Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 64 (2024) 262–268

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

SMAR 2024 – 7th International Conference on Smart Monitoring, Assessement and Rehabilitation of Civil Structures

Assessing Asphalt Pavement Pre-Compaction with Paver Screed Frequency Measurements

Leandro Harries[a]*, David Kempf[a], Matthias Scheidig[a], Maximilan Schütz[a], Moritz Middendorf[a], Kazim Uzar[a], Xiaohui Su[a], Stefan Böhm[a], Jia Liu[a]

[a]Technical University of Darmstadt, Otto-Berndt-Str. 2, 64287 Darmstadt, Germany

---

Abstract

The quality and longevity of an asphalt road depends on the accurate compaction of the asphalt pavement. Particular emphasis should be placed on the pre-compaction process involving the paver's screed. Inadequate or excessive pre-compaction can result in paving errors and inhomogeneities within the pavement, which even expert roller operation cannot rectify. In practical paving, however, the degree of pre-compaction is rarely determined, so that one is dependent on the empirical knowledge and assessments of the paving personnel. Within the context of the research initiative, InfraROB (Grant Agreement No.: 955337), an innovative system was devised to infer the extent of pre-compaction by leveraging the resonance frequency of the paver's screed. This system comprises a rugged, enclosed acceleration sensor capable of capturing high-speed accelerations and a Wi-Fi-enabled control unit for data storage and processing. To validate this system, a series of test pavements were constructed using an asphalt binder mix (AC 16 BS), deliberately varying the speed of the tamper compaction unit in four steps from 0 rpm up to 1500 rpm. Half of the test lanes were longitudinally compacted with rollers, allowing for the examination of the asphalt pavement in its partially pre-compacted state. To achieve this, drill cores were extracted, and their density was assessed in the laboratory. Through the application of Fast Fourier Transformation, the measured resonance frequency data was analysed and subsequently correlated with the outcomes of the drill core inspections. This analysis revealed a strong logarithmic relationship between the average peak acceleration and the bulk densities measured, with a high coefficient of determination exceeding 0.9. The presented method enables real-time assessment of the pre-compaction status of asphalt pavement, offering support to paving personnel, optimising roller usage, and enhancing asphalt pavement quality.

---

* Corresponding author. Tel.: +49615116-23826.
E-mail address: lharries@vwb.tu.darmstadt.de

2452-3216 © 2024 The Authors. Published by ELSEVIER B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of SMAR 2024 Organizers
10.1016/j.prostr.2024.09.243

© 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of SMAR 2024 Organizers

Keywords: Asphalt; Paver; Compaction; Resonance Frequency; Acceleration Sensor

1. Introduction

To guarantee the durability of asphalt pavements under the weight of traffic, detrimental deformations need to be minimal. Adequate resistance to deformation and effective load distribution to the subgrade or underlying ground are essential factors. Compaction quality plays a pivotal role in achieving the requisite level of deformation resistance and the ability to endure temperature fluctuations and weathering stresses. (Rosauer 2010)

To achieve proper compaction, the hot mix asphalt (HMA) undergoes a two-step process: initial compaction by the paver screed and final compaction using rollers. While the paver can achieve a high Marshall density, reaching the ultimate compaction level necessitates using rollers. The rollers may shift the HMA when insufficient pre-compaction, resulting in surface irregularities and microstructure inhomogeneities. Conversely, excessive pre-compaction can disrupt the rolling compaction scheme of the rollers, preventing the aggregates from orienting horizontally, which can negatively influence the stiffness and overall properties of the asphalt pavement (Kaliske et al. 2021). Therefore, achieving a degree of pre-compaction within a specific range is important. For practical paving, however, it is also relevant to quantify this degree to plan the roll application accordingly or to adapt it to the pre-compaction state achieved (Utterodt 2013).

The aim of the investigations is, therefore, to develop a method and test it in a field trial that should allow one to estimate the degree of pre-compaction live during paving and react immediately to incorrect adjustments.

