

ANNUAL SUMMARY REPORT

P59 – Best Practice in Non-destructive Testing of Assurance of Asphalt – Year 3 (2019–20)

ARRB Project No.: 014920

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SUMMARY

The purpose of this project was to evaluate the suitability of the Pavement Quality Indicator (PQI) as a non-destructive density conformance test for asphalt layers during construction. Conformance testing (for payment purposes) requires that the PQI test method produces accurate results comparable to current asphalt core and nuclear gauge density measurement methods.

The suitability of the PQI as a conformance testing device was assessed by evaluating the correlation between PQI and core density as well as several variables (such as mix type, temperature, and layer thickness) that may impact the PQI readings. Additionally, the application of draft TMR Test Method Q326 *Compacted Density of Asphalt – Electromagnetic Surface Contact Device* on project density data gave insight into how the device might perform as a quality assurance density measuring device during construction.

Several variables affecting the PQI readings were evaluated. Of these variables, the mix type of the layer being tested was shown to be particularly influential on the PQI readings and the study confirmed the need for applying a mix-specific density bias to the PQI readings. Pavement temperature at the time of measurement proved to have a small but important effect on the PQI readings due to the range of potential pavement temperatures experienced in the field. For the range of layer thickness included in the study, the thickness of the layer did not show an influence on the results. The device is known to be sensitive to moisture and surface texture, however, an evaluation of these two variables was not included in the study.

The decision to implement the device for density compliance testing should ideally be based on how closely the performance (i.e., precision and accuracy) of the PQI matches the performance of other acceptable non-destructive test methods such as the nuclear density gauge (NDG).

A comparison between the performance of the PQI device, NDG and asphalt cores found that the standard deviations of the density values were similar for the datasets with comparable sample sizes, which suggest that a similar level of precision exists between the three methods of density measurements. Preliminary indications are that the NDG may be more accurate than the PQI device. This finding is however based on a limited dataset and did not include any side-by-side testing using both devices.

Two case studies (using the data provided) were undertaken to assess the impact of using the PQI for density compliance on two construction projects. The PQI readings were compared to the densities obtained from asphalt cores at the same location, and the number of false negative (Type 1 error) and false positive (Type 2 error) PQI results were determined. One of the case studies showed that the device has the potential to be used as a conformance test, whereas the second case study was less conclusive.

The following updates to draft test method Q326 are recommended:

- a procedure to check and update the bias during construction
- a note to avoid using the PQI when any moisture is present on the surface

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ACKNOWLEDGEMENTS

ARRB would like to acknowledge the assistance from AfPA and their members who provided field data.

- a procedure to remove uncharacteristic values from the dataset used to calculate the density bias
- limitations on the pavement temperature while carrying out PQI testing
- possible replacement of the cloverleaf pattern with repeated testing at a single position, pending outcomes from further studies.

It is also recommended that a controlled study be undertaken to assess the proposed updates to test method Q326 and the relative performance of the PQI device against the NDG.

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1 INTRODUCTION

1.1 BACKGROUND

The Queensland Department of Transport and Main Roads (TMR) currently accepts the use of field cores and the nuclear density gauge (NDG) to assess the density of asphalt layers for both quality control (QC) and quality assurance (QA) purposes. While historically being effective methods for assessing the level of compaction achieved on projects, the destructive nature of asphalt cores and the extensive safety, training and calibration requirements of NDGs have prompted a desire to explore alternative methods that are non-destructive, operationally more practical and safer.

Year 1 of this multi-year National Asset Centre of Excellence (NACOE) project evaluated current best practice in non-destructive density test methods for product acceptance of asphalt layers (Beecroft & Boshier 2017). A review of local and international practices found that asphalt cores are still the preferred method for the acceptance of density measurements during construction. Density measurements obtained with NDGs are also widely used within the asphalt industry, both locally and internationally. Non-nuclear density testing devices such as the Pavement Quality Indicator (PQI) shown in Figure 1.1 have shown promise in several international studies and were therefore selected for further investigation by TMR.

Figure 1.1: PQI 380 device



Source: TransTech Systems Inc (2019).

Several contractors in Queensland already use the PQI as a process control tool during construction, with generally positive feedback. In Year 2 of the project, an industry workshop held in December 2017 requested local asphalt suppliers to supply historic PQI density data and provide comparative density results obtained from upcoming construction projects using the PQI. A draft TMR test method Q326 (refer to Appendix A) was also developed for the PQI to guide the data collection process by the asphalt suppliers that participated in the study (Ahrari & Beecroft 2019).

1.2 PURPOSE

The purpose of Year 3 of the NACOE project was to evaluate the density data provided by industry to evaluate the suitability of using the PQI as a conformance test for the compaction of asphalt layers during construction.

1.3 SCOPE

The project evaluated the strength of the correlation between the PQI readings and densities obtained from asphalt cores on several construction projects, as well as possible factors that may influence the PQI results during testing. Though the methods discussed below (e.g., bias calculation) attempt to overcome variations that are experienced in practice, the conclusions in this report are limited to the data available. A large variety of mix designs exist and collecting large datasets for all of them will only be possible with more time and industry adoption of the technology and test method.

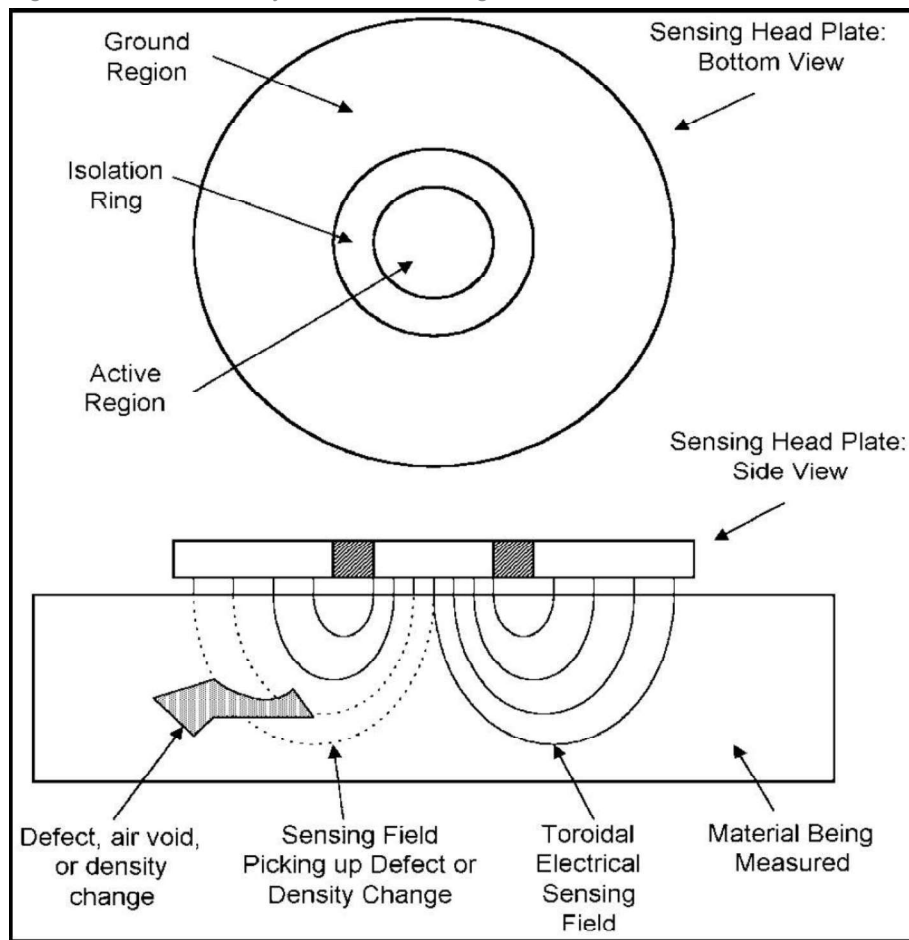
1.4 REPORT STRUCTURE

Section 2 of the report presents additional literature that has been sourced since the start of the project. Section 3 provides an overview of the data collection process, followed by a comprehensive analysis of the data provided in Section 4 (including an evaluation of the effect of different variables on the PQI readings and the correlation of PQI–core densities). Section 5 documents two case studies undertaken using the data provided to assess the effectiveness of using the PQI at a project level. Section 6 discusses the benefits of using the PQI over traditional density measurement methods and how the implementation of the device has a bearing on the interpretation of the results. Finally, the project conclusions and recommendations for future work are summarised in Section 7.

2 LITERATURE UPDATE

The PQI does not directly measure the density of a material, but rather infers the density from the dielectric properties of the asphalt mix. The technical brief produced by TransTech Systems Inc (2016) provided a detailed description of how the PQI measures the density of a material. The device measures the capacitance of a material, as shown in Figure 2.1, which is a function of the relative permittivity of an asphalt mix, the size of the area through which the electrical field travels and the distance the field needs to travel between two conductors, as shown in Equation 1.

Figure 2.1 PQI density measurement diagram



Source: TransTech Systems Inc (2016)

$$C = \frac{k \times \epsilon_0 \times A}{d}$$

1

where

C = capacitance (F)

k = relative permittivity of the material

ϵ_0 = permittivity of a vacuum (F/m)

A = area between two conducting surfaces (m²)

d = distance between two conducting surfaces (m)

Apart from the relative permittivity of the material (k) all the other variables in Equation 1 are controlled by the device. The permittivity of the material is proportional to the volume fraction of each component material of the asphalt mix and each component material's permittivity. The four components of an asphalt mix and their typical permittivity are shown in Table 2.1.

Table 2.1: Typical permittivity of asphalt components

Component material	Typical relative permittivity
Bitumen	2.8
Aggregate	3 to 5
Water	80
Air	1

Source: TransTech Systems Inc (2016).

The volume fraction of the aggregates, being the largest, should in theory have the greatest influence on the permittivity of the total asphalt mix, however, due to the low permittivity of air and the high permittivity of water, the presence of either of these two components in the mix, will have a substantial influence on the permittivity of the asphalt. For example, the asphalt will have a higher permittivity if the voids in the mix are filled with water compared to air only, thus resulting in a difference in capacitance. The relative change in the capacitance calibrated to a measured density (i.e., core density) is then used to estimate the density of the asphalt.

Several international studies have previously evaluated the factors that influence the density readings obtained with the PQI. In Australia, White (2019) also evaluated the variables that may influence PQI readings and found that changes in the asphalt temperature and moisture content at the time of testing were significant. The effect of moisture on the density readings was believed to be complicated by the texture depth and the potential for surfaces with a higher texture depth to retain water, however, this was not validated in the study.

White (2019) also found that repeated PQI readings at a single position provided more consistent results as opposed to taking the density readings in a cloverleaf pattern recommended in the operating manual supplied by the equipment manufacturer (TransTech Systems Inc 2019). This issue was also considered during the development of test method Q326 given that measuring multiple positions adjacent to each other could introduce an error into the average reading. It was however initially agreed to adopt the cloverleaf pattern in test method Q326 as recommended by the equipment manufacturer.

3 DATA COLLECTION

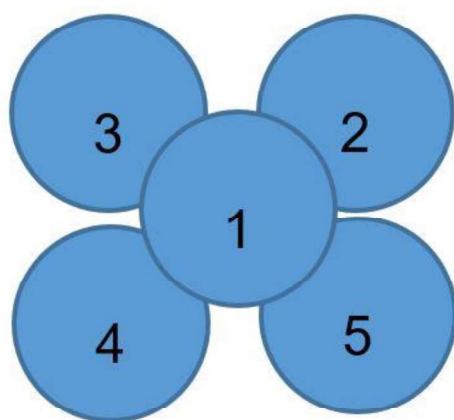
In 2017, a request was made to local asphalt suppliers in Queensland to participate in a study to evaluate the use of the PQI on asphalt construction projects. Participants were requested to gather PQI, NDG and core density data on active construction projects for analysis by the NACOE project team (Ahrari and Beecroft 2019).

