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ASPHALT PAVEMENT COMPACTION CONTROL: RELEVANCE OF LABORATORY AND NON-DESTRUCTIVE TESTING METHODS OF DENSITY

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Abstract. Assurance of asphalt pavement layer compaction, expressed by air voids ratio between field and laboratory bulk density, is one of the main criteria of the asphalt pavement durability. Thus, destructive measures should be applied, and many asphalt samples should be taken on site in order to determine the representative compaction level of constructed pavement. With the fast development of technologies, new methods should be considered for fast, non-destructive and accurate determination of asphalt bulk density on site. As there are quite few non-destructive methods related to asphalt pavement density measurement, there is a need to make comparison of such methods. Currently, when GPR methods are used to determine the density, calibration cores are used in all cases to estimate the unknown or unmeasured variables or conditions that may affect the results of dielectric value measurements. The aim of this study is

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to develop a regression model that can predict the bulk density of the compacted asphalt layer without coring, using the design values of the bulk density determined in the type tests of asphalt mixtures or other currently used non-destructive testing technologies (in this case PQI and NDG) and GPR measured dielectric constant values.

Keywords: air voids content, asphalt pavement, compaction, density, ground penetrating radar (GPR), non-destructive testing (NDT).

Introduction

The level of compacted asphalt mixture in-place density is the most important parameter that affects the satisfactory long-term performance of pavement under traffic. The asphalt mixture density is directly related to air voids. If the density is too high, the amount of air voids will be significantly small and due to plastic flow, it can make asphalt pavement susceptible to rutting, shoving, or bleeding. A too-low density or high air voids can cause cracking, moisture damage, pavement ravelling and binder oxidation or aging. Properly compacted pavement is resistant to shear and other deformations, the wearing course becomes more resistant and further compaction of the pavement takes place under traffic (Brown, 1990; Decker, 2017; TRB, 2006; McDaniel and Levenberg, 2013). Asphalt mixture in-place density must be controlled to ensure a long-lasting performance of the pavement. For many decades, core drilling has been used to determine in-place density by applying standard methods. Coring is very popular because it provides accurate measurements; however, this method is destructive, expensive and time-consuming. It results in the holes made in the pavement. Although these holes are usually filled with cold asphalt mixture, there is still a big chance that potholes will eventually appear in the drilled areas. Besides, core drilling affects the driving comfort and impairs the aesthetic appearance of the asphalt wearing layer. Finally, the in-place density is determined over a small area, so the overall quality of asphalt layer compaction cannot be determined (Zhao and Al-Qadi, 2019).

The in-place density of the asphalt pavement can be determined without damaging the asphalt pavement. This can be done using non-destructive testing (NDT) techniques. Asphalt pavement quality during and after the compaction process can be evaluated using NDT devices such as nuclear density gauge (NDG) or electromagnetic pavement quality indicator (PQI). The use of these technologies does not damage the asphalt pavement; tests are carried out fairly quickly and cheaply (Leng et al., 2018; Zhang et al., 2017). However, as with cores, the quality is determined only at local points, and the quality of compaction of the entire road section is not specified. Properly calibrated PQI is accurate for quality control applications; however, the PQI has higher variability than the core and nuclear gauge measurements (Romero, 2002). The presence of moisture has a significant effect on measurement accuracy (Leng et al., 2018), but temperature does not significantly affect the density as measured by the PQI (Williams, 2008). The main advantage of NDG is that calibration cores are not necessary, no negative effects of the presence of moisture are observed, the results obtained are accurate enough, but due to the safety requirements, this technology is not attractive. Ground penetrating radar (GPR) technology can be advantageous in this case, as it does not damage the asphalt pavement (Ameri et al., 2014), measurements are done quickly, cheaply, and most importantly, the in-place density is determined across the entire length of the road (Kassem et al., 2016).

With the view to conduct compaction control using this NDT method, in 2018 and in 2019 the research was conducted on four newly built or reconstructed highways Kaunas-Marijampolė-Suvalkai (A5), Vilnius–Utena (A14) and on reconstructed road section Šilalė–Žadeikiai (4105). The tests were performed on two different layers of asphalt. The in-place density of asphalt was established by standard methods and was compared with the results determined using GPR and other NDT methods. Regression models were developed to predict the bulk density of the compacted asphalt layer without coring.

1. Determination of asphalt pavement layer in-place density using NDT

Nuclear density gauge (NDG) is the most common NDT method for measuring in-place density and it is able to provide reasonably accurate results (Kvasnak et al., 2007). The nuclear asphalt density gauge consists of one radioactive source and two density measurement detectors, operating in backscatter mode where gamma photons that penetrate the asphalt must be scattered or reflected from transmitter to reach the detectors (see Figure 1) (Troxler Electronic Laboratories, 2021). This NDT method can be used on most asphalt types, except for open graded asphalt. Using this technology, the density of asphalt can be measured when the asphalt layer thickness is in the range of 25 to 100 mm. The gauge must be calibrated periodically in the density range of 1.72 to 2.76 kg/m^3 and the density drift should not exceed 0.5% (Maritime Services, 2015).

Although this technology is an NDT tool which is sufficiently reliable and widely applicable in civil engineering, the main disadvantages are that the density is measured in a small area and NDG carries potential safety risks due to the use of radiative materials. Very strict requirements are set for its maintenance, storage, transportation and operation on site (IAEA, 1996).

Another type of NDT equipment used to determine asphalt density or the degree of compaction is EM density gauges, also known as non-nuclear density gauges. One of the most popular devices currently used to measure asphalt density is electromagnetic pavement quality indicator (PQI). The PQI is used to measure asphalt bulk density and the dielectric value or constant of the asphalt mixture. The measurement is conducted using an electromagnetic field generated under the sensing plate (Mata et al., 2018).