2. Literature Study

The market already offers various systems for recording the compaction status during paving. One widely used method is isotope probes (Troxler probe, according to the manufacturer Troxler Electronic Laboratories). The probes use a small amount of radioactive material for measurement and can be used to approximately a depth. 10 cm. Caesium-137 is used as a gamma emitter or americium as a neutron emitter. The layer thickness to be measured must be entered manually. Official approvals must be obtained, and requirements must be fulfilled for the purchase, storage, transportation, and operation. The operating personnel must be specially trained in radiation protection. In addition to the radiometric measurement method, an electronic measurement (capacitive method) of density is also possible. In this case, the electrical properties of the asphalt are used for the measurement. The advantage of this method is that no official requirements need to be met for its use. However, the measuring method only allows measurement close to the surface and is unsuitable for large layer thicknesses. In practice, the radiometric and capacitive methods are used at the earliest after the first rolling pass. These methods always require additional personnel to carry them out and the asphalt pavement must be walked on before final compaction, which can result in imprints on the surface. (Kappel 2016)

Area-wide dynamic compaction control (FDVK) is a roller-integrated method for measuring and documenting compaction success using dynamically excited rollers. It is based on measuring the interaction between the roller drum and the subsoil. By keeping the roller parameters constant (travel speed, oscillating mass, excitation force and direction, excitation frequency and static load), changes in the movement behaviour of the drum can be assigned to the subsoil conditions. The drum acts as a measuring tool, records its movement behaviour using a sensor and transfers the data to a processor unit for processing, which outputs and stores the compaction value. This means that no additional personnel are required for recording. Still, as the measurement only takes place during rolling, the information can only be used to adjust the screed's compaction units after a considerable delay. (FGSV 2019)

In addition to physical measurement methods, there are also various model approaches that, for example, specify the degree of compaction as a function of the paving speed, the tamper speed, and the tamper stroke. Wan and Jia for example, illustrate these relationships based on vibration theories and investigated the influence of the excitation frequency on the compaction success. They first set up a Kelvin-Voigt spring/damper model, which is intended to represent the movement behaviour of the mix in the vertical and paving direction. Using the model, they could determine how the degree of compaction adjusts depending on the excitation frequency of the vibration unit at different tamper speeds. (Wan and Jia 2019)

These models are only suitable for practical use to a limited extent, as they only apply to the validated asphalt mix types and external influences, such as temperature drops, are not considered.

3. Measurement Screed Resonance Frequency

3.1. Paving Program and Core Extraction

As part of the InfraROB research project, a trial paving was carried out on the premises of TPA Bad Hersfeld, Germany. The Volvo (ABG) P6820D paver was used with a single tamper screed of type VB 78. In order to provoke the widest possible range of different degrees of pre-compaction, two lanes were paved, each with three or two sections in which the tamper frequency was systematically changed (cf. Figure 1). The range of change was between 0 rpm and 1500 rpm, which covers the entire spectrum from minimum to maximum adjustable frequency of screed type VB 78. The tamper stroke of the VB 78 screed is not adjustable and is a constant 5 mm. The vibration unit was disabled during the entire trial paving process.

