relation between compacity and the number of gyrations (energy). In-short, compacity is equal to 100 minus the volume of air voids (in %). The European approach is that at certain energy levels (typically, 60, 100 or 120 gyr, depending on the mixture type), air voids are quantified and checked against the thresholds set in specifications.

In a simplified manner, laboratory compaction is approximately a continuous process (all compaction energy is applied at constant temperature and in a very short period), whereas field compaction is more of a discrete process (every roller pass happens at a different temperature with occasionally several minutes break between passes).

In brief, standard laboratory compaction ignores mixture cooling, roller differences and the effect of the underlaying road structure. Part of the uncertainty around field compacity can be explained by this missing link between laboratory and field compaction.

1.2 *Motivation and objective*

The main motivation of this work is to predict field compacity based on laboratory data in order to prevent and to explain field compaction failures more quantitatively.

The objective is to develop a numeric model that helps bridge the gap between laboratory and field compaction. The model should clearly identify the risk of compactability problems and demonstrate how different field compaction scenarios may help mitigate or exacerbate this risk.

2 GYRATORY COMPACTION AND THE SIGMOIDAL MODEL

To study the workability and compactability of asphalt mixtures, the analysis of compaction data – particularly the gyratory compactor – has gained widespread attention. An advantage of the gyrations-compacity curve is that it captures all the specific characteristics of the asphalt mixture (binder content, binder grade, aggregate geometry, grain size distribution, etc.). However, drawing conclusions from the raw data can be quite challenging. Therefore, the use of fitting models can be very helpful.

The sigmoidal model (Equation 1), proposed by Moutier (1996), fits the gyrations-compacity data in a log-linear scale using a sigmoid curve.

$$C = \frac{C_0 + C_\infty \times \beta_4 \times N_g^{\beta_3 \times (C_\infty - C_0)}}{1 + \beta_4 \times N_g^{\beta_3 \times (C_\infty - C_0)}} \tag{1}$$

where N_g = number of gyrations; C = compacity at N_g; C_0 = lower asymptote; C_∞ = upper asymptote; β_3 and β_4 are shape parameters associated with the slope and inflection point of the curve.

These four parameters (further designated as sigmoidal parameters) – C_0, C_∞, β_3 and β_4 – drive the behavior of the curve and allow the determination of important characteristics, such as the position of the compaction inflection point (CIP) and the slope of the curve at the CIP.

Earlier work quantified the repeatability and reproducibility of the sigmoidal parameters and concluded that the sigmoidal model provides a good fitting, showing low root mean squared errors (Crucho et al. 2024).

However limited to the laboratory conditions, the analysis of the sigmoidal parameters can give clear indications regarding the workability and compactability of a specific asphalt mixture. Two interactive diagrams – C_0-C_{CIP} and β_4/β_3-β_3 – provide an easy-to-follow visual representation (Margaritis et al. 2023).

3 MODEL TO PREDICT FIELD COMPACITY

3.1 *Model*

The field compacity model (FCM) assumes the energy-compacity law as defined by the gyratory compaction test and is based on the sigmoidal fit. To account for different roller loads (vertical pressure) and mixture cooling (compaction temperature) several gyrator tests were performed (temperatures of 150, 135, 120, 105 and 90°C, and vertical pressures of 200 and 600 kPa) and respective sigmoidal parameters determined. The evolution of the sigmoidal parameters within the range of temperature and vertical pressure was established through linear regression. Finally, by interpolation, each sigmoidal parameter was determined for the desired temperature and vertical pressure. Thus, an infinite number of sigmoidal curves can be generated, matching the temperatures and compaction pressures applied in the field.

To predict field compacity through the sigmoidal curve, the number of roller passes have to be converted into number of gyrations. To tackle the variety of rollers and compaction configurations, it is proposed the concept of equivalent number of loads (ENL). In static compaction, ENL is the number of axle passes over a certain point, and when vibration is applied, a factor of 1.43 is used to account for the dynamic effects. Following, ENL are converted into number of gyrations considering an empirical coefficient (k), equal to eight for steel drums axles and equal to four for pneumatic tire axles. The vertical pressure given by each axle was estimated through the manufacturer's technical specification.