Only one asphalt supplier (Contractor A) provided the project team with PQI and asphalt core density data obtained from a construction project using the test method Q326. However, another asphalt supplier (Contractor B) provided density data that were collected in 2003 prior to the start of this study and the development of test method Q326. The PQI device was updated in 2016 and the data provided by Contractor B should therefore be treated with caution given that it may not necessarily represent the latest PQI technology and test method.

It was originally intended to collect additional data such as pavement temperature, layer thickness and mix type to evaluate the effect these factors have on the PQI readings. Unfortunately, not all the data provided included the temperature and layer thickness information.

Test method Q326 was developed based on the principles in ASTM D7113 *Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods* (ASTM International 2016). The PQI density readings are taken in a cloverleaf pattern at each of the five positions shown in (Figure 3.1), and the readings are averaged to a representative PQI value for that specific location. For this study, a core was taken from the centre of the cloverleaf pattern (Position 1). The core density and the average of the five PQI readings formed a data pair, which were the basis of the subsequent analysis.

Figure 3.1: Cloverleaf pattern



Source: Beecroft and Boshier (2017).

In practice, a density bias (difference between core density and PQI reading) should be determined in accordance with test method Q326 using a minimum number of 10 cores, which is then applied to the PQI readings at subsequent locations. For this study, however, the raw PQI readings supplied by Contractor A did not include a density bias so that a correlation could be drawn between the two methods of density measurement, and the suitability of the PQI evaluated.

As mentioned previously, the data supplied by Contractor B was collected prior to the study and had a density bias already applied. The raw PQI data without the density bias applied were therefore not available for the analysis.

The data provided by the two asphalt suppliers did not include any comparative NDG measurements and results from an earlier Queensland Transport (1995) study were used to compare the variability between asphalt core, PQI and NDG density measurements.

4 DATA ANALYSIS

4.1 AVAILABLE DATA

Table 4.1 provides a detailed breakdown (by asphalt mix type) of the data provided by the two asphalt suppliers that participated in the study. There were 610 PQI–core density data pairs in total, from 67 lots across 8 different asphalt mixes. The AC20-18-A, AC20H-18-A and SM14 asphalt mixes had the most data pairs. The data supplied by Contractor A also included some surface temperature and layer thickness information.

Table 4.1: PQI data breakdown

Mix type	Mix code	Asphalt supplier	Number of lots ⁽¹⁾	Number of PQI–core data pairs	Number of data pairs with temperature information	Number of data pairs with layer thickness information
Dense graded asphalt (14 mm nominal size)	AC14	Contractor A	1	6	6	6
Dense graded asphalt (14 mm nominal size)	AC14H-18	Contractor A	4	27	27	27
Dense graded asphalt (20 mm nominal size)	AC20-18-A	Contractor A	14	119	119	116
Dense graded asphalt (20 mm nominal size)	AC20-18-B	Contractor A	2	10	10	8
Dense graded asphalt (20 mm nominal size)	AC20H-18-A	Contractor A	24	173	170	170
Dense graded asphalt (20 mm nominal size)	AC20H-18-B	Contractor A	1	10	10	10
Stone mastic asphalt (14 mm nominal size)	SMA14-18	Contractor A	1	11	11	11
Stone mastic asphalt (14 mm nominal size)	SM14	Contractor B	20	254	0	0
Total		–	67	610	353	348

1. A lot was defined as the testing carried out during a single day.

Table 4.2 provides a summary of the density values obtained from the cores and PQI readings for each asphalt mix. The PQI densities were generally higher than the core densities, apart from the AC20H-18-A mix where the average core density was higher than the average PQI density.

Table 4.2: Summary of density results (without a density bias applied)

Mix code	Core density range (t/m ³)	Average core density (t/m ³)	PQI density range (t/m ³)	Average PQI density (t/m ³)
AC14	2.465–2.413	2.441	2.546–2.519	2.535
AC14H-18	2.483–2.387	2.431	2.511–2.421	2.476
AC20-18-A	2.516–2.390	2.460	2.646–2.422	2.543
AC20-18-B	2.505–2.418	2.458	2.601–2.523	2.554
AC20H-18-A	2.544–2.413	2.483	2.524–2.38	2.447

AC20H-18-B	2.504–2.419	2.473	2.538–2.499	2.523
SMA14-18	2.347–2.257	2.307	2.405–2.341	2.373

Note: Contractor B data already had a density bias applied and the results are therefore not included in this table.

4.2 FACTORS AFFECTING PQI READINGS

4.2.1 ASPHALT MIX TYPE

Ahrari and Beecroft (2019) and White (2019) previously reported that the asphalt mix type was a possible contributor to the variability observed in the PQI readings between different mixes. As mentioned in Section 2, the permittivity of the different components in an asphalt mix (i.e., bitumen, aggregate, water and air) can contribute to differences in PQI readings between different mix types.

Figure 4.1 shows the PQI and core density data pairs provided by Contractor A for different asphalt mixes (without a density bias applied). The dataset provided by Contractor B was not included in the mix type analysis given that the PQI readings had a density bias already applied and the density measurements have therefore already been corrected (in theory) for the specific asphalt mix used in construction.

The data shows that for the same core density a range of PQI readings can be measured and that different asphalt mixes can result in more varied (scattered) readings. As an example, for mix AC20-18-A a core with a density of 2.5 t/m³ could have a PQI reading of between 2.43 t/m³ and 2.62 t/m³. This difference in PQI readings could affect the level of compaction measured by 7%.

Figure 4.1: PQI and core density data pair results by mix type (without a density bias applied)

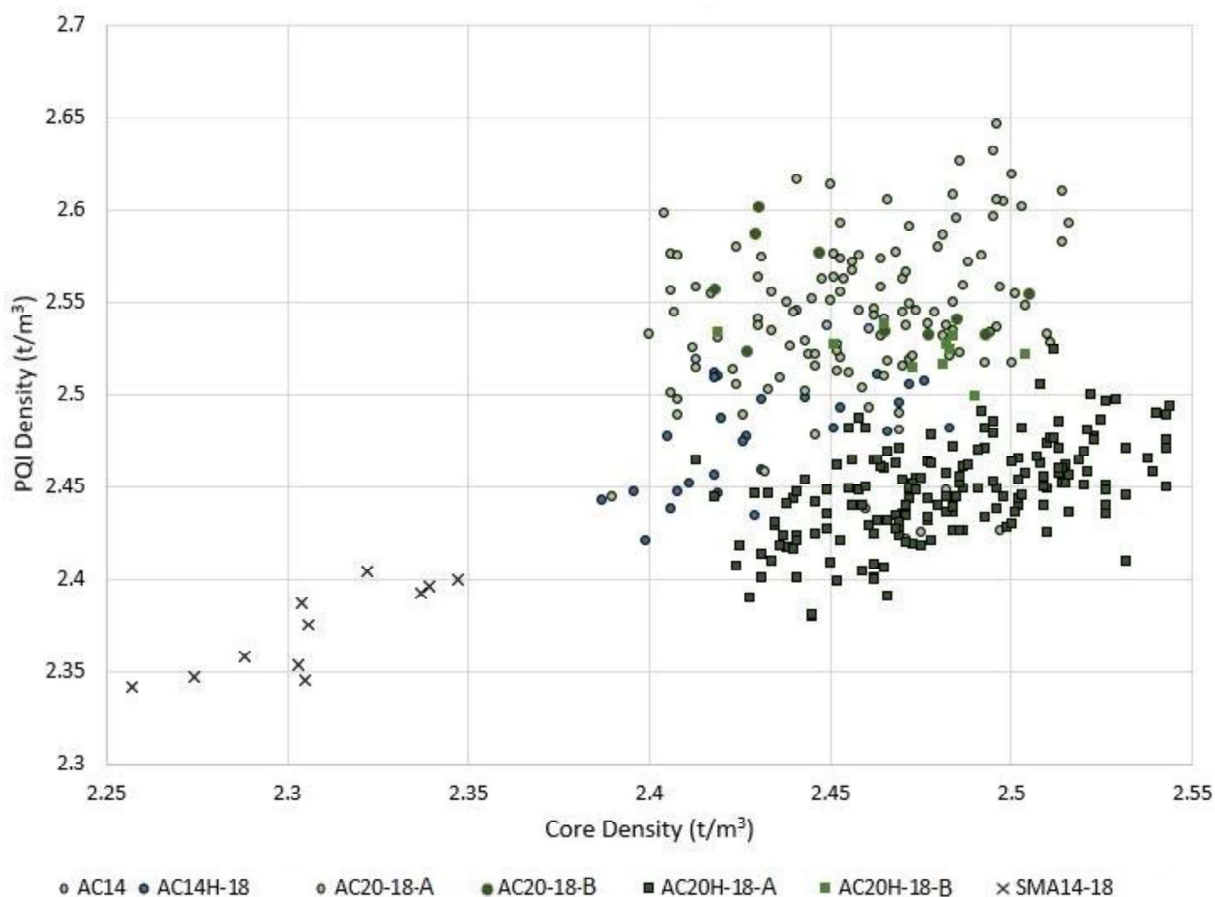
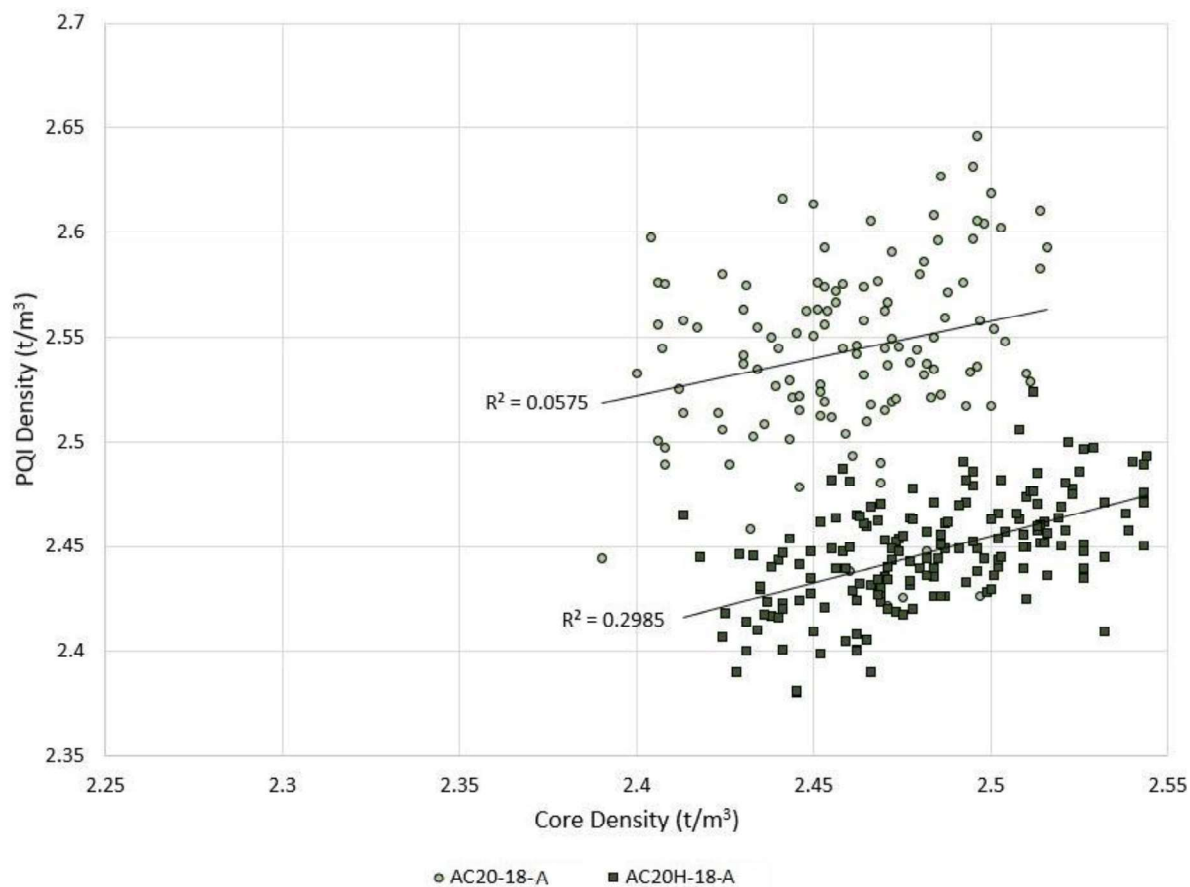


Figure 4.2 shows the PQI and core density values for the asphalt mixes with the largest datasets (i.e., AC20-18-A and AC20H-18-A). It also shows a linear regression line to approximate the relationship between the core densities and PQI readings.