To determine the reliability of this method, various studies have been conducted. Romero after his field study concluded that the calibrated PQI was accurate for quality control applications; however, the PQI had higher variability than the core and nuclear gauge measurements (Romero, 2002). Leng found that the accuracy of PQI measurements could be considerably improved after calibration, the error percentage was reduced from 15% to 1.5% and the effect of the presence of moisture on measurement accuracy became insignificant (Leng et al., 2018). Li stated that for the calibration of PQI values, sand patch test was not recommended, more precise values could be achieved by calculating the difference between the average PQI values and the actual density of cores, which could be taken as the modification value (Li et al., 2019). Williams also concluded that temperature did not significantly affect the

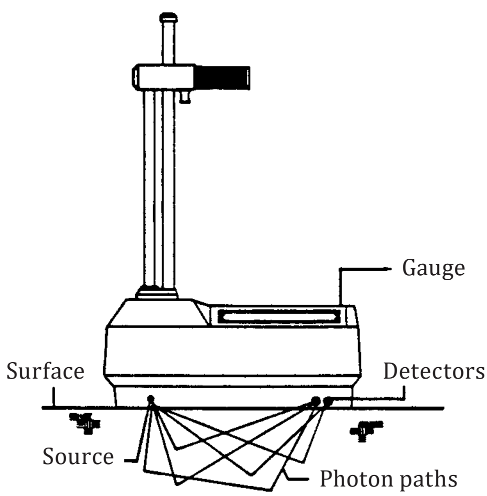


Figure 1. Nuclear density gauge operation scheme

density as measured by the PQI (Williams, 2008). After field study Shah concluded that PQI-380 performed well under field conditions of varying temperature and the coefficient of correlation was near to 0.9 (Zaman et al., 2019). However, just like nuclear density gauge and cores, the density of asphalt with PQI is determined only at specific points, and the quality of compaction of the entire road section is not specified.

Ground penetrating radar technology can be advantageous in this case as it does not damage the asphalt pavement, measurements are done quickly, cheaply, and most importantly, the in-place density is determined across the entire length of the road (Kassem et al., 2016). GPR technology uses high and ultra-high frequency (10 MHz – 2.5 GHz) electromagnetic waves by transmitting and recording their reflection from different surfaces and pavement structure layers at different depths.

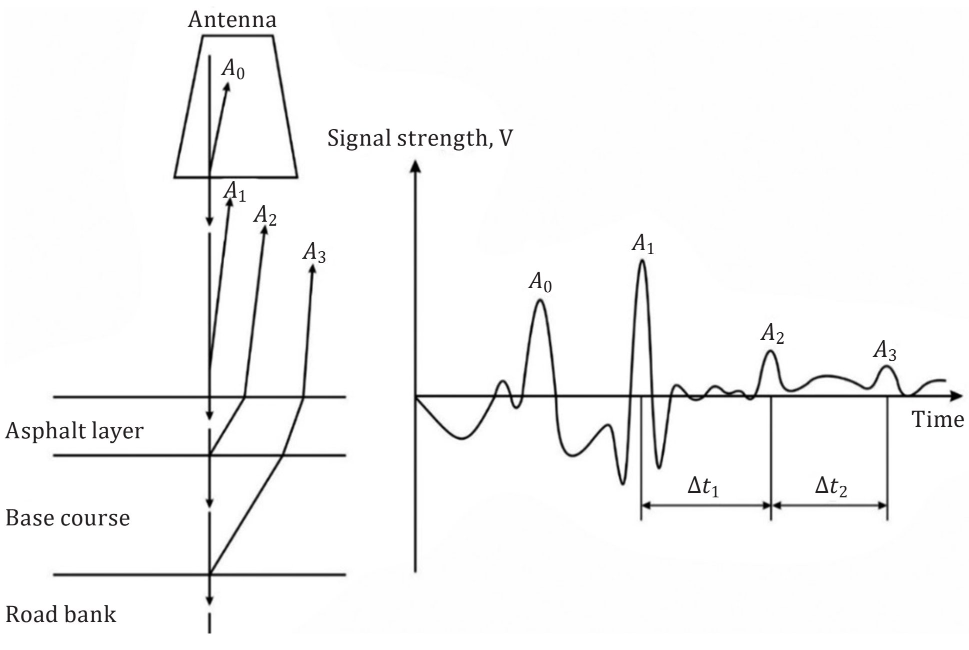
To measure the pavement density or air voids by the GPR method, an air-coupled antenna mounted on the vehicle at a height of 0.3 to 0.5 m above the surface of the pavement is used, and measurements can be performed at the speed up to 80–100 km/h without interfering with traffic. The antenna transmits short pulses of electromagnetic energy to the road structure. Some pulses are reflected from the surface or deeper layers of the pavement and return back to the antenna. Depending on the dielectric properties of the material, the electromagnetic waves are reflected differently. The equipment records the "travel" time of the wave. The reflected energy is presented in the form of the wave (see Figure 2). The propagation and reflection of the waves depend on the electrical properties of the materials, such as magnetic susceptibility, relative dielectric permittivity or dielectric value, and electrical conductivity (Saarenketo, 2006). Dielectric value or constant is calculated according to Equation (1) (Saarenketo and Scullion, 2000; Shangguan et al., 2016).

$$\varepsilon_{\mathrm{AC}} = \left(\frac{A_{\mathrm{m}} + A_1}{A_{\mathrm{m}} - A_1} \right)^2, \tag{1}$$

where $\varepsilon_{\mathrm{AC}}$ – the dielectric value of the asphalt surface layer; A_1 – the amplitude of the reflection of GPR signal from the surface in volts; A_{m} – the amplitude of the reflection from a large metal plate in volts.

The dielectric value of the asphalt mixture depends on the volumetric and dielectric properties of its components (aggregates, bitumen and air) and their proportions in the mixture (Al-Qadi et al., 2011). During the compaction process, the volumetric content of aggregates and bitumen, with higher dielectric value than air, increases proportionally in the mixture. Thus, the more the asphalt pavement is compacted, the higher its dielectric value is (Saarenketo, 2013).

Three models were proposed for the determination of asphalt pavement density (Al-Qadi et al., 2011) based on the rayleigh mixing formula described in (Sihvola, 1989) mixing theory. Models are shown in equations: CRIM Complex Refractive Index model and Bottcher model (Leng et al., 2011). Aggregate density, maximum asphalt mixture density, and bitumen content are evaluated in the mix design. The dielectric value and density of bitumen are taken as constant (Sebesta et al., 2012). The dielectric value of the aggregate needs to be back-calculated using information from field core data. The CRIM and Bottcher models previously were successfully used in other areas, and their parameters are easily obtainable. The Bottcher model later has been modified and named ALL (2) (in honour of the scientists who created it: (Al-Qadi et al., 2011; Wang et al., 2018). This model is proved to be an accurate density prediction method using GPR (Wang et al., 2018), the error of density results measured with standard methods and with GPR did not exceed 1.1% (Sebesta et al., 2012).