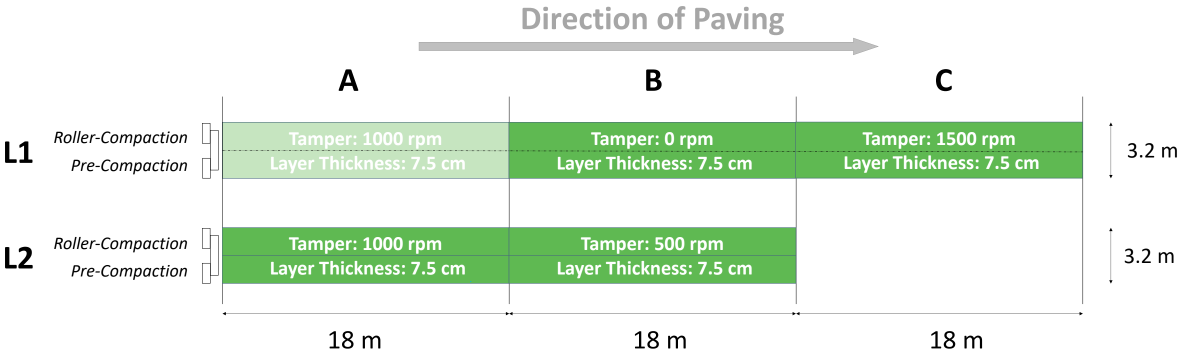

Fig. 1. Construction plan of the test track in Bad Hersfeld, Germany

The light green field is to be understood as a test field and was not included in the evaluation. The sections themselves have a length of 18 m each. At this length, it can be assumed that the screed is in a steady state (Utterodt 2013). The target layer thickness of 7.5 cm was achieved with small deviations in all relevant fields despite the drastic change in tamper frequency.

An asphalt concrete AC 16 BS with the specifications in Table 1 was laid. As shown in Figure 1, the lanes were only roller-compacted on one side in the longitudinal direction. This ensured that the cores could be removed from the pre-compacted mix. The cores were taken at the end of each section. The drill cores located in the joint area of the base screed and the extending screed were used for evaluation (cf. Figure 2). Therefore, a total of three cores were analysed for each section.

Table 1: HMA Properties

HMA Properties	AC 16 BS
Binder Type	50/70
Binder Content	4.2 M.-%
Aggregate Bitumen Affinity (24 h)	60 %
Reclaimed Asphalt	0 %
Aggregate Type	Diabas/Basalt
Aggregate Shape	Mainly Cubic Shaped
Maximum Density Aggregate Mix	2.723 g/cm3
Reference Bulk Density	2.516 g/cm3

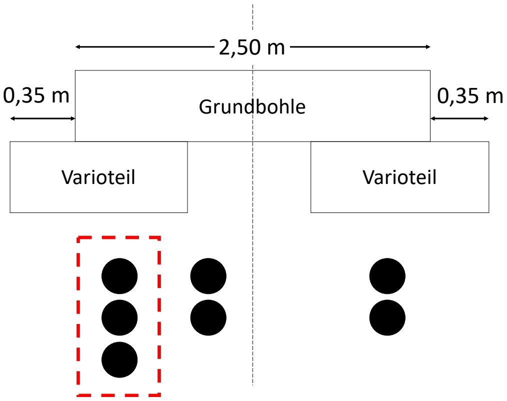

Fig. 2. Extraction concept and location of the extracted drill cores; only the drill cores in the red dashed box were used for the evaluation

3.2. Measuring Unit and Evaluation Methodology

The ADXL345 acceleration sensor from ANALOG DEVICES measured the screed resonance frequencies. The sensor can be used in a temperature range of -40 °C to 85 °C and has the ability that it can record accelerations of up to ±16 g at an output data rate of up to 3200 Hz. The sensor was controlled via a microcontroller (see Figure 3 left), which can be controlled via W-Lan using a laptop or smartphone. The microcontroller and the acceleration sensor were encased for temperature and dust protection. Using a strong magnet, the acceleration sensor was attached to a fixed part of the base plank (see Figure 3, right). This fixed element of the base screed is rigidly connected to the base plate and is, therefore, able to adequately emit the screed's resonance frequencies.