Figure 4.2: PQI and core density data pairs for the AC20-18-5300 and AC20H-18-5157 mixes (without a density bias applied)



The PQI densities (without any density bias applied) of the AC20-18-A mix varied between 2.42 t/m³ and 2.65 t/m³ (0.23 t/m³ difference), whereas the core densities varied between 2.39 t/m³ and 2.52 t/m³ (0.13 t/m³ difference) for the same mix. The PQI densities (without any density bias applied) of the AC20H-18-A mix ranged between 2.38 t/m³ and 2.57 t/m³ (i.e., 0.19 t/m³ range) and also had a higher variability compared to the core densities (i.e., 0.12 t/m³ range).

For both mixes, the range in PQI densities measured was higher than the range in core densities.

The low R-squared values of the PQI–core density relationship for the AC20-18-A and AC20-18-5157 asphalt mixes suggest that there is a poor linear correlation between the PQI and core densities if no density bias is applied, and that there are possibly other variables that have a larger influence on the PQI–core density relationship.

The Pearson correlation coefficients determined for the AC20-18-A and AC20-18-5157 mixes were 0.240 and 0.546, respectively, which also suggests that the PQI readings have a weak linear correlation with the core densities measured and that the data are clustered around the average core density and average PQI reading. This clustering is however expected due to the measurements that have been taken on a project where specified levels of compaction are being targeted. This is also confirmed by the low covariance values (i.e., 3.12×10^{-4} t/m³ and 4.37×10^{-4} t/m³) of the two mixes shown in Figure 4.2. A covariance of zero indicates that the data points are evenly distributed around an average value. The low covariance values therefore suggest that drawing a linear relationship between the PQI and core densities would be less appropriate for the datasets provided and that the covariance rather than the R-squared value would be a better descriptor of the relationship between the PQI and core densities.

The analysis presented above was carried out for each mix of the asphalt mixes included in the study and the results are summarised in Table 4.3.

Table 4.3: Summary of statistical results (by mix type)

Mix type	Number of lots	Number of data pairs	R-squared value	Pearson correlation coefficient	Covariance (t/m ³)	Average residual density (t/m ³)
AC14	1	6	0.505	0.711	1.41E-04	0.032
AC14H-18	4	27	0.348	0.590	4.30E-04	0.093
AC20-18-A	14	119	0.057	0.240	3.12E-04	0.044
AC20-18-B	2	10	0.199	-0.446	-3.71E-04	0.087
AC20H-18-A	24	173	0.299	0.546	4.37E-04	0.097
AC20H-18-B	1	10	0.225	-0.474	-1.27E-04	0.038
SMA14-18	1	11	0.707	0.841	5.67E-04	0.050

All the mixes analysed, except for mix SMA14-18, had relatively low R-squared values (i.e., below 0.55) which suggest a poor linear correlation between the core densities and PQI readings (without any density bias applied). Asphalt mix SMA14-18 had a higher R-squared value of 0.707, but the mix also had a relatively small sample size.

The Pearson correlation coefficient varied between 0.240 and 0.841, indicating that the correlation between the PQI readings and core densities differ depending on the asphalt mix type. The negative Pearson correlation coefficient and covariance values determined for the AC20-18-B and AC20H-18-B asphalt mixes suggest that a negative relationship between the core density and PQI readings exists, however, this is possibly as a result of the small sample sizes available for these mixes.

The covariance values for the datasets analysed are close to zero, indicating that the PQI readings are generally clustered around the average density values.

The average residual density (defined as the average of the absolute difference between the PQI and core densities) of the asphalt mixes analysed varied between 0.032 t/m³ and 0.097 t/m³. This difference in the density measured with the PQI and cores is considered to be significant.

The analysis presented above supports the findings in the literature that the asphalt mix type does influence the density measurements obtained from the PQI device.

4.2.2 ASPHALT TEMPERATURE

White (2019), amongst other researchers, previously found that the temperature of the asphalt at the time of testing can also influence the PQI readings.

Contractor A recorded the asphalt surface temperatures at the time of testing and the results are shown in Figure 4.3. The data provided suggest that an increase in the asphalt temperature at the time of testing results in an increase in the PQI reading, however, this relationship is less apparent if the mix types are evaluated individually.

Figure 4.3: All PQI and temperature data (without a density bias applied)

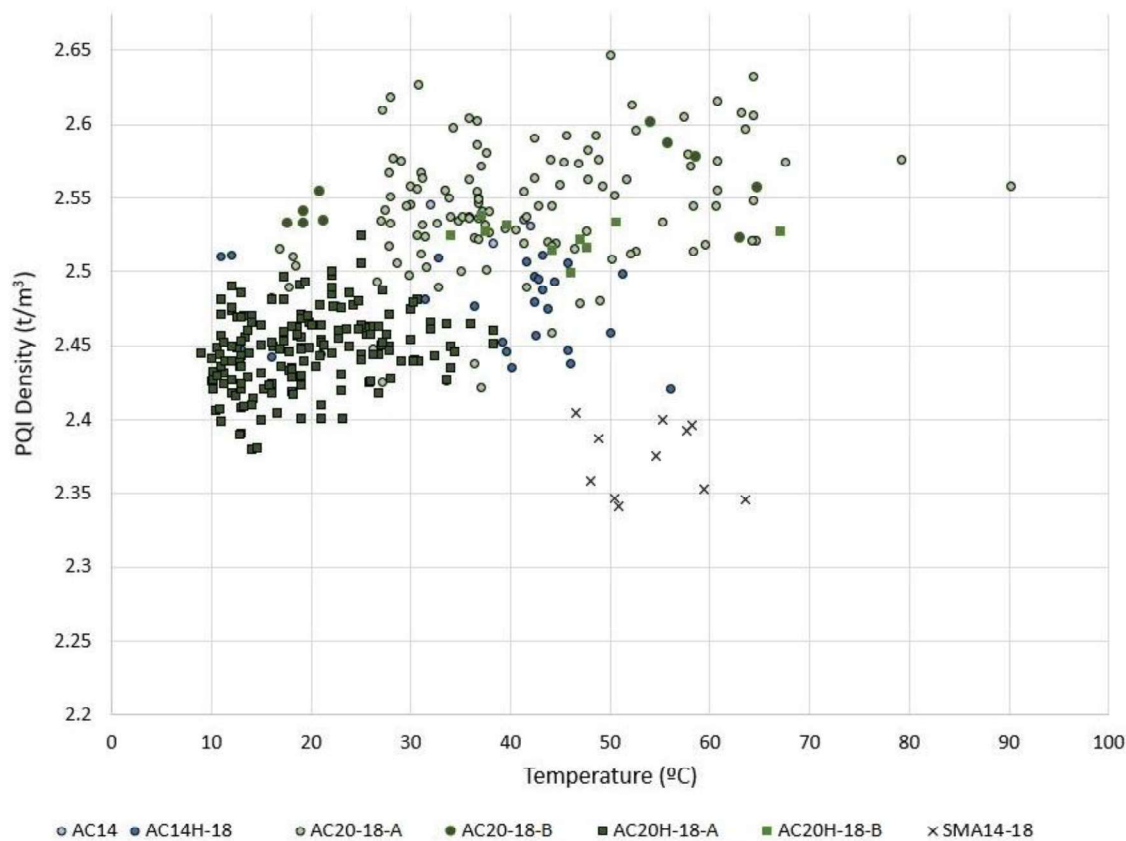
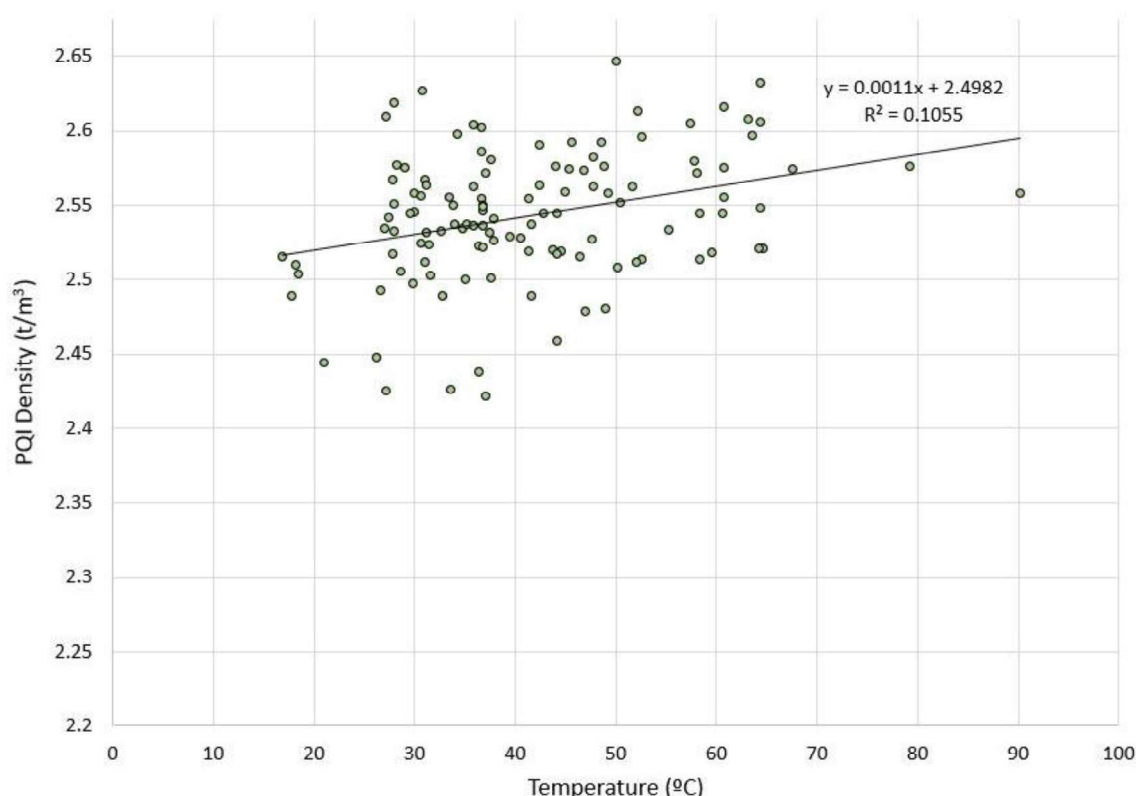


Figure 4.4 shows the same PQI–temperature relationship for the AC20-18-A mix type only. The PQI readings ranged between 2.421 t/m³ and 2.646 t/m³ over a temperature range of 16.8 °C to 90 °C. The low R-squared value of 0.106 indicates a poor linear relationship between the PQI readings and temperature, and that variables other than temperature likely have a larger influence on the PQI–core density relationship. The Pearson correlation coefficient for the PQI and temperature data is 0.325, indicating that the data tends more towards a cluster rather than a linear relationship. The positive Pearson coefficient also indicates that an increase in temperature resulted in an increased PQI reading.

The slope of the line of best fit in Figure 4.4 is $1.1 \times 10^{-3} \text{ t/m}^3/\text{°C}$ which indicates that on average a difference in density of 0.081 t/m³ was observed with the PQI over an asphalt temperature range of 73.4 °C throughout the project. A difference of 0.081 t/m³ in the PQI reading could result in a percentage compaction difference of 3%. It is worth noting that the slope of the PQI–temperature relationship observed in this study is similar to a slope of $1 \times 10^{-3} \text{ t/m}^3/\text{°C}$ previously reported by White (2019) where the temperature effect was assessed at a single test location. The slope of the line of best fit for the other asphalt mixes included in the study varies between $-1.4 \times 10^{-3} \text{ t/m}^3/\text{°C}$ and $1.0 \times 10^{-3} \text{ t/m}^3/\text{°C}$, suggesting both a positive and negative relationship between PQI readings and asphalt temperature.