Note: A_0 – amplitude of the reflection in the antenna; A_1 – amplitude of surface layer reflection; A_2 – amplitude of the base layer reflection; A_3 – amplitude of the subgrade reflection; Δt_1 – time of wave propagation in asphalt pavement; Δt_2 – time of wave propagation in the base layer.

Figure 2. Operation diagram of air-coupled antenna of Ground Penetrating Radar

$$G_{\mathrm{mb}} = \frac{\dfrac{\left(\varepsilon_{\mathrm{AC}} - \varepsilon_{\mathrm{b}}\right)}{\left(3\varepsilon_{\mathrm{AC}} - 2.3\varepsilon_{\mathrm{b}}\right)} - \dfrac{\left(1 - \varepsilon_{\mathrm{b}}\right)}{\left(1 - 2.3\varepsilon_{\mathrm{b}} + 2\varepsilon_{\mathrm{AC}}\right)}}{\dfrac{\left(\varepsilon_{\mathrm{s}} - \varepsilon_{\mathrm{b}}\right)}{\left(\varepsilon_{\mathrm{s}} - 2.3\varepsilon_{\mathrm{b}} + 2\varepsilon_{\mathrm{AC}}\right)} \dfrac{\left(1 - P_{\mathrm{b}}\right)}{G_{\mathrm{sb}}} - \dfrac{\left(1 - \varepsilon_{\mathrm{b}}\right)}{\left(1 - 2.3\varepsilon_{\mathrm{b}} + 2\varepsilon_{\mathrm{AC}}\right)} \left(\dfrac{1}{G_{\mathrm{mm}}}\right)}, \qquad (2)$$

where G_{mb} – bulk density of asphalt mixture, kg/m^3; G_{mm} – maximum density of asphalt mixture, kg/m^3; P_{b} – binder content, %; G_{b} – density of binder, kg/m^3; G_{sb} – bulk density of aggregate, kg/m^3; $\varepsilon_{\mathrm{AC}}$ – dielectric value of asphalt mixture; ε_{b} – dielectric value of binder; ε_{s} – dielectric value of aggregate.

Aggregate density, maximum asphalt mixture density, and bitumen content are evaluated in the mix design. The dielectric value and density of bitumen are taken as constant. Bitumen density was determined to be 1.015 kg/m^3 and bitumen dielectric value was 3 (Sebesta, Saarenketo, and Scullion, 2012). The dielectric value of the aggregate needs to be back-calculated using information from field core data (Wang et al., 2018). This parameter is very important as studies have shown that improper selection of this value can strongly affect the results (Wang, Al-Qadi, and Cao, 2020).

By applying the ALL model, asphalt pavement was measured with GPR during the performance of pavement compaction and test errors did not exceed 3%. It was suggested to install the GPR directly on the road roller machine and carry out measurements in a continuous manner until the asphalt pavement compaction works are finished (Wang, Zhao, and Al-Qadi, 2018). The suggestion was conditioned by the previously conducted studies, which determined that the pavement temperature that was measured with GPR did not significantly influence the dielectric properties of the pavement (Al-Qadi et al., 2011). Algorithms were also proposed to estimate the possible amount of moisture found in the mixture during the performance of compaction works. Asphalt pavements with different densities and pavement moisture contents (Shangguan, Al-Qadi, and Lahouar, 2014) have been investigated for the development and validation of algorithm (Shangguan et al., 2016).

Many studies have been conducted without applying any model, simply by comparing the density or the air void content of the asphalt pavement cores with the dielectric value of the pavement. Many studies have shown that the correlation between these values is strong (Sebesta, Saarenketo, and Scullion, 2012; Ameri et al., 2014; Sebesta et al., 2006; Popik et al., 2010) or moderate (Sebesta et al., 2006; Berthelotet al., 2009; Sebesta, Saarenketo, and Scullion, 2012).

2. Collection of research data

In 2018 and 2019, the research was conducted on four newly built or reconstructed roads. The 11.68 km section of the highway Kaunas-Marijampolė-Suvalkai (A5) and 4 km road section of highway Vilnius–Utena (A14) were reconstructed into four-lane highways (see Figure 3) and the 7.03 km section in Šilalė–Žadeikiai road (4105) was reconstructed.

In this study, measurements were carried out on a 14 cm thick base asphalt pavement layer of asphalt mixture AC 32 PS, intermediate 8 cm thick asphalt layer of AC 22 AS asphalt (A5), 6 cm single-layer asphalt base pavement from the mixture AC 16 PD on the former gravel road (4105), 10 cm thick base asphalt pavement layer of asphalt mixture AC 22 PS and intermediate 9 cm thick asphalt layer of AC 16 AS asphalt (A14). The minimum length of each test section was 1 km.

Asphalt bulk density measurements were carried out on each test section of constructed asphalt layer using non-destructive and destructive methods. The layer bulk density was determined using four non-destructive and destructive technologies, namely, nuclear thin layer density gauge Troxler 4640-B (NDG), electromagnetic pavement quality indicator PQI-380 (PQI), GSSI 1 Hz GPR horn type antenna (GPR), and by drilling cores and testing them in the laboratory (Core). All test points for one test section and layer were examined on the same day and under the same pavement surface conditions. Measurements in test sections No. 1–4 were performed in June 2018 and in 2019, and in test sections No. 5 and No. 6 in September 2019. Detailed information on experimental sections and asphalt mixtures and their properties is presented in Table 1.

Figure 3. Location of testing sites, Vilnius–Utena road (A14)

The PQI equipment was calibrated before measurements. Offset value was determined by calculating the difference between the average PQI value and the bulk density of core at calibration. PQI measurements were made in average mode (Sebesta and Zeig, 2003; TransTech Systems Inc., 2019); five PQI readings were taken as showed in Figure 4 and the average result was recorded.