The FCM predicts field compacity by analyzing the sequence of compaction actions applied to the pavement in a step-by-step manner. Initially, the effect of the paver ($n = 0$), which provides some degree of compaction, is assumed equivalent to four gyrations ($Ng_0 = 4$) at 150 kPa, with the corresponding compacity determined using Equation 2. Subsequently, for each roller pass (n), FCM predicts compacity using Equation 2 and Equation 3.

$$CP_n = \frac{C_{0n} + C_{\infty n} \times \beta_{4n} \times Ng_n^{\beta_{3n}(C_{\infty n} - C_{0n})}}{1 + \beta_{4n} \times Ng_n^{\beta_{3n}(C_{\infty n} - C_{0n})}} \tag{2}$$

$$Ng_n = k_n \times ENL_n + 10^{\left(\frac{\log \frac{CP_{n-1} - C_{0n}}{\beta_{4n}(C_{\infty n} - CP_{n-1})}}{\beta_{3n}(C_{\infty n} - C_{0n})}\right)} \tag{3}$$

where n = roller pass number; Ng_n = number of gyrations at n; CP_n = compacity at n; C_{0n}, $C_{\infty n}$, β_{3n} and β_{4n} are the sigmoidal parameters determined for the conditions (temperature and vertical pressure) of pass n; ENL_n = equivalent number of loads corresponding to pass n and k_n = axle type factor.

To practicaly demonstrate the FCM-approach, Figure 1 presents a simple example with three roller passes (at 135, 120 and 90°C).

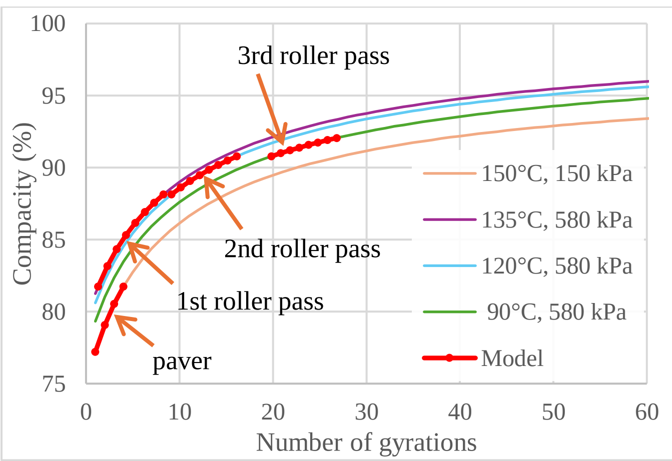

Figure 1. Example of gyrator curves obtained at different temperatures and compacity evolution according to the FCM.

3.2 *Initial verification*

The initial validation of the model was made through a job site monitored by the BRRC. During laying and compaction, data about the number of passes, mid-layer temperature and density of the mixture after each pass was collected. A 4 cm surface layer of conventional hot mix asphalt (AC 10) was paved. At this job site, the compaction started (at 135°C) with a pneumatic-tire roller (6 passes) and then with a three-wheeled steel drum roller (12 passes). The vertical pressures were 230 and 520 kPa for the axles of the pneumatic-tire roller and the three-wheeled steel drum roller, respectively. The final pass was at 70°C. In the laboratory, gyratory tests were conducted following the program indicated in § 3.1.

Figure 2 shows the FCM prediction and the respective field compacity. Field compacity was calculated based on field density measurements taken with a Troxler nuclear density gauge. The repeatability and reproducibility of the nuclear density gauge were determined to be 39 and 42 kg/m^3, respectively (Duerinckx & Vanelstraete 2021), resulting in a variability of approximately ± 1.6% in compacity. In Figure 2 the grey dashed lines represent the measured value ± repeatability. The point where a temperature of 90°C was reached, is also indicated. Below 90°C (all points to the right of the red dashed line), the values of the sigmoidal parameters were obtained by extrapolation. On this jobsite, the density at ENL=0 (after the paver and before the 1st roller pass) was not measured. In general, FCM predicted well field compacity. A limitation of this approach is that the overcompaction effect is not considered. In the field, density can start to decrease if the compaction effort is too high or happens under too low temperatures. Caution should be taken when using FCM for such conditions.