Given that the study did not include multiple temperature measurements at a single PQI location, further work is recommended to investigate the effect of temperature on the PQI readings.

Figure 4.4: PQI vs asphalt temperature – AC20-18-5300 mix (without a density bias applied)



The analysis presented above was also carried out for the other asphalt mixes included in the study and the results are summarised in Table 4.4.

Table 4.4: Summary of statistical results (PQI density vs temperature)

Mix code	Number of lots	Number of data pairs	R-squared value (without bias)	Pearson correlations coefficient	Covariance (t/m ³)	Slope of line of best fit (t/m ³ /°C)
AC14	1	6	0.298	-0.546	-0.0187	-1.4 x 10 ⁻³
AC14H-18	4	27	0.029	-0.170	-0.0601	-0.4 x 10 ⁻³
AC20-18-A	14	119	0.106	0.325	0.1886	1.1 x 10 ⁻³
AC20-18-B	2	10	0.256	0.506	0.2832	0.6 x 10 ⁻³
AC20H-18-A	24	170	0.071	0.267	0.0476	1.0 x 10 ⁻³
AC20H-18-B	1	10	0.011	-0.106	-0.0113	-0.1 x 10 ⁻³
SMA14-18	1	11	0.022	-0.150	-0.0198	-0.7 x 10 ⁻³

The R-squared values for the different asphalt mixes ranged from 0.011 to 0.298, indicating a poor correlation between temperature and the PQI readings. The low R-squared values also suggest that the density readings are influenced by factors other than just temperature.

The Pearson correlation coefficient for the mixes analysed varied between -0.546 and 0.506, where the negative values were typically observed for the mixes with smaller sample sizes. A negative Pearson correlation coefficient suggests a negative relationship between the PQI readings and temperature, whereby a reduction in asphalt temperature will result in lower PQI readings. However, the data for the mixes with larger sample sizes suggest a positive relationship between PQI and temperature, similar to a positive relationship observed by White (2019), and that larger sample sizes are required to draw significant conclusions.

The covariance values are relatively low and ranged between -0.0198 t/m^3 and 0.283 t/m^3 for the different asphalt mixes, indicating the results are generally clustered around the average density and temperature values, but less so than the PQI–core density results.

4.2.3 LAYER THICKNESS

The effect of the thickness of asphalt being tested, and the potential for underlying layers to influence PQI measurements is also considered as a variable that may influence the density results. No data were available for the density and composition of the underlying layers of the asphalt pavements included in the study and the analysis was therefore limited to the thickness of the asphalt layer that was tested.

Core thickness values were available for most of the data provided by Contractor A, whereas the dataset provided by Contractor B did not include any thickness information. Figure 4.5 shows the PQI readings compared to the core thickness. The core thicknesses cluster around 50 mm and 100 mm, with the PQI densities ranging between 2.34 t/m^3 and 2.65 t/m^3 .

Figure 4.5: PQI density vs core thickness (without a density bias applied)

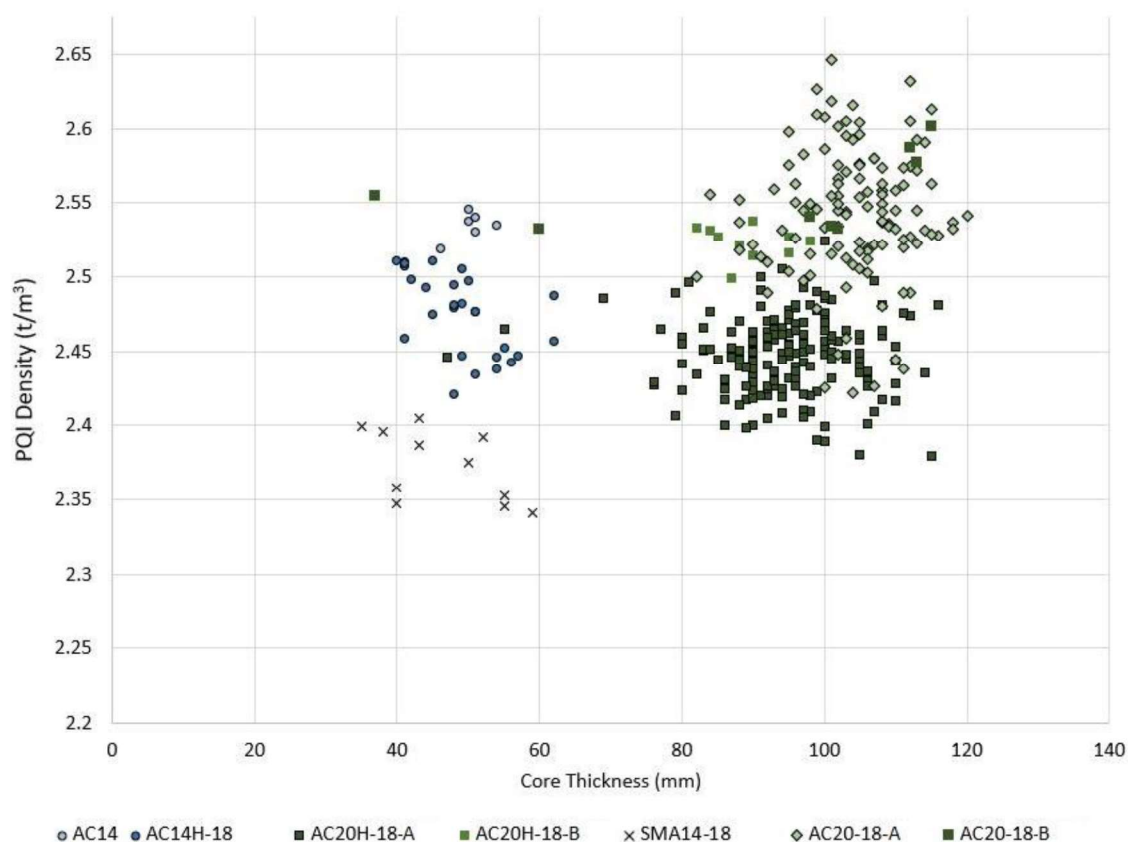


Table 4.5 provides a summary of the statistical parameters derived from the dataset.

Table 4.5: Summary of statistical results (PQI density vs layer thickness)

Mix code	Number of lots	Number of data pairs	R-squared value	Pearson correlation coefficient	Covariance (t/m^3)
AC14	1	6	0.319	0.565	0.0135
AC14H-18	4	27	0.305	-0.552	-0.0935
AC20-18-A	14	119	0.003	0.052	0.0167
AC20-18-B	2	10	0.197	0.444	0.3452
AC20H-18-A	24	170	0.001	-0.029	-0.0070
AC20H-18-B	1	10	0.024	-0.154	-0.0091

SMA14-18	1	11	0.302	-0.549	-0.1080
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The R-squared values for the linear relationship between the PQI readings and layer thickness ranged between 0.001 to 0.319, suggesting a poor correlation between the PQI readings and core thickness. The R-squared values also tend to be smaller for larger sample sizes, which indicates that the higher R-squared values for the asphalt mixes with smaller sample sizes could be due to their small sample size as opposed to necessarily indicating a strong correlation between the PQI readings and layer thickness.

Similarly, the Pearson correlation coefficient tends to be smaller for the asphalt mixes with larger sample sizes and shows both positive and negative correlations depending on the mix type. This suggests that either the PQI responds differently to the change of thickness depending on mix type, or that no real relationship exists.

The covariance values show that the PQI readings and thickness values are evenly clustered around the averages, but not necessarily as close as the PQI–core density data. The high covariance value determined for the AC20-18-B mix is due to the PQI readings taken for multiple layer thicknesses for the same mix type (e.g., 50 mm and 100 mm layer thickness).

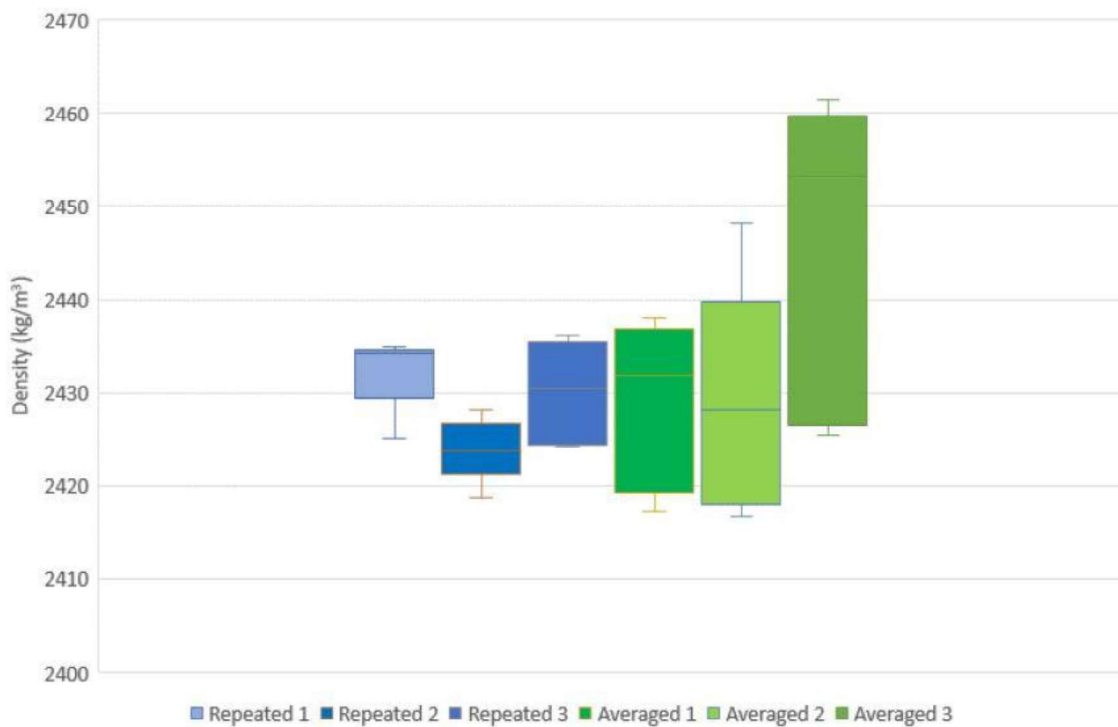
Based on the data provided, no relationship between the PQI readings and layer thickness could be drawn. Test method Q326 method requires that the nominal depth of material being tested should be input into the device which could account for the consistency in PQI readings with varying layer thickness.

4.2.4 SINGLE POSITION VS CLOVERLEAF PATTERN MEASUREMENTS

White (2019) previously evaluated the effect of taking repeated PQI measurements at a single position on the readings compared to the multiple positions used with the cloverleaf method. The cloverleaf pattern is typically used to allow for multiple readings at the same location which can be used to evaluate whether the device is properly seated at the time of the test. Proper seating is important as the readings are sensitive to the presence of air between the device and surface of the layer being tested.

White (2019) found that repeated testing at a single position provided more consistent results compared to the cloverleaf pattern. Figure 4.6 shows the PQI readings from three locations where the repeated single position results are compared to the average cloverleaf results, confirming that using the cloverleaf pattern during testing increased the variability in the readings.

Figure 4.6 Repeated PQI readings compared to cloverleaf



Source: White (2019).

A direct comparison between repeated readings at a single position and the cloverleaf pattern could not be made based on the data collected in this study given that no repeated measurements were taken. A comparison was however possible between the PQI readings taken at Position 1 and the average of cloverleaf pattern readings (Position 1 to 5) for different test locations (Figure 4.7). The three mixes with the largest dataset were included in the analysis and the results used did not include a density bias correction factor. It should be noted that the results from three different asphalt mixes were used in the analysis rather than three separate locations evaluated by White (2019), as shown in Figure 4.6.