Table 1. Test sites and asphalt mixture information

Test section		S1	S2	S3	S4	S5	S6
Road No.		A14	A5	A14	4105	A14	A14
Asphalt mix type (binder)		AC 22 PS 50/70	AC 32 PS 50/70	AC 16 AS PMB 45/80-55E	AC 16 PD 70/100	AC 16 AS PMB 45/80-55E	AC 22 PS 50/70
Pavement layer		Base	Base	Interme-diate	Base-pave-ment (wea-ring course)	Interme-diate	Base
Thickness of the layer, cm		10.0	14.0	9.0	6.0	9.0	10.0
Asphalt mix design information	**Binder content, %**	3.8	3.8	4.2	5.2	4.2	3.8
	Maximum density, Mg/m^3	2.587	2.547	2.529	2.495	2.529	2.587
	Bulk density, Mg/m^3	2.451	2.377	2.420	2.460	2.420	2.451
	Air void content, %	5.2	7.4	4.3	1.4	4.3	5.2
	Main aggregate	Dolomite					

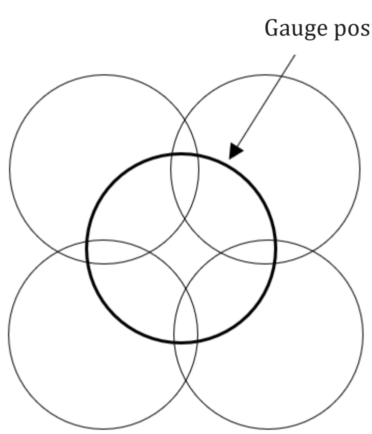


Figure 4. Pattern of PQI positions for each test point

PQI measurements were made with a gauge placed parallel to the compaction direction, although other studies show that the effect of gauge measurement direction on PQI measurement is insignificant (Leng et al., 2018). In addition, studies have shown that surface pavement markings such as spray paint have no significant effect on gauge accuracy, whereas presence of moisture can have an effect on readings (Timm, 2013; Leng et al., 2018). Therefore, measurements were made on dry asphalt pavement, except for road section No. 4, which had some test points with visual presence of moisture.

Troxler 4640-B gauge was calibrated before measurements as specified in the operation manual (Troxler Electronic Laboratories, 2009). Three readings were taken at each test point and the average result was recorded. All measurements were performed in compliance with all safety requirements. NDG measurements were made with gauge placed parallel to the compaction direction.

All testing points were measured using a 1 Hz GPR horn type antenna and following the guidelines (LRA, 2011) and the GPR equipment

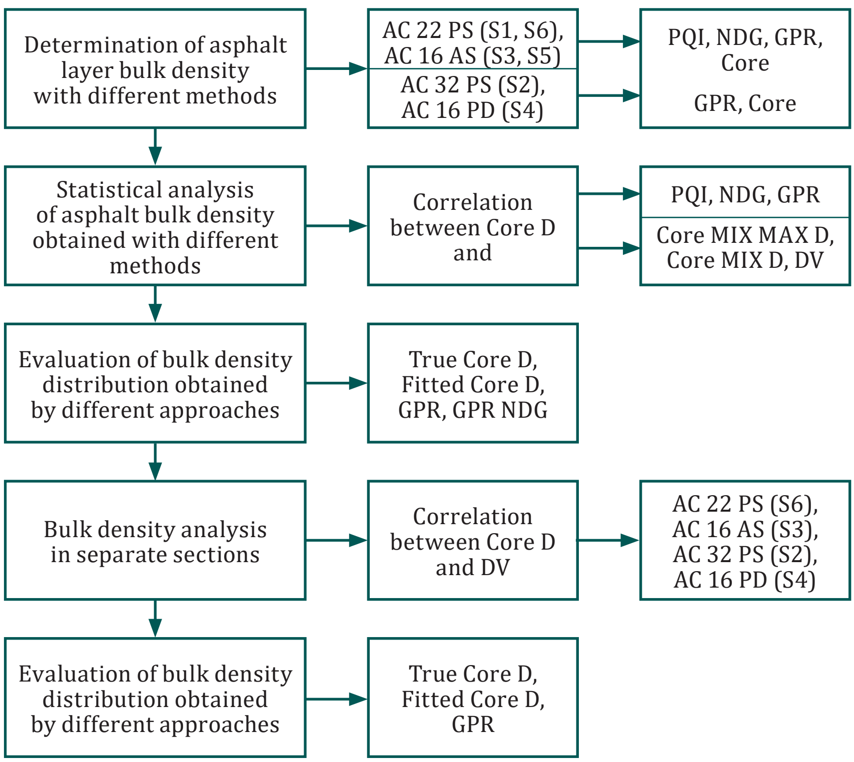


Figure 5. A simplified experimental plan

manufacturer's manual. The GPR antenna was calibrated using a metal plate before and after the measurements. The dielectric value of the asphalt pavement was determined at each test point. After analysing the primary GPR data using the Road Doctor program, the average dielectric value of the measured section was determined. The measurement point closest to this value was identified in the GPR data diagram, and an additional calibration core was drilled after the coordinates of its location were established (Saarenketo, 2012). On the basis of the results of previous studies (Baltrušaitis, Vaitkus, and Smirnovs, 2020), the GPR mathematical model ALL was chosen. Using ALL mathematical model, the experimental bulk density was calculated based on the pavement dielectric value and other asphalt mixture and cores data, using Equation (2) (Sebesta et al., 2012).

To avoid destructive testing, the use of the results of other non-destructive methods for the prediction of the density of compacted asphalt layers should also be considered. In test sections No. 1, No. 3 and No. 6, the possibility to use the bulk layer density values determined in the same locations with NDG for ALL model instead of the calibration core values was explored.

After GPR measurements were made, the cores were drilled in the specified measurement points according to the European standard EN 12697-27 (CEN, 2017). Then the bulk density of cores (Core D) was established according to LST EN 12697-6 using the SSD method (CEN, 2012). Standard core test results were compared with NDT test results.

After standard and NDT tests, all results were systematized and statistically evaluated. Regression models were developed to predict the bulk density of the compacted asphalt layer without coring. A simplified experimental plan is shown in Figure 5.