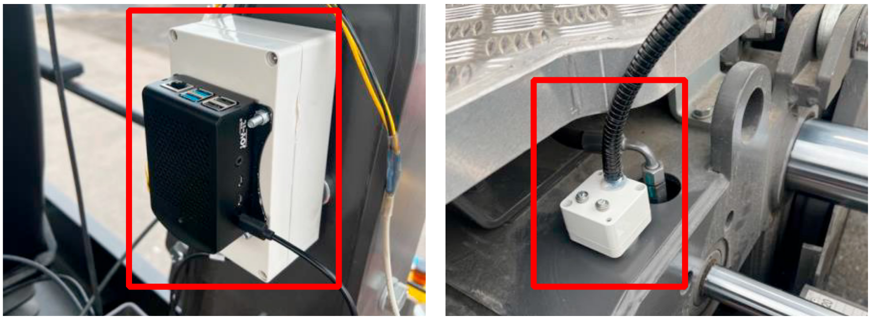

Fig. 3. Setup and installation of the measuring sensors

If the screed was only excited by the tamper unit and no other disturbance variables were present, a sinusoidal vibration would be measurable according to equation (1) where y is the amplitude, $\hat{y}$ is the initial amplitude, ω the angular frequency, t the time and φ the initial phase. However, the screed is excited to vibrate by several compaction units. In addition, further vibrations (disturbance factors) from other exciters, such as the tractor, lead to further superpositions. The screed also rests on the asphalt material, resulting in a damped vibration. (Wan and Jia 2019)

$$y = \hat{y}\, sin(\omega t + \varphi) \tag{1}$$

However, according to Fourier's theorem, all oscillation superpositions can be broken down into individual sinusoidal oscillations (Guicking 2016). The fast Fourier transform (FFT) is a highly optimized implementation of the discrete Fourier transform (DFT) (cf. equation (2)), which converts discrete signals from the time domain to the frequency domain.

$$X(k) = \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi}{N}kn} \tag{2}$$

The evaluation and analysis of the vibration data for the vertical direction (Z-axis) is carried out in several steps. Figure 4 shows an example of the procedure for lane L1. First, the measured resonance frequencies can be visualized as raw data and then exported for the respective sections. The individual sections are calibrated so that the acceleration due to gravity is calculated out. Finally, the dominant resonance frequency and the average peak acceleration can be calculated using FFT.

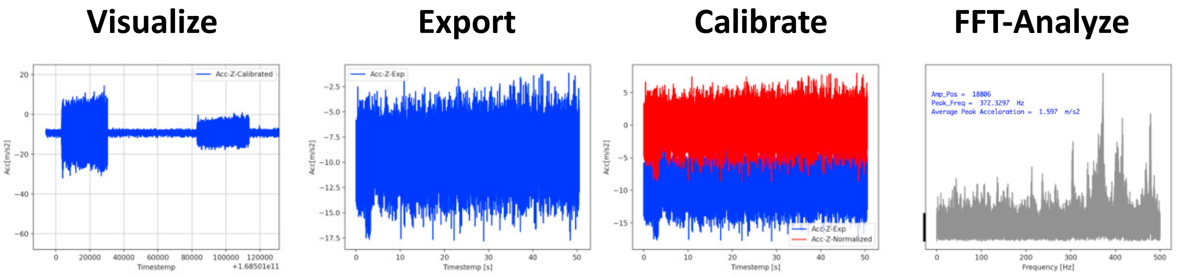

Fig. 4. Evaluation scheme of the resonant frequency data

4. Data Evaluation

4.1. Conventional parameters and FFT analysis

Table 2 shows the results of the layer thickness measurement, the bulk density, the peak frequency, and the average peak frequency as a dependency of the tamper speed. The layer thickness measurement and the bulk density determination were carried out per the German regulations TP Asphalt-StB Part 8 (FGSV 2012) and TP Asphalt-StB Part 6 (FGSV 2016). The peak frequency describes the frequency that occurs most frequently after the FFT analysis. The average peak acceleration is calculated using the average of the individual peaks of the calibrated acceleration.

Table 2. An example of a table.