Figure 4.7: Average Position 1 readings vs average cloverleaf pattern readings

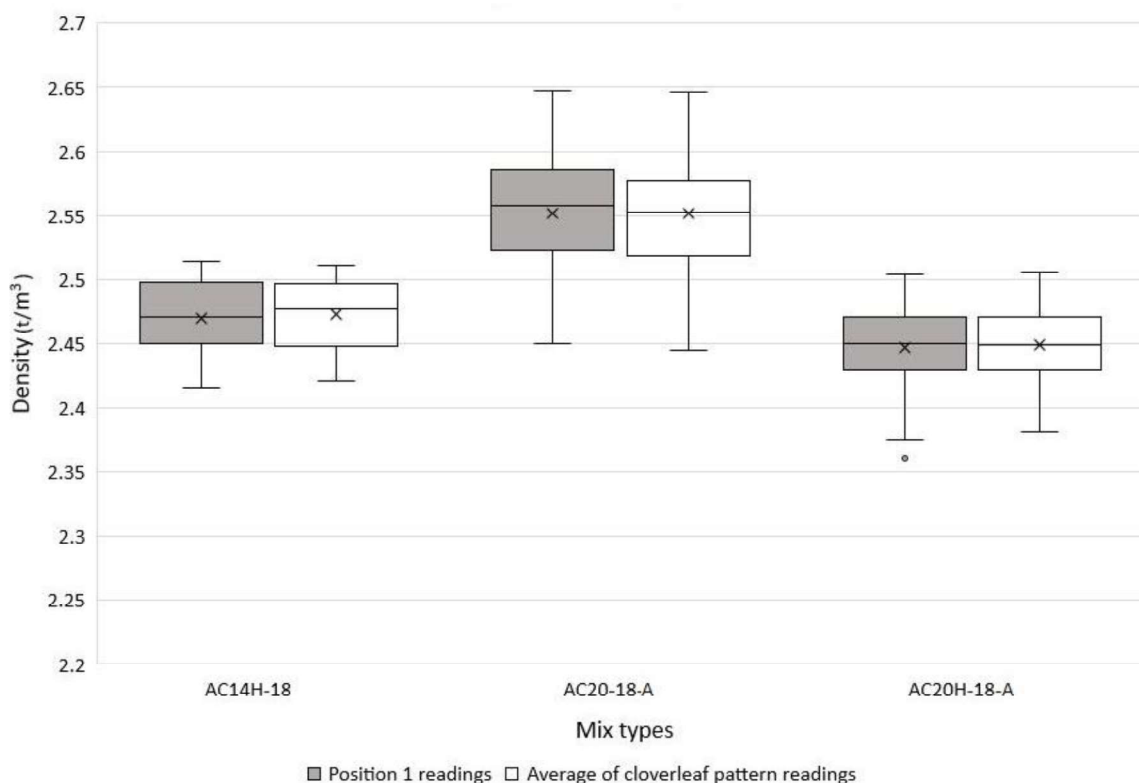


Figure 4.7 shows that there was only a slight narrowing in the inter-quartile density ranges, and little to no change in the average density values for the single position versus cloverleaf measurements. The analysis undertaken could not confirm that repeated testing at one position improves the precision of the PQI values when compared to the cloverleaf pattern, however, it did suggest that the cloverleaf pattern method offers only marginal improvement in reducing the variability in the density readings obtained with the PQI device.

4.3 CORRELATION BETWEEN ASPHALT CORE AND PQI DENSITIES

The purpose of the analysis presented in this section was to evaluate the relationship between the asphalt density measured with the PQI and cores, as well as the effect a density bias factor has on this relationship. In this analysis the core densities were assumed to be precise and accurate (i.e., the 'gold' standard). It should however be noted that there is likely inherent variability within the core density measurements that will impact on the precision and accuracy of the core densities, which in turn may have an impact on the correlation observed between the PQI device and asphalt cores.

4.3.1 METHOD FOR DETERMINING A DENSITY BIAS

The density bias between asphalt cores and the PQI can be determined using Equation 2 in test method Q326.

$$B_p = \overline{D}_c - \overline{\rho}_D \quad 2$$

where

B_p = asphalt density bias (t/m³)

$\overline{D}_c$ = average core compacted density for at least 10 test sites (t/m³)

$\overline{\rho}_D$ = average device density for at least 10 test sites (t/m³)

The TMR (2019) NDG testing manual (hereafter referred to as the NDG method) adopts a similar approach to determine the bias for nuclear gauges. However, there is an additional step where 'uncharacteristic' NDG–core density pairs are removed from the bias calculation. This additional step involves calculating a standard error between the NDG and core results, which should fall within a 0.025 t/m³ standard error value. If the standard error is above 0.025 t/m³, the NDG–core data pair with the highest error is removed and the procedure repeated until the standard error falls below 0.025 t/m³. A maximum of 20% of data pairs may be removed after which the NDG is deemed unsuitable under the test conditions. If the 0.025 t/m³ error and 20% removal limits are met, the bias is determined according to Equation 3 (TMR 2019).

$$B_p = \overline{D}_c - \overline{\rho}_G \quad 3$$

where

B_p = asphalt density bias (t/m³)

$\overline{D}_c$ = average core compacted density for at least 10 test sites (t/m³)

$\overline{\rho}_G$ = average NDG density for at least 10 test sites (t/m³)

The density bias is then applied to the device readings to produce a more accurate reading of the actual density of the material determined using standard methods (such as asphalt core densities).

Both these methods were used on construction lots with 10 or more data pairs (as required by the test methods) to evaluate the different density bias determination procedures and how the Q326 method and the

NDG method results might differ. A total of 19 lots were included in the analysis that met the requirement of 10 or more data pairs.

The PQI and asphalt core density results (with and without applying a density bias) are shown in Figure 4.8. The density bias was determined for each lot in accordance with test method Q326 and then applied to that specific lot, which should be considered as a best-case scenario given that the bias was continuously updated, which is unlikely to occur during construction. The figure shows that applying a density bias significantly improves the overall PQI–core density correlation. The R-squared value for the raw data without any bias applied was 0.180 compared to 0.786 for the PQI values adjusted based on the bias determined in accordance with test method Q326.

Figure 4.8: Effect of test method Q326 bias on the density readings (per lot)

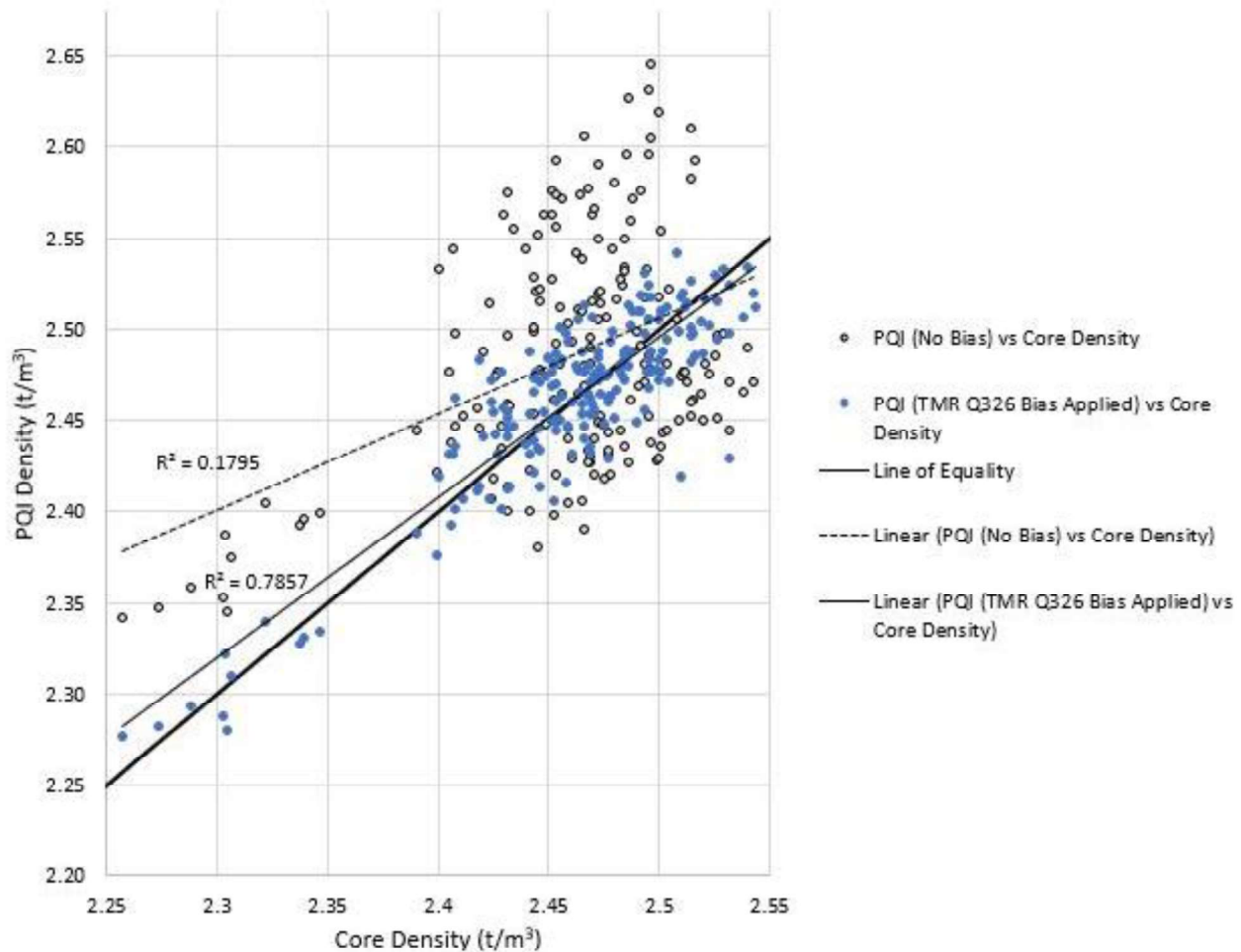


Figure 4.9 shows the PQI and core density data using a density bias determined in accordance with test method Q326 and the NDG method, respectively. The figure shows how the removal of uncharacteristic values affected the other PQI readings as a result of the different methods of bias determination. The R-squared value of the relationship between the PQI readings and core densities using the bias determined in accordance with the NDG method is 0.864, resulting in a marginal improvement of 0.078 compared to the bias determined in accordance with test method Q326.