3. Research data analysis

In this section, the results of statistical analysis are presented. The descriptive characteristics as min, max, median, mean ± standard deviation (SD), and the 1st and 3rd quartiles (Q1 and Q3) and box-plot diagram are used to describe distribution of Core D values in each test section. For evaluation of the dependencies between Core D and other factors, the correlation coefficients *r* are calculated, ANOVA for comparing Core D values between sections is used and linear regression models for Core D predictions are estimated: single regression model suitable for all test sections included in the analysis and different linear regression models for each section separately were chosen. For measure goodness of fit of estimated regression models, the determination coefficient R^2 was calculated and analysis of the model residuals performed. To test hypothesis about the normal distribution in the data, the Jarque–Bera test was used. Durbin Watson statistic was used to detect the autocorrelation in model residuals.

The mean of all Core D measurements is observed as 2.45 ± 0.04 Mg/m^3. After evaluating the descriptive characteristics of the Core D in each section (see Table 2 and Figure 6), it was found that the average density in test section No. 1 is significantly higher than in the others ($p < 0.001$). In section No. 6, where the same mixture (AC22PS) was used as in test section No. 1, the mean Core D was closer to section No. 1. The variation of Core D is slightly higher in sections No. 2 and No. 5, but the mean of core density of the four sections No. 2, No. 3, No. 4 and No. 5 does not differ statistically significantly from each other ($p = 0.327$).

Table 2. Descriptive characteristics of Core D in different test sections

Test section	Min	Q1	Median	Average	SD	Q3	Max
S1	2.456	2.485	2.494	2.491	0.016	2.504	2.515
S2	2.374	2.395	2.428	2.429	0.034	2.459	2.472
S3	2.391	2.429	2.457	2.447	0.031	2.463	2.498
S4	2.394	2.414	2.434	2.433	0.028	2.453	2.479
S5	2.377	2.406	2.422	2.429	0.037	2.455	2.496
S6	2.428	2.449	2.461	2.463	0.021	2.481	2.502

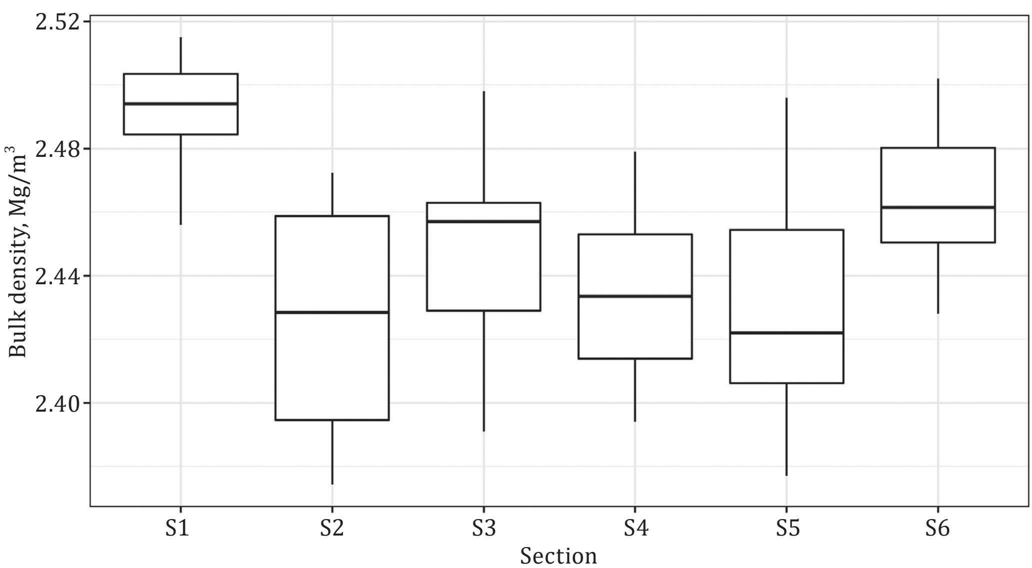


Figure 6. Box-plot diagram of the Core D values

During the first stage of analysis, the correlation between the asphalt layer bulk density evaluated by NDT methods and the Core D was observed. All 6 sections were measured with a GPR antenna, and the bulk density of asphalt layer was calculated at the locations of asphalt core drilling using the ALL model. In test sections No. 1, No. 3, No. 5, and No. 6, the same locations were additionally measured with PQI and NDG measuring devices.

Evaluation of correlation between the core and the NDT results shows that the results of the GPR correlates well or very well, from $r = 0.557$ on test section No. 1 to 0.902 on test section No. 2 (see Table 3). The worst correlation between cores and GPR results that was found in test section No. 5 could have been influenced by the moisture present in some of the test points. Previous studies have shown that when measuring with a 1 Hz antenna more reliable results are obtained for measurements of single layer asphalt (Baltrušaitis, Vaitkus, and Smirnovs, 2020). Measurement of the two-layer asphalt pavement in this study showed the results similar to the single-layer pavement measurements.

Table 3. Correlation of bulk density determined by different methods with Core D

Correlation *r* with Core D						
Test section	S1	S2	S3	S4	S5	S6
No of test points	27	18	17	10	20	17
PQI	0.297	–	0.172	–	0.398	0.196
NDG	0.472	–	0.490	–	0.551	0.557
GPR	0.557	0.902	0.807	0.828	0.182	0.721

Comparison of the results of the cores and the PQI shows that correlation between the cores measured by standard methods and the PQI results is weak or non-existent; correlation varies from $r = 0.172$ on test section No. 3 to $r = 0.398$ on test section No. 5.

Since GPR and PQI technologies operate in the same way as EM waves, presence of moisture in asphalt may influence the accuracy of both measurements.

Correlation between the NDG and core results is better than PQI: from 0.472 on test section No. 1 to 0.557 on test section No. 6. The main advantage of this technology is that calibration cores are not necessary, no negative effects of the presence of moisture are observed, the results obtained are accurate enough, but due to the safety requirements, this technology is not attractive.

The analysis of the results shows high correlation between Core D and densities determined using GPR technology. The correlation with NDG was worse but very similar in all test sections. The application of PQI technology did not show a reliable correlation, so it was decided not to examine these data further in this study.