Tamper Speed [rpm]	Layer Thickness [cm]	Bulk Density [g/cm3]	Peak Freq. [Hz]	Average Peak Acc. [m/s2]
0	7.6	2.262	368.52	0.190
500	7.1	2.268	409.53	0.516
1000	7.2	2.287	359.57	1.832
1500	7.6	2.298	84.44	8.481

4.2. Regression analysis

Firstly, Figure 5 shows the correlation between the average peak acceleration and the tamper speed. With a Pearson correlation coefficient (PCC) of 0.9956, it is already clear how closely the two parameters are linked. According to the regression analysis, the increase in the set tamper frequency leads to an exponential increase in the average peak acceleration, which may indicate that the tamper speed is close to one of the screed system's natural frequencies.

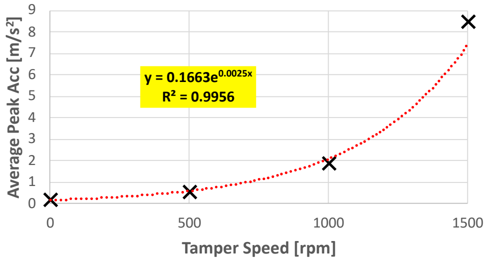

Fig. 5. Correlation between average peak acceleration and tamper speed

To be able to make a statement about the degree of pre-compaction as a function of the measured resonance parameters, these were also examined using a regression analysis. Figure 6 (a) shows the correlation between the determined peak frequency and the degree of compaction. With a PCC of 0.6296, the correlation is only weak. In addition, higher peak frequencies tend to lead to a decrease in compaction, which is also considered implausible.

The correlation between the average peak acceleration and the degree of compaction in Figure 6 (b) can be demonstrated with a PCC of 0.9768. The increase in the degree of compaction as a function of the average peak acceleration follows a logarithmic function so it can be assumed that saturation will occur despite a further increase. This correlation agrees with the investigations (Böhmer 1974), which also demonstrated a logarithmic correlation between tamper frequency and degree of compaction based on tests with a screed on a laboratory scale. Due to the high PCC, determining the average peak acceleration is regarded as a suitable parameter for real-time estimation of the degree of pre-compaction.

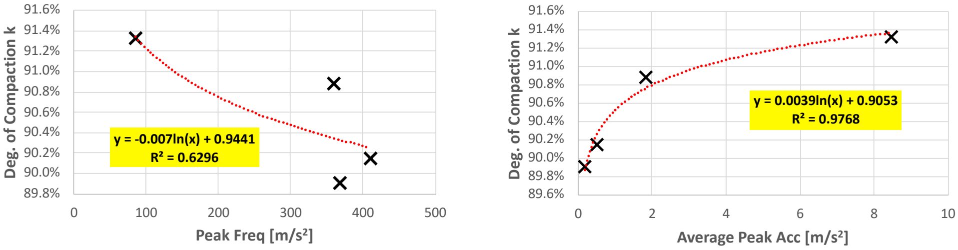

Fig. 6. (a) Correlation between peak frequency and degree of compaction; (b) Correlation between average peak acceleration and degree of compaction

5. Conclusion and Outlook

A measuring system tailored for these investigations was utilized to resonance frequencies on the paver screed during trial pavings. This system recorded data, which was subsequently evaluated through FFT analysis, allowing for correlations to be drawn with the bulk densities of core samples extracted from the pavement. A robust correlation coefficient of 0.9768 (PCC) was established between the average peak acceleration and the level of pre-compaction achieved. Such findings underscore the promise of the developed method in practical paving scenarios, offering valuable support to paving personnel and facilitating the optimization of roller usage.

To further substantiate the system's efficacy and versatility, it is imperative to conduct additional trial paving encompassing a diverse range of asphalt mixes and varied paving conditions. Moreover, leveraging the recorded vibration data for modelling purposes presents a promising avenue for further exploration. Notably, the current iteration of the system already possesses the capability to output the strength of resonance frequencies. In practical paving scenarios, compaction units are often iteratively adjusted till the screed operates “smoothly”. Introducing predefined limit ranges within the system's output parameters could facilitate the real-time assessment of compaction unit settings, indicating whether the screed is being set to run evenly. Consequently, this manual step in screed adjustment could be quantified and streamlined through automation, offering significant efficiency gains and standardization within the paving process. This represents a pivotal advancement towards achieving greater precision and consistency in pavement construction practices.