Figure 4.9: Effect of TMR NDG bias compared to TMR Q326 bias (per lot)

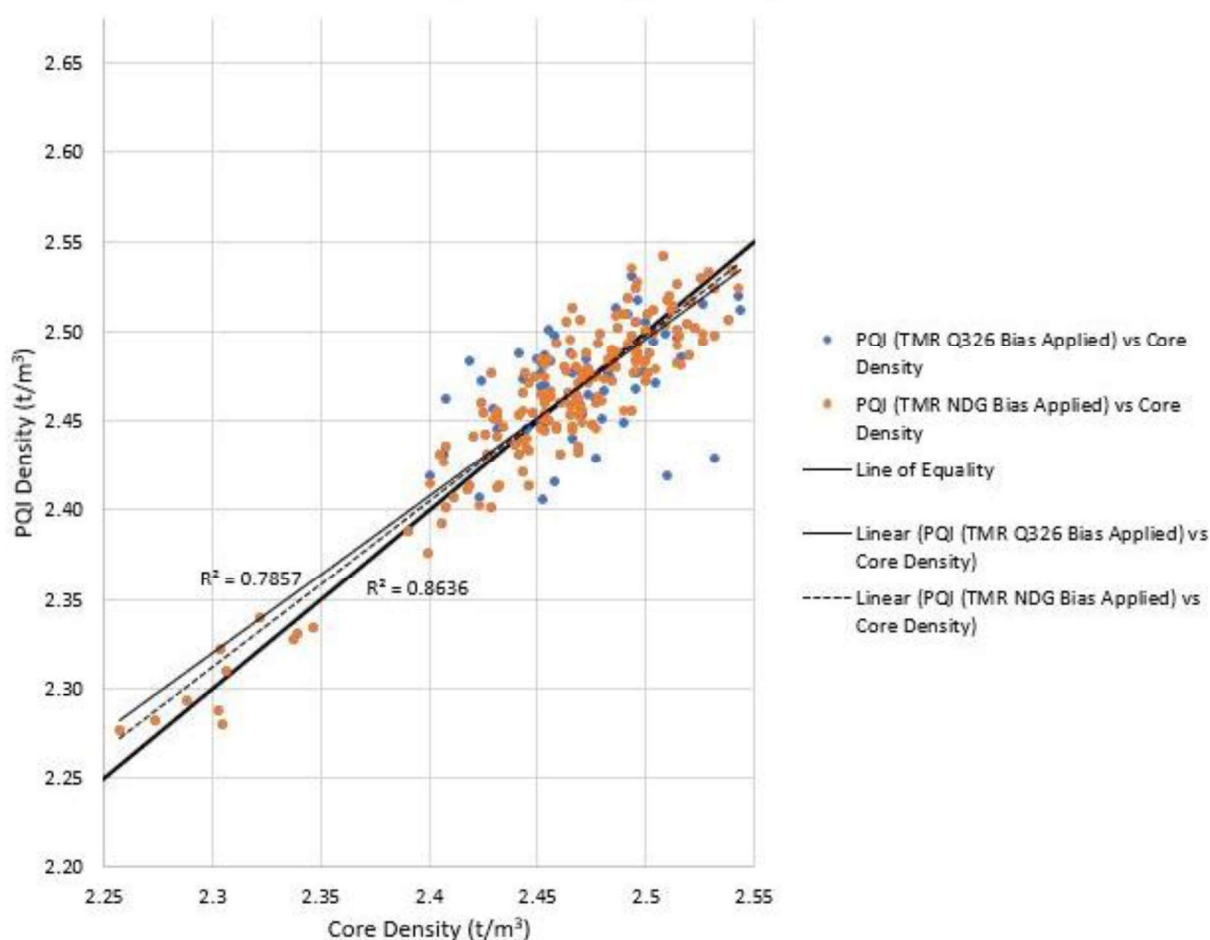


Table 4.6 provides a summary of how many lots had 1,2 or 3 data pairs removed due to the pairs not meeting the requirement of being within the 0.025 t/m³ standard error range specified in the NDG method. The table also shows the average difference in the bias values determined for both test methods. The removal of data pairs seems to have had little effect on the actual bias that will be applied to the PQI readings in general; however, in specific cases the removal of uncharacteristic values can result in significant changes in the bias. One lot had two data pairs removed, changing the bias from 0.0192 t/m³ to 0.0024 t/m³, which could change the level of compaction measured by 0.6%.

Table 4.6: Removal of uncharacteristic PQI values

Number of data pairs removed	Number of lots where data was removed	Q326 method		NDG method	
		Average lot bias (t/m ³)	Average standard error (t/m ³)	Average lot bias (t/m ³)	Average standard error (t/m ³)
1	3	-0.036	0.028	-0.034	0.022
2	3	-0.067	0.039	-0.074	0.021
3	1	-0.129	0.031	-0.119	0.023

The percentage of lots where uncharacteristic data pairs were found was 37%, however, only 5% (i.e., 1) of the lots exceeded the maximum limit of 20% for uncharacteristic data pairs allowable in the NDG method. This suggests that the PQI device would be suitable for testing the density of asphalt if applying requirements in the NDG method.

Furthermore, 12 of the 191 (6.3%) data pairs that made up the lots with 10 or more data pairs were outside the 0.025 t/m³ standard error limit specified in the NDG method. It is understood that in the original

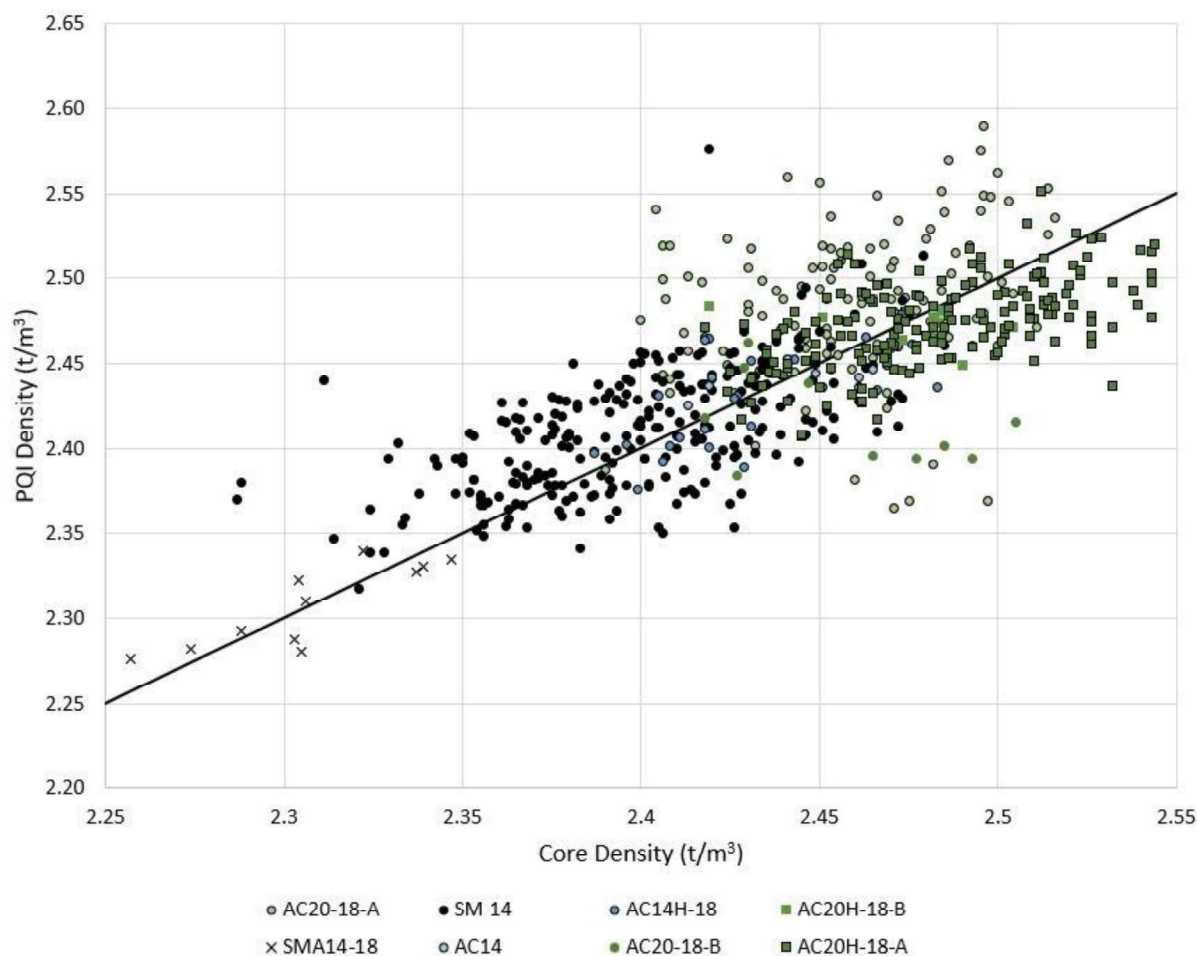
development of the NDG method, an allowable 0.025 t/m³ standard error limit was determined based on available data to ensure that only 5% of 'uncharacteristic' values would be removed from the dataset without removing a significant number of data pairs.

Based on the analysis undertaken, a 0.025 t/m³ standard error limit therefore appears to be reasonable for the PQI device given that only 6.3% data pairs had to be removed from the bias determination.

4.3.2 APPLYING A DENSITY BIAS TO THE PQI READINGS

A project-specific density bias was calculated in accordance with test method Q326 and applied to the PQI readings provided by Contractor A. The resulting PQI–core density pairs are shown in Figure 4.10. The data sourced from Contractor B were also included in this analysis, but it should be noted that the density bias applied to the PQI readings may not necessarily be consistent with the procedures in test method Q326 given that the data was obtained prior to the development of the test method.

Figure 4.10: PQI–core density pairs (with a single density bias applied)



Most of the density values cluster around the line of equality, however, the data for mix AC20-18-A are more dispersed in comparison to the other mixes included in the study. This suggests that the correlation between PQI readings and core densities could vary between different types of asphalt.

The statistical parameters (after the project-specific density bias was applied) of the PQI–core data summarised in Table 4.7 are the same as those found in Table 4.3, except for a significant reduction in the residual density values. The lower residual values indicate that the project-specific bias has improved the agreement between the PQI and core densities but has not changed the distribution of the density results. The average residual density of the updated data varied between 0.013 t/m³ and 0.053 t/m³ and represents a 1.5% difference in the compaction measured using either asphalt cores or the PQI device.

Table 4.7: Summary of PQI–core statistical parameters (with a single density bias applied)

Mix code	Number of lots	Number of data pairs	R-squared value	Pearson correlation coefficient	Covariance (t/m ³)	Average residual density (t/m ³)
AC14	1	6	0.505	0.711	1.41E-04	0.014
AC14H-18	4	27	0.348	0.590	4.30E-04	0.019
AC20-18-A	14	119	0.057	0.240	3.12E-04	0.043
AC20-18-B	2	10	0.199	-0.446	-3.71E-04	0.053
AC20H-18-A	24	173	0.299	0.546	4.37E-04	0.024
AC20H-18-B	1	10	0.225	-0.474	-1.27E-04	0.023
SMA14-18	1	11	0.707	0.841	5.67E-04	0.013
SM14	20	254	0.381	0.617	8.19E-04	0.026

It is important to note that only a single project-specific density bias was determined for each asphalt mix and applied to the PQI readings in Figure 4.10 (i.e., the bias was not updated again throughout the testing). In practice, the density bias should be monitored and adjusted throughout a project to account for possible changes in conditions and asphalt properties (e.g., the NDG method requires the bias to be checked after every 10,000 tonnes of asphalt placed).

To evaluate the effect a more frequently updated density bias would have on the PQI readings, a bias was determined for each lot using test method Q326 and re-analysed in the same way as above. The results with an updated density bias per lot are shown in Table 4.8. The analysis results show that by updating the bias on a lot-by-lot basis would result in the average residual density values becoming zero, as the difference between the average core and PQI value is the same as the bias value applied. The R-squared values also improved significantly for the mix types with more than one lot of when the density bias was updated more frequently.

Table 4.8: Summary of PQI–core statistical parameters (with an updated density bias per lot applied)

Mix code	Number of lots	Number of data pairs	R-squared value	Pearson correlation coefficient	Covariance (t/m ³)	Average residual density (t/m ³)
AC14	1	6	0.505	0.711	1.41E-04	0.000
AC14H-18	4	27	0.523	0.723	5.92E-04	0.000
AC20-18-A	14	119	0.419	0.647	6.06E-04	0.000
AC20-18-B	2	10	0.675	0.822	9.24E-04	0.000
AC20H-18-A	24	173	0.502	0.708	5.80E-04	0.000
AC20H-18-B	1	10	0.225	-0.474	-1.27E-04	0.000
SMA14-18	1	11	0.707	0.841	5.67E-04	0.000

Note: SM14 is not included in the updated bias summary as applying a bias to data that already has a bias would not be comparable to the other data

The improvement observed in the correlation between the PQI readings and core densities when the density bias was updated more frequently supports the need for monitoring and updating the bias throughout a construction project.

4.4 VARIATION IN DIFFERENT DENSITY MEASURING METHODS

An option to evaluate the effect of the variability of the PQI device will have on quality assurance testing is to compare its variability to the variability of currently accepted methods (e.g., asphalt cores and NDG devices). The available core data were used for this analysis, however the data provided by the two asphalt suppliers did not include any comparative NDG results. The typical variability expected in NDG results were therefore

assessed using data sourced from a previous Queensland Transport (1995) study. Table 4.9 shows the breakdown and quantity of NDG data sourced from the previous study.