During the second stage of analysis, the data of dielectric constant (DV) values at each core drilling point, the bulk density (Core MIX D) of laboratory compacted core mix specimen and the maximum core mix density (Core MIX MAX D) were used to perform statistical analysis in order to evaluate how these factors were related with the Core D.

Scatter plot of the Core D and dielectric value (DV) (see Figure 6) shows similar linear dependencies between Core D and DV in all test sections – as the DV values increase, the Core D values tend to increase as well. However, one can see in the graph that there is a tendency for DV values differ between test sections (even for mixtures of the same type). It may be influenced by aggregate properties, bitumen binder content in the mixture, and possible residual moisture content, which can significantly increase DV results. In this case, the same type of mixture (AC 16 AS) was tested in test sections No. 3 and No. 5, but in different season and under different pavement conditions (there may be residual moisture in section No. 5). In section No. 3, the DV ranges from 4.8 to 5.2, and in No. 5 it is from 5.5 to 6.4.

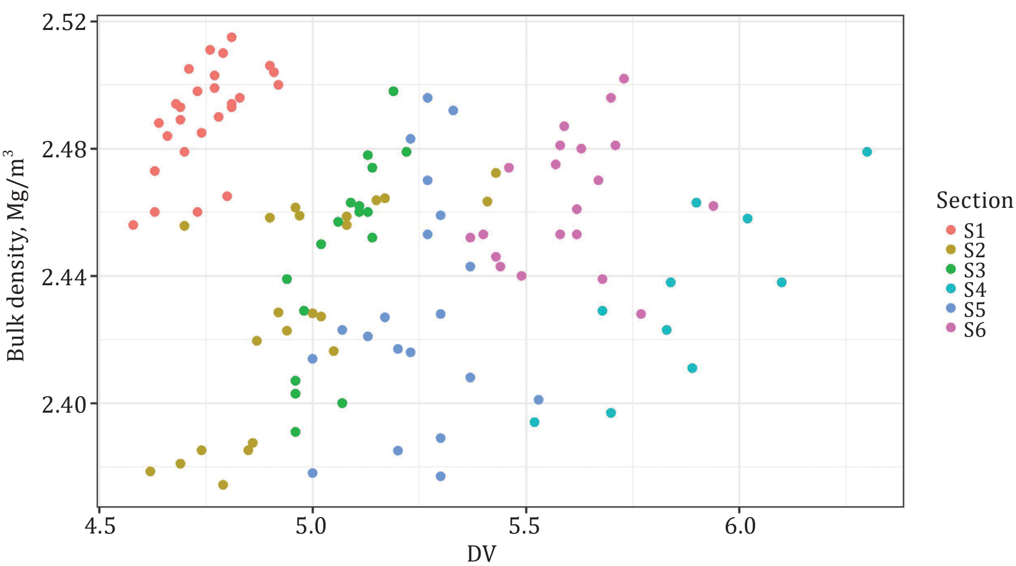


Figure 7. Scatter plot between DV and Core D in all test sections

As it is seen in the scatter plot (see Figure 7), there are some measurement points in section No. 2 and section No. 6, which have strong evident deviation from a common linear trend. Therefore, these outliers, namely, four measurement points from section No. 2 and three measurement points from section No. 6, were excluded from the further statistical analysis.

The further correlation analysis (see Table 4) shows that in all test sections, except for test section No. 5, the relation between Core D and dielectric value is quite strong. The correlation ranges from 0.560 in test section No. 1 to 0.900 in test section No. 2. The correlation between Core D and DV in test section No. 5 is very low, $r = 0.187$. Such a low correlation may be caused by residual humidity, which remained because of excessively short time between the last rain and the start of the measurements. Therefore, data of test section No. 5 were excluded from further analysis. Since the moisture content of the asphalt layer has a significant impact on the values of DV results and their reliability, further research is necessary to evaluate the possibility to determine the moisture content of the measured asphalt layer, for which inductive electromagnetic moisture meters or other technologies could be applied.

The bulk density values of the samples compacted from the core asphalt mixture correlate quite well with the Core D values. The correlation coefficient varies from 0.611 in test section No. 1 to 0.843 in test section No. 2. Therefore, this variable together with the dielectric value is included in the regression model.

The correlation of the values of the core mixture maximum density (Core MIX MAX D) with Core D is unstable and even its direction differs depending on the test sections. In test sections No. 2 and No. 6, it is positive (0.711 and 0.45) whereas in test sections No. 1, No. 3 and No. 5 it is negative (−0.308, −0.565 and −0.538). After assessing the significance of the correlations, it was decided not to use Core MIX MAX D in the modelling.

Table 4. Correlation between Core D and asphalt core mixture laboratory densities and dielectric values

Test section	S1	S2	S3	S4	S5	S6
Core MIX MAX D	−0.308	0.711	−0.565	–	−0.538	0.450
Core Mix D	0.611	0.843	0.823	0.852	0.826	0.650
DV	0.560	0.900	0.807	0.811	0.187	0.720

Based on the results of descriptive and correlation analysis, the regression model to evaluate the relationship between Core D and other two factors, DV and Core MIX D, was developed (see Equation 3). Both factors included in the model are statistically significant ($p < 0.0001$). Considering the above-mentioned excessive difference of the Core D and DV means in Sections No. 1 and No. 4 (see Figure 7), the corrective factors (dummy variables) S1 and S4 were included in the model. According to the estimated parameters of these dummy variables, the modelled Core D values in section No. 1 in average are 0.07 Mg/m^3 higher than in other sections, and Core D values in section No. 4 are 0.09 Mg/m^3 lower than in other sections. Increasing the scope of the tests by performing measurements on the AC22AS asphalt layer would allow correcting the corrective factors or excluding them from the model completely. The estimated regression model explains 85% variability of the Core D around its mean ($R^2 = 0.85$).

$$\text{CoreD} = 0.1_{p=0.67} + 0.07 \times \text{DV}_{p=<0.0001} + 0.815 \times \text{CoreMIXD}_{p=<0.0001} + 0.07 \times \text{S1}_{p<0.0001} - 0.09 \times \text{S4}_{p<0.0001} \quad (3)$$

To evaluate the reliability of the developed regression model, the Core D values at the measurement points of all test sections are recalculated using the obtained formula. The obtained fitted Core D values are plotted against the True Core D values determined by standard methods, the values obtained by applying the ALL model (GPR) and density values of GPR NDG (see Figure 8). The differences between True Core D and estimated Core D are treated as model residuals. The mean of model residuals is less than 0.0001 Mg/m^3 (see Table 5), while the mean of differences between Core D and GPR is slightly higher, 0.009 ± 0.039 Mg/m^3. The hypothesis about the normality of model residuals was not rejected (p = 0.44), but DV = 1.578 (p = 0.008) statistics indicates there exists autocorrelation in model residuals which implies that the model should be improved in future by making more measurements or by refining and harmonizing the measurement conditions or including additional factors in the model. In conclusion, the developed regression model revealed the existing strong relation between Core D, DV and CoreMixD, but due to existing and not identified factors that lead to differences between test sections, this model for Core D prediction should be revised.