Acknowledgements

This paper was carried out in the framework of the InfraROB project (Maintaining integrity, performance and safety of the road infrastructure through autonomous robotized solutions and modularization), which has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No. 955337. It reflects only the author’s view. Neither the European Climate, Infrastructure and Environment Executive Agency (CINEA) nor the European Commission is in any way responsible for any use that may be made of the information it contains.

References

Böhmer, Peter. 1974. “Verdichtung Bituminösen Mischgutes Beim Einbau Mit Fertigern [Compaction of Bituminous Mixtures during Paving with Pavers].” Dissertation, Karlsruhe: Technische Hochschule Karlsruhe.

FGSV. 2012. *TP Asphalt-StB - Teil 8: Volumetrische Kennwerte von Asphalt-Probekörpern Und Verdichtungsgrad [TP Asphalt-StB - Part 8: Volumetric Parameters of Asphalt Specimens and Degree of Compaction]*. Ausgabe 2012. Köln: FGSV Verlag.

———. 2016. *TP Asphalt-StB - Teil 6: Raumdichte von Asphalt-Probekörpern [TP Asphalt-StB - Part 6: Volume Density of Asphalt Specimens]*. Edition 2016. Köln: FGSV Verlag.

———. 2019. *H VAE: Leitfaden Zur Herstellung von Verkehrsflächen Aus Asphalt - Hinweise Zur Sicherstellung Einer Anforderungsgerechten Ebenheit [H VAE: Guidelines for the Production of Asphalt Traffic Surfaces - Instructions for Ensuring Evenness in Accordance with Requirements]*. Ausgabe 2019. Vol. 735. Köln: FGSV Verlag.

Guicking, Dieter. 2016. *Schwingungen [Oscillations]*. 1. Auflage. Göttingen: Springer Vieweg.

Jia, Jie, Honghai Liu, and Yipin Wan. 2019. “Dynamic Characteristics Modelling of the Tamper–Asphalt Mixture Interaction: Application to Predict Asphalt Mat Density.” *International Journal of Pavement Engineering* 20 (5): 530–43. https://doi.org/10.1080/10298436.2017.1316642.

Kaliske, Michael, Markus Oeser, Lutz Eckstein, Sabine Leischner, Wolfram Ressel, and Frohmut Wellner, eds. 2021. *Coupled System Pavement - Tire - Vehicle: A Holistic Computational Approach*. Vol. 96. Lecture Notes in Applied and Computational Mechanics. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-75486-0.

Kappel, Marc. 2016. *Angewandter Straßenbau: Straßenfertiger Im Einsatz [Applied Road Construction: Road Pavers in Action]*. Edition 2. Wiesbaden: Springer Vieweg.

Rosauer, Verena. 2010. “Abschätzung Der Herstellungsbedingten Qualität Und Lebensdauer von Asphaltdeckschichten Mit Hilfe Der Risikoanalyse [Estimation of the Production-Related Quality and Service Life of Asphalt Wearing Courses with the Aid of Risk Analysis].” Dissertation, Darmstadt: Technische Universität Darmstadt.

Utterodt, Ronald. 2013. “Der Einfluß Schwankender Mischguttemperaturen Und Materialfüllstände Vor Der Einbaubohle Auf Ausgewählte Funktionseigenschaften Einer Deckschicht Aus Splittmastixasphalt [The Influence of Fluctuating Mix Temperatures and Material Levels in Front of the Screed on Selected Functional Properties of a Stone Mastic Asphalt Wearing Course].” Dissertation, Berlin: Technische Universität Berlin.

Wan, Yipin, and Jie Jia. 2019. “Nonlinear Dynamics of Asphalt-Screed Interaction during Compaction: Application to Improving Paving Density,” Construction and Building Materials, , no. 202, 363–73.