Table 4.9: NDG data breakdown

Site	Number of lots	Number of data pairs
1	3	30
2	3	30
3	3	30

Source: Queensland Transport (1995).

The average density and standard deviation of the data (without a density bias applied) were calculated for each lot and dataset (representing a different method of measurement) and then averaged overall. The decision to analyse the data by lot first was done to avoid any influence from any other variables that might change between the different lots (e.g., lot size). A comparison between the average density, standard deviation, and residual density values for the PQI, asphalt core and NDG data is provided in Table 4.10 and Table 4.11.

The two tables compare the average and standard deviation values of the PQI, NDG and core densities without a density bias applied, as well as the resulting residual density values after a project-specific bias was applied to the results. The average and standard deviation values for the PQI, NDG and core densities were calculated without applying a density bias given that this would result in the average values being the same, whereas the residual density values were calculated with a bias applied to show how the PQI would perform once calibrated in comparison to the NDG.

Table 4.10: PQI vs core density comparison

Mixes	Number of lots	Number of data pairs	Average PQI density (t/m ³) ⁽¹⁾	Average Core density (t/m ³)	PQI standard deviation (t/m ³) ⁽¹⁾	Core standard deviation (t/m ³)	Average residual density ⁽²⁾ (t/m ³)
AC14	1	6	2.535	2.441	0.009	0.021	0.014
AC14H-18	4	27	2.480	2.433	0.026	0.026	0.025
AC20-18-A	14	119	2.539	2.460	0.028	0.025	0.045
AC20-18-B	2	10	2.554	2.458	0.020	0.013	0.053
AC20H-18-A	24	173	2.447	2.480	0.020	0.026	0.025
AC20H-18-B	1	10	2.523	2.473	0.011	0.024	0.023
SMA14-18	1	11	2.373	2.307	0.024	0.028	0.013

1. Indicates no project bias was applied.

2. Indicates a project bias was applied.

Table 4.11: NDG vs core density comparison

Site	Number of lots	Number of data pairs	Average NDG density (t/m ³) ⁽¹⁾	Average core density (t/m ³)	NDG standard deviation (t/m ³) ⁽¹⁾	Core standard deviation (t/m ³)	Average residual density ⁽²⁾ (t/m ³)
1	3	30	2.472	2.515	0.033	0.031	0.014
2	3	30	2.459	2.492	0.034	0.030	0.022
3	3	30	2.479	2.532	0.041	0.035	0.020

1. Indicates no project bias was applied.

2. Indicates a project bias was applied.

The average PQI readings were generally higher than the core density measurements, whereas the average densities measured with the NDG in the previous Queensland Transport (1995) study were lower than the core densities. The PQI and NDG devices produced similar residual density values which suggest that both

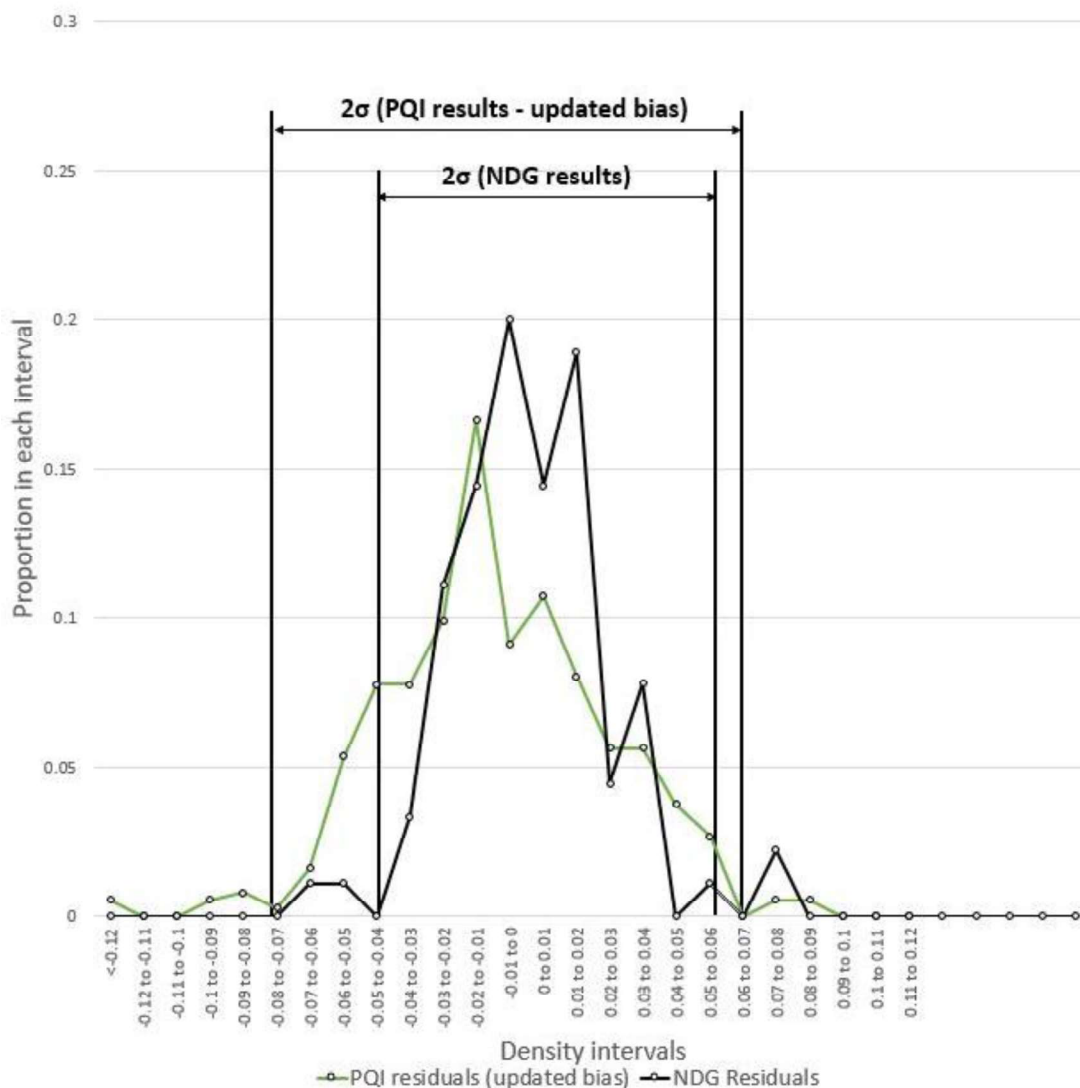
these devices are less accurate than the core density measurements. This supports the requirement for the use of a project-specific density bias to improve the accuracy of PQI and NDG density measurements.

The standard deviation of the density values measured using the three methods were similar, except for the asphalt mixes with relatively small sample sizes (i.e., AC14, AC20-18-B and AC20H-18-B). The difference in standard deviation determined for the asphalt densities indicate that a similar level of precision exists between asphalt cores, PQI and NDG devices.

The higher residual values for the PQI also suggest that the NDG produced more accurate results overall. However, there were two asphalt mixes (i.e., AC20-18-A and AC20-18-B) that had relatively high average residual density values for the PQI device. The higher residual density values for these two mixes could possibly be due to using a single project-specific bias for mix AC20-18-A that has a large sample size, and the small sample size associated with mix AC20-18-B. The range of average residual density values using the PQI becomes 0.013 t/m³ to 0.025 t/m³ when these two mixes are excluded from the analysis, which compares more favourably to the residual density values using the NDG.

Figure 4.11 also shows the probability distribution of the PQI residual density values for the AC20-18-A and SM14 asphalt mixes and the NDG data obtained from the previous Queensland Transport study. The PQI readings were adjusted using the updated density bias procedure discussed in Section 5.2 of this report. The narrower confidence interval for the NDG results suggest that the NDG is more accurate than the PQI device based on the available data.

Figure 4.11: Probability distribution of residual densities (PQI vs NDG)



The difference in level of accuracy between PQI and NDG devices and the use of the cloverleaf measuring pattern should be further investigated in future studies.

4.5 SUMMARY OF DATA ANALYSIS

The effect of asphalt mix type, temperature, layer thickness, measuring pattern and density bias determination on the PQI readings was evaluated in Section 4. Other variables (such as moisture and surface texture depth) identified in the literature that could potentially affect the PQI readings were not included in the study.

The data collected for the study also indicate that the asphalt mix type does have an influence on the PQI readings, and a project-specific density bias should therefore be applied to the density results. In some cases, a range of 7% in the level of compaction measured was observed if no density bias was applied to the PQI readings.

Asphalt temperature does seem to have a weak but important influence on the PQI readings given the range of possible temperatures expected to occur at the time of testing.

Asphalt thickness appears to have little effect on the PQI readings. This is probably due to the layer thickness being accounted for as an input parameter into the PQI device during testing which also limits the effect of the underlying layers on the PQI readings.

Most of the Pearson correlation coefficient values for the PQI–core density results were positive, meaning that an increase in core density generally coincided with a higher PQI reading. Importantly, the covariance between the PQI and core density values were typically very low for the datasets evaluated which suggest that the PQI is consistently measuring the same property.

The R-squared values for the PQI–core density, mix type and thickness correlations were typically low which suggest that other variables (such as moisture, texture depth and measuring pattern) were affecting the PQI readings.

An assessment of the cloverleaf measuring pattern against single position readings suggests that the cloverleaf pattern does not necessarily reduce the variability in the PQI readings, however it may offer users the ability to locate positions where the device was not correctly seated.

Two density bias determination methods were evaluated in accordance with test method Q326 and the NDG method, respectively. It was found that the NDG method for determining a density bias would be appropriate for the PQI device.

The PQI and NDG devices produced similar residual density values which suggest that both these devices are less accurate than core density measurements. This supports the requirement for the use of a project-specific density bias during construction.

Finally, the difference in standard deviation of the density determined using the three measurement methods were relatively small, which indicates a similar level of precision between asphalt cores, PQI and NDG devices.

5 CASE STUDIES

The analysis undertaken as part of the study found that the PQI device is less accurate in measuring density compared to asphalt cores but does have a similar level of precision. Two case studies (using the data provided) were undertaken to determine the potential impact on compaction conformance testing when using the PQI device instead of asphalt cores to determine the density of asphalt placed during construction.

The PQI readings and core densities provided for two construction projects were compared against the compaction requirements specified in TMR's technical specification *MRTS30 Asphalt Pavements* (TMR 2020b). The characteristic compaction values error types for each lot were also assessed using the two methods of density measurement.

For the purposes of the analysis, Type 1 errors were defined as instances where the core density 'the actual density' met the specified compaction criteria, but the PQI readings were outside the characteristic compaction limits. Type 2 errors were defined as instances where the core density lies outside the specified compaction limits and the PQI readings were within the specification limits.

5.1 CASE STUDY 1

Case Study 1 represents the most complete dataset. The dataset comprised of 119 PQI–core density pairs and included the maximum density of the asphalt mix. The raw data provided did not have a density bias applied by the device.

Figure 5.1 shows the per cent air voids (i.e., level of compaction) in the sequence that the PQI and core densities were measured. The per cent air voids were defined as the bulk density (obtained from the PQI and asphalt cores) divided by the maximum density of the asphalt mix. The PQI readings were adjusted with a density bias calculated in accordance with test method Q326 and using the core measurements taken in the first construction lot. Initially, the compaction values determined with the PQI track the compaction values obtained from the asphalt cores relatively closely until the 35th data pair after which the PQI readings increase and start to overestimate the density of the asphalt. A significant drop in the PQI readings occurred near the end of the project, for unknown reasons.