Table 5. Descriptive characteristics of model residuals and differences between Core D and GPR

	Min	Q1	Median	Mean	Q3	Max	SD
Core D – GPR	–0.0996	–0.0124	0.0075	0.0092	0.0311	0.1123	0.039
True Core D – Fitted Core D	–0.0359	–0.0071	–0.0013	0.0000	0.0116	0.0281	0.014

The obtained density values of GPR NDG are shown in Figure 8. As one can see in the graph, the GPR NDG values are even more distant from the True Core D values than the GPR values determined by the standard ALL method. It can be concluded that the use of NDG values instead of calibration cores is not appropriate.

The variable Core MIX D used in the estimated linear regression model is obtained from laboratory compacted samples of core mixture; therefore, it is necessary to assess the possibility to use the design bulk density values (D MIX D) of asphalt mixtures instead of this value in order to avoid destructive tests. Assessment of correlation between Core MIX D included in the regression model and D MIX D shows that the correlation is small, reaching only 0.3. Theoretically, the values of Core MIX D should increase with increasing D MIX D, but considering the available data, this theoretical assumption is not clear. Therefore, it can be concluded that it is not correct to use D MIX D values instead of Core MIX D value in the developed model. To completely eliminate destructive testing, it is necessary to perform additional studies and to use the data obtained by the standard test methods for the asphalt mixtures sampled during asphalt compaction instead of the design bulk densities of the actual bulk density.

After evaluating the obtained results, it can be concluded that it is not possible to apply the general model to the mixtures of different types of asphalt; therefore, it is necessary to consider the possibility to create separate mathematical models for different types of asphalt mixtures