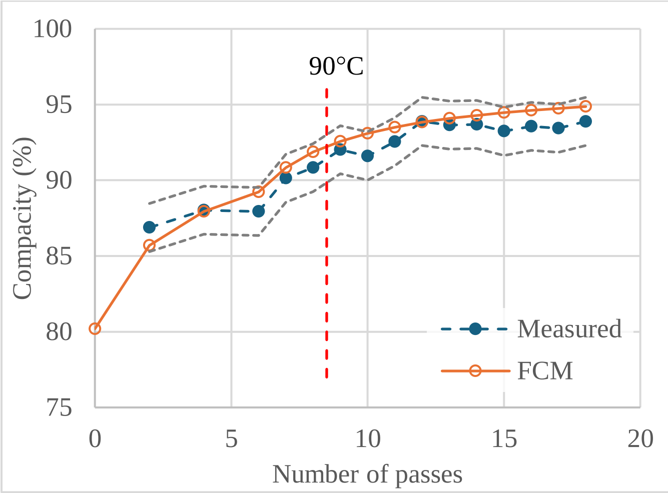

Figure 2. Measured compacity and prediction of the FCM for the case of an AC 10 surface layer.

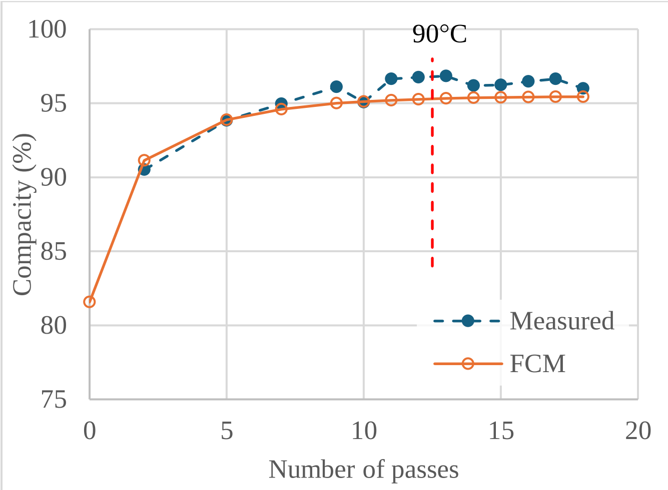

Figure 3. Measured compacity and prediction of the FCM for the case of an AC 14 surface layer.

4 CASE STUDIES

4.1 *Mixture AC 14 surf*

Following the approach described in § 3.2, BRRC monitored another job site (Francken & Leonard 2002) where the paved mixture was a 5 cm thick conventional AC 14. At this site, only the static three-wheeled roller was used (similar to the one used in the previous case). In total, 18 roller passes were applied. The first pass occurred at 130°C and the final pass at 56°C. With respect to the gyrator data, as information for this exact mixture was not available, a similar mixture from the BRRC database, and respective temperature sensitivity, was used. In this case, the vertical pressure sensitivity was assumed equal to the previous AC 10 mixture. Figure 3 presents the results of the model. Regardless of the considered simplifications, the overall prediction was acceptable.

4.2 *Mixture AC 16 base*

In the literature, Bijleveld et al. (2016) reported field compaction data for an 8 cm thick base layer (mixture AC 16) compacted by a 10 ton combined roller (pneumatic tire front axle and steel drum rear axle). However, no gyratory data were reported. To bypass the lack of data, a similar mixture was found in the BRRC database, and the respective gyrator data used here. Also, the temperature and vertical pressure sensitivity were assumed. The FCM prediction is presented in Figure 4.