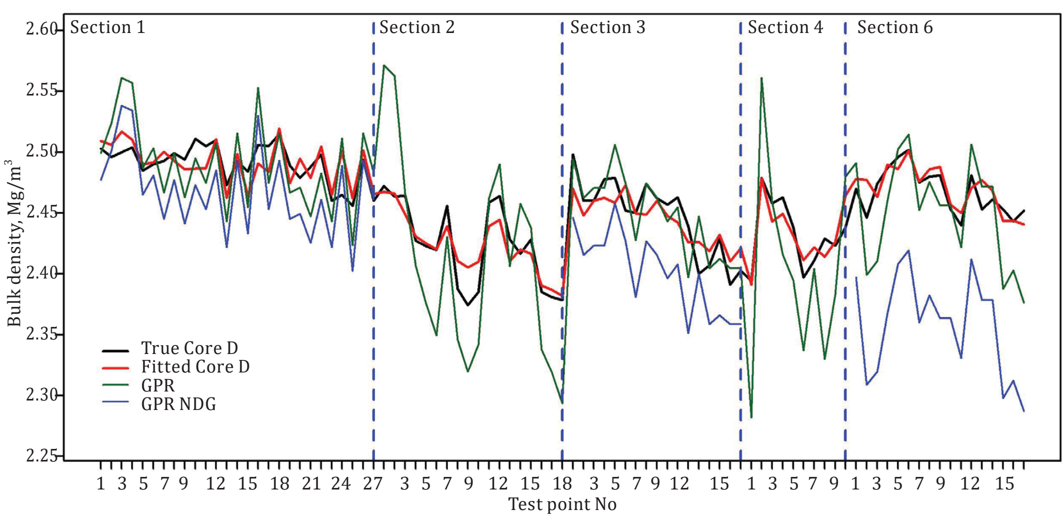


Figure 8. Distribution of asphalt density values obtained by different methods

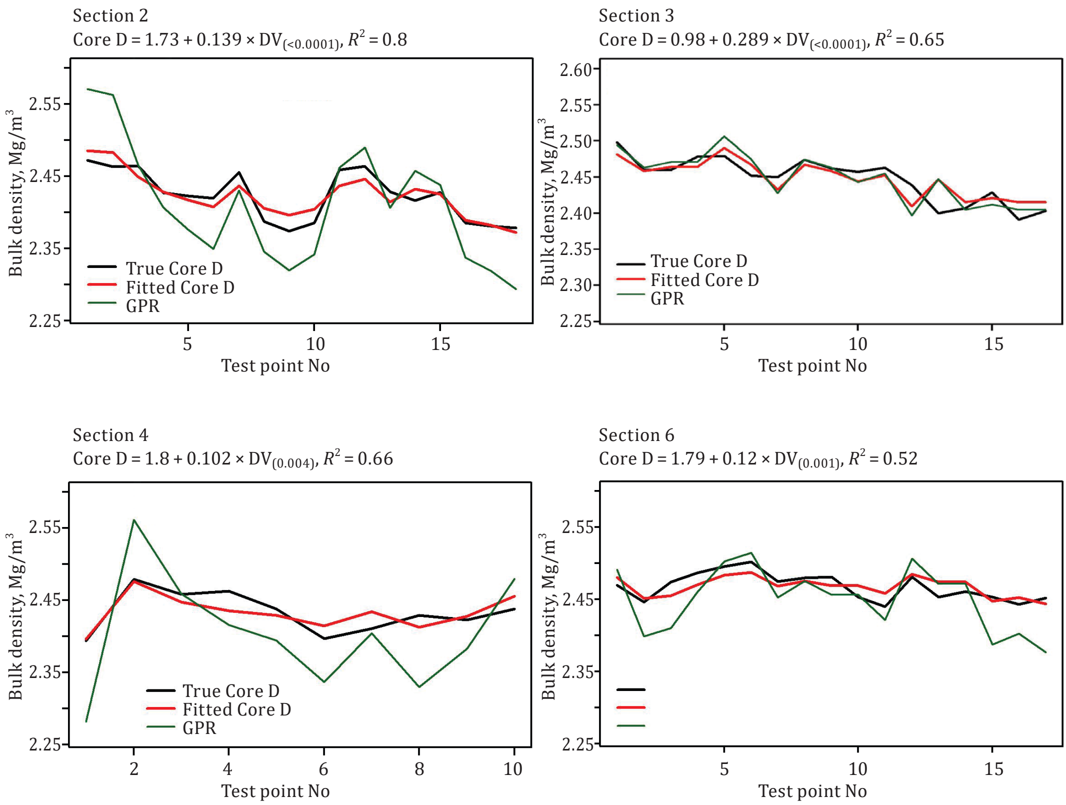


Figure 9. Graph of calculated asphalt density values obtained by different methods

Table 6. Descriptive statistics of model residuals

Residuals	Test section	Min	Median	Mean	Max	SD
True Core D -Fitted Core D	S2	−0.022	0.001	0.000	0.0220	0.015
	S3	−0.047	0.004	0.000	0.0297	0.018
	S4	−0.023	0.000	0.000	0.0278	0.016
	S6	−0.021	0.005	0.000	0.0191	0.013
Core D – GPR	S2	−0.100	0.024	0.013	0.0851	0.053
	S3	−0.047	0.000	−0.001	0.0422	0.020
	S4	−0.082	0.042	0.028	0.1123	0.060
	S6	−0.026	0.018	0.017	0.0756	0.032

in order to estimate the bulk density of asphalt layer. It was decided to use only dielectric values measured by GPR for the evaluation of these models, as DV significantly correlated with the bulk densities of the cores. Only the test sections with a strong or very strong (greater than 0.7) correlation of the dielectric value with the core bulk density were selected for evaluation of regression model in each section. Separate regression models were evaluated for test sections No. 2, No. 3, No. 4, and No. 6. The developed models for each section are presented in Figure 9. The parameters of DV are statistically significant in all of them, R^2 varies from 0.5 to 0.8. It means that the dielectric value DV explains 80% of values of the core bulk density in test section No. 2 and only 50% of values of the bulk density in test section No. 6. In test sections No. 3 and No. 4, similar values of R^2 were observed (65% and 66%, respectively). To evaluate the goodness of fit of estimated models, the fitted Core D values are plotted against the Core D values determined by standard methods and the values obtained by applying the ALL model (GPR) (see Figure 9).

After evaluating the model residuals in each section, one can see that the mean of the residuals is zero in all test sections and the mean of differences between Core D values and GPR ranges from −0.001 in test section No. 3 to 0.028 in test section No. 4 (see Table 6). A model is considered good if the mean of the residuals is about zero, the distribution of residuals is normal, residuals are with constant variance and not correlated. The hypothesis about normal distribution of model residuals is not rejected in all four models, accordingly, $p = 0.448$, $p = 0.332$, $p = 0.79$ and $p = 0.503$. DW statistics detects the autocorrelation in model residuals just in S6 section ($DW = 1.08$, $p = 0.014$), for all other sections No. 2, No. 3 and No. 4 the hypothesis that residuals are serially uncorrelated was not rejected (accordingly, $DW = 1.6$ ($p = 0.144$), $DW = 2.157$ ($p = 0.569$), $DW = 1.498$ ($p = 0.210$)).

After evaluation of all goodness of fits of estimated models, it can be stated that all the developed models are suitable for prediction, but due to the small number of measurements their reliability must be verified in other test sections of a similar type of asphalt mixture and layer.

Conclusions

After evaluating the descriptive characteristics of the bulk density of asphalt cores in each section, it was found that the average density in test section No. 1 was significantly higher than in other sections ($p < 0.001$).

PQI is the least reliable NDT tool for estimating the density of the paved asphalt layer. The correlation between the cores measured by standard methods and the PQI results is weak or non-existent; correlation varies from r = 0.172 on test section No. 3 to 0.398 on test section No. 5. Correlation between the NDG and core results is much higher and varies from 0.472 on test section No. 1 to 0.557 on test section No. 6. The main advantage of this technology is that calibration cores are not necessary, no negative effects of the presence of moisture are observed, the results obtained are accurate enough, but due to the safety requirements, this technology is not attractive. To eliminate destructive testing, it is not appropriate to use NDG values instead of calibration cores.

Bulk density values of the samples compacted from the core asphalt mixture correlate quite well with the core bulk density values. The correlation coefficient varies from 0.611 in test section No. 1 to 0.843 in test section No. 2. Therefore, this variable together with the dielectric value is suitable for modelling Core D. It is not appropriate to use D MIX D values instead of Core MIX D value in the developed model. To eliminate destructive testing, it is necessary to perform additional studies and to use data obtained by the standard test methods for the asphalt mixtures sampled during asphalt compaction instead of the design bulk densities of the actual bulk density.

Statistical analysis shows that correlation between Core D and DV in all test sections, except for test section No. 5, is strong. The values of correlation coefficient vary from 0.560 in test section No. 1 to 0.900 in test section No. 2. The correlation of test section No. 5 is only 0.187; such a low correlation may be determined by residual humidity of asphalt layer. The Core D and DV values in sections No. 1 and No. 4 differ from the rest of the sections. Therefore, it was not possible to apply the model suitable for all sections and only the corrective factors (dummy variables) suitable for them had to be applied.

The developed general linear regression model for all sections shows that there is a relationship between the modelled factors, but this relationship differs in some sections. Therefore, the general model for all test sections is more suitable in estimating the relation, but not for prediction purposes. To adapt the model for predictions, it is necessary to refine it by adding additional factors, making more measurements, or refining and harmonizing the measurement conditions, or to create an individual model for each test section.

Following the development of individual models for each asphalt mixture under testing, it is stated that these models are suitable for prediction, but due to a small number of measurements their reliability must be checked on other sections of a similar type of asphalt mixture and layer position.

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