4.3 *Mixture AC 20 base*

Another case study is an AC 20 base mixture that in the field (6 cm thick layer) presented problematic compaction. Some deviations during the production process led to a mixture with a low binder content and the respective gyratory specimens revealed 11.5% air voids (at N_g=60).

Regarding field compaction, only the type of rollers, production temperature, date and time of the day were known. In this case, MultiCool (2024) was used to generate the cooling curve. The number of passes was estimated based on our experience and the usual workflow of that contractor. The gyratory data was obtained, but only at a compaction temperature of 150°C. Thus, the temperature and vertical pressure sensitivity were assumed. Despite the lack of accurate field monitoring and all the necessary assumptions, the FCM predicted the insufficient final compacity well (Fig. 5). FCM predicted 85.9% of compacity where field cores showed an average of 85.3%.

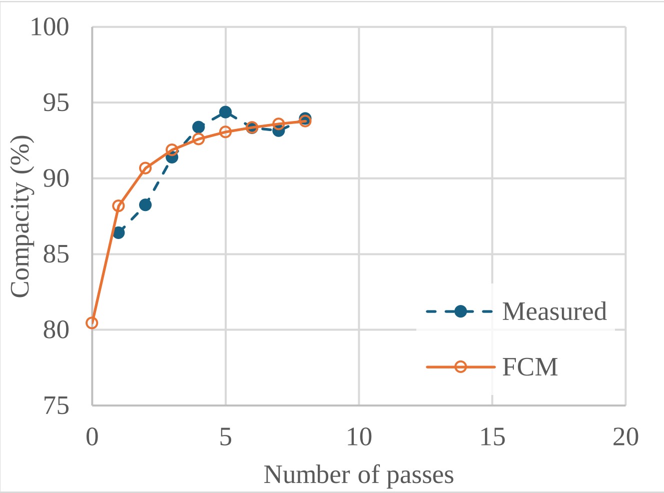

Figure 4. Measured compacity and prediction of the FCM for the case of an AC 16 base layer.

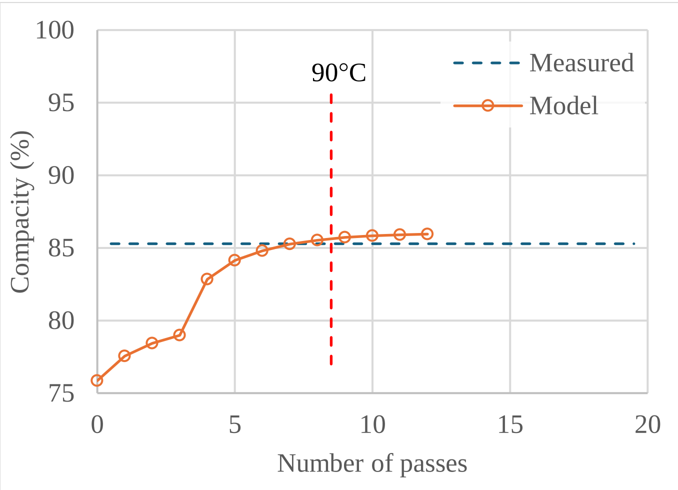

Figure 5. Final compacity and prediction of the FCM for the case of an AC 20 base layer.

5 CONCLUSIONS

The FCM was able to predict field compacity well for a variety of asphalt mixtures and field compaction conditions, including a mixture with known compaction problem. This highlights the ability of the model to pinpoint mixtures with potential problematic compaction, facilitating the study of new mixture compositions and/or additives (e.g. WMA production).

When gathering all gyratory data (compaction under different temperatures and vertical pressures) is not possible, the use of generic parameters can be considered. In the analyzed case studies this approach gave acceptable results.

By using mixture cooling models and rollers properties, the FCM enables the simulation of an infinite variety of field scenarios in a rapid manner.

Despite the positive conclusions reached thus far, the FCM should be further validated with additional cases of problematic compaction. Future research should also explore other mixture types, such as stone mastic asphalt and porous asphalt, and further investigate the effects of temperature and vertical pressure sensitivity depending on the mix type.

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