Figure 5.1: Sequential per cent air voids – AC20-18-5300 mix

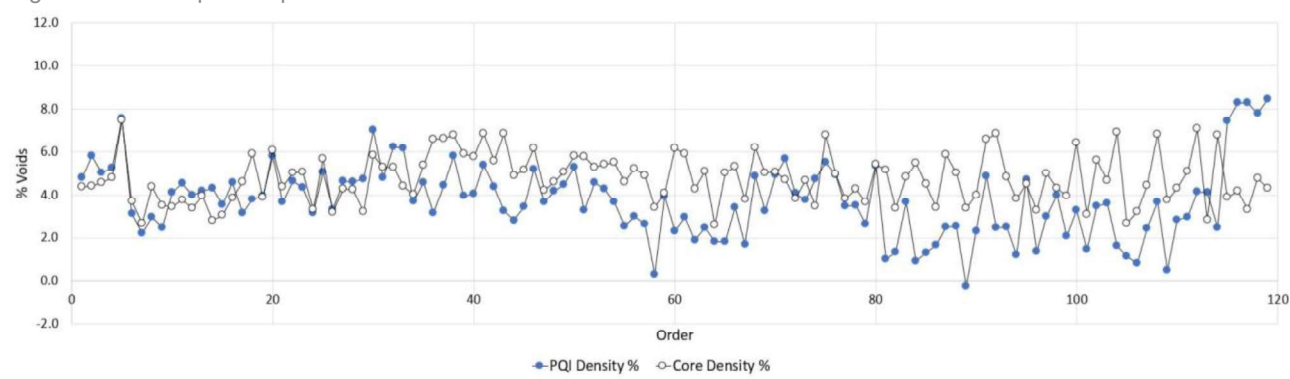
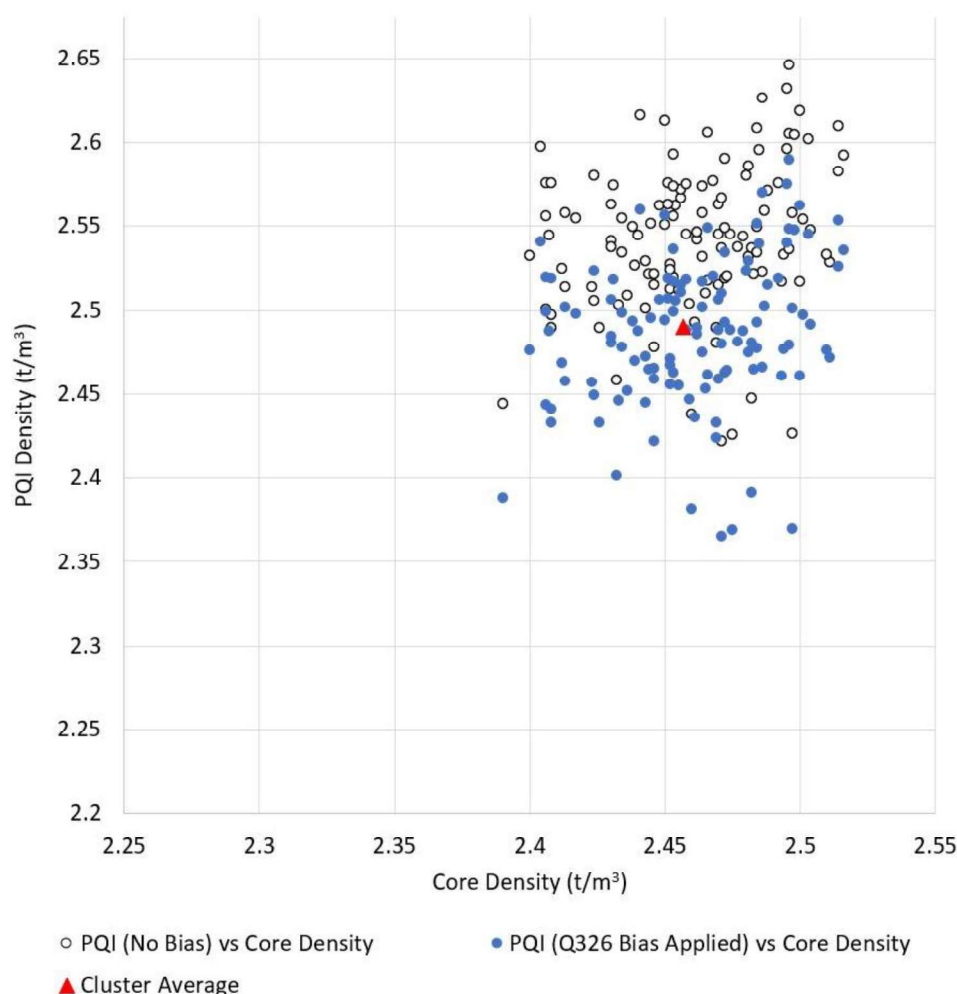


Figure 5.2 shows the scatter plot of the PQI readings and core densities. The figure shows the effect a density bias of -0.057 t/m^3 has on the PQI readings, which is to shift the average of the PQI readings to be more in line with the core densities. The red triangle shows the averages of the core densities and PQI readings after the density bias was applied. The two averages are not equal, which is a result of the bias only being calculated by an initial lot of cores. The pattern of the data stays the same, as the bias does not have an impact on how the data is distributed. The covariance for the PQI–core data pairs is $3.12 \times 10^{-4} \text{ t/m}^3$ which suggests that the density results are evenly clustered around the average values, suggesting that the PQI device is measuring the density characteristic of the asphalt.

Figure 5.2: PQI vs core densities – AC20-18-5300 mix



The characteristic air voids content for each construction lot were calculated in accordance with test method Q020 (TMR 2020a) using both the core densities and PQI readings. These characteristic values were compared against the lower (3%) and upper characteristic (7%) limits specified in MRTS30 (TMR 2020b).

Table 5.1 provides a summary of the number of the number of 'pass', 'fail' and error types produced by the PQI device. A pass and fail result were defined as a scenario where both the core density and PQI reading falls within or outside the specified characteristic compaction limits. As mentioned previously, the number of Type 1 and Type 2 errors produced by the PQI device was also evaluated. Type 1 errors represent construction lots where the PQI incorrectly identifies the asphalt as being non-conforming, whereas Type 2 errors represent construction lots where the PQI incorrectly identifies the asphalt as conforming to the specified compaction limits.

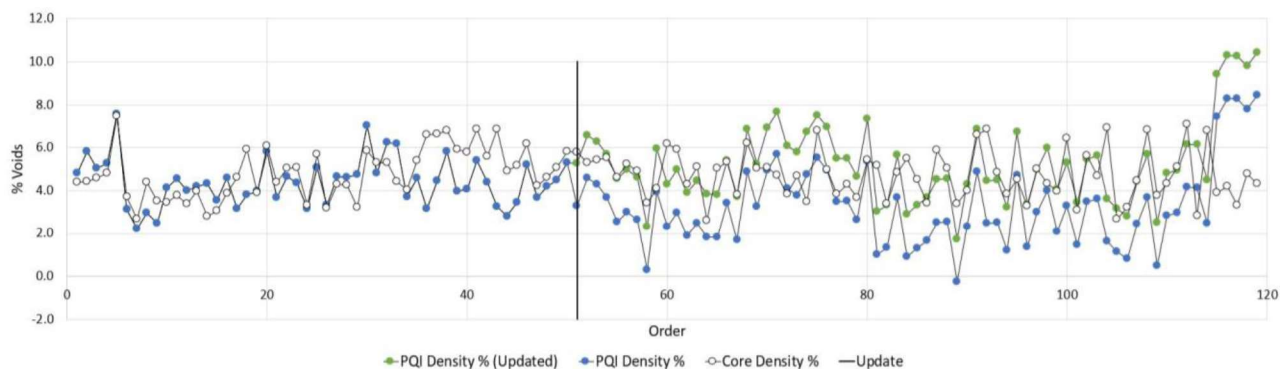
Table 5.1: Summary of Case Study 1 results – AC20-18-5300 mix

Mix type	Number of lots	Number of pass results	Number of fail results	Number of Type 1 errors	Number of Type 2 errors	Average residual density (t/m³)
AC20-18-A	14	6	0	8	0	0.043

The PQI readings resulted in eight construction lots with Type 1 errors which equates to 75% of the total number of lots included in the case study. The PQI device would therefore have incorrectly identified these lots as being non-conforming. There were no Type 2 errors observed, which is likely due to the PQI generally overestimating the density compared to the asphalt cores.

As mentioned previously, the PQI readings started to differ from the core densities after the 35th reading, which suggest either a change in the PQI operation or a change in the properties of the asphalt mix. Another analysis was carried out where the density bias was recalculated from construction lot number 7 onwards using the cores numbered 50 to 60. The updated density bias was then applied to the PQI readings after the 50th data pair and the updated densities are shown in Figure 5.3, where the vertical line shows the point at which the updated density bias was applied.

Figure 5.3: Sequential per cent air voids – AC20-18-5300 mix (with updated bias)



The updated bias decreased the number of Type 1 errors and improved the agreement between the PQI and core densities.

Table 5.2 provides a summary of the revised pass, fail and error types after the updated density bias was applied. The total number of Type 1 errors decreased significantly (i.e., by 50%) after the updated density bias was applied which resulted in the number of passing results increasing to 10. This demonstrates the need for monitoring and updating the density bias throughout construction. It is also worth noting that updating the bias more frequently will decrease the difference between the PQI values and the average core values, which in turn will decrease the number of Type 1 and Type 2 errors.

Table 5.2: Summary of Case Study 1 results – AC20-18-5300 mix (with an updated bias applied)

Mix type	Number of lots	Number of pass results	Number of fail results	Number of Type 1 errors	Number of Type 2 errors	Average residual density (t/m ³)
AC20-18-A	14	10	0	4	0	0.032

5.2 CASE STUDY 2

Case Study 2 represented the largest dataset comprising 254 PQI–core density pairs. As mentioned previously, the data provided by Contractor B already had a density bias applied to it using the inbuilt bias function on the device.

Figure 5.4 shows the per cent air voids in the sequence that the PQI and core densities were measured. The PQI readings in this case study are generally closer aligned with the core densities compared to the first case study up until the 75th data pair whereafter the difference between the densities becomes more significant. The reason for the closer alignment between the two methods is not clear at this stage.

Figure 5.4: Sequential per cent air voids – SM14 mix

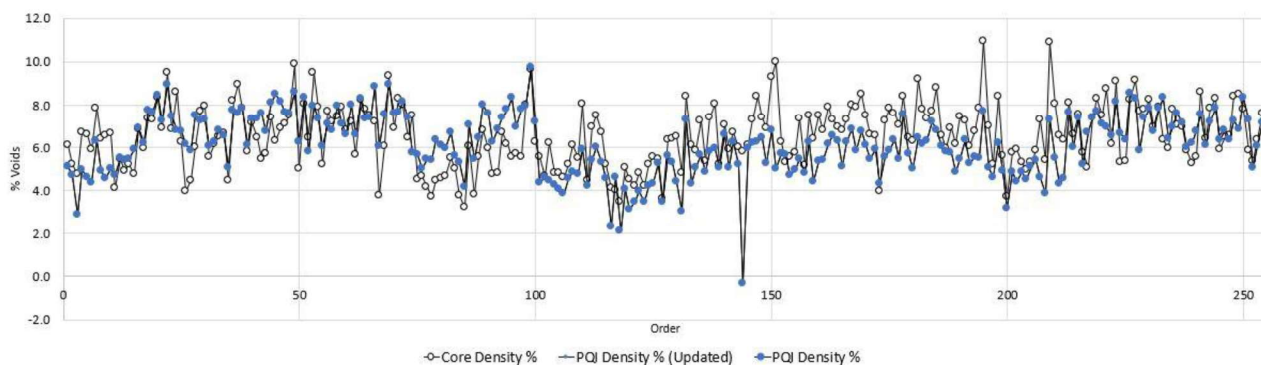


Figure 5.5 shows the scatter plot of the PQI values and core densities with a density bias applied. The covariance for the PQI–core data pairs is $8.19 \times 10^{-4} \text{ t/m}^3$ which suggests that the density results are evenly clustered around the average values, similar to the results in Case Study 1. The data in Case Study 2 is however more linear than the data in Case Study 1, with the PQI and core densities having a Pearson coefficient of 0.617 as compared to Case Study 1 which has a Pearson coefficient of 0.24.

Figure 5.5: PQI vs core densities – SM14 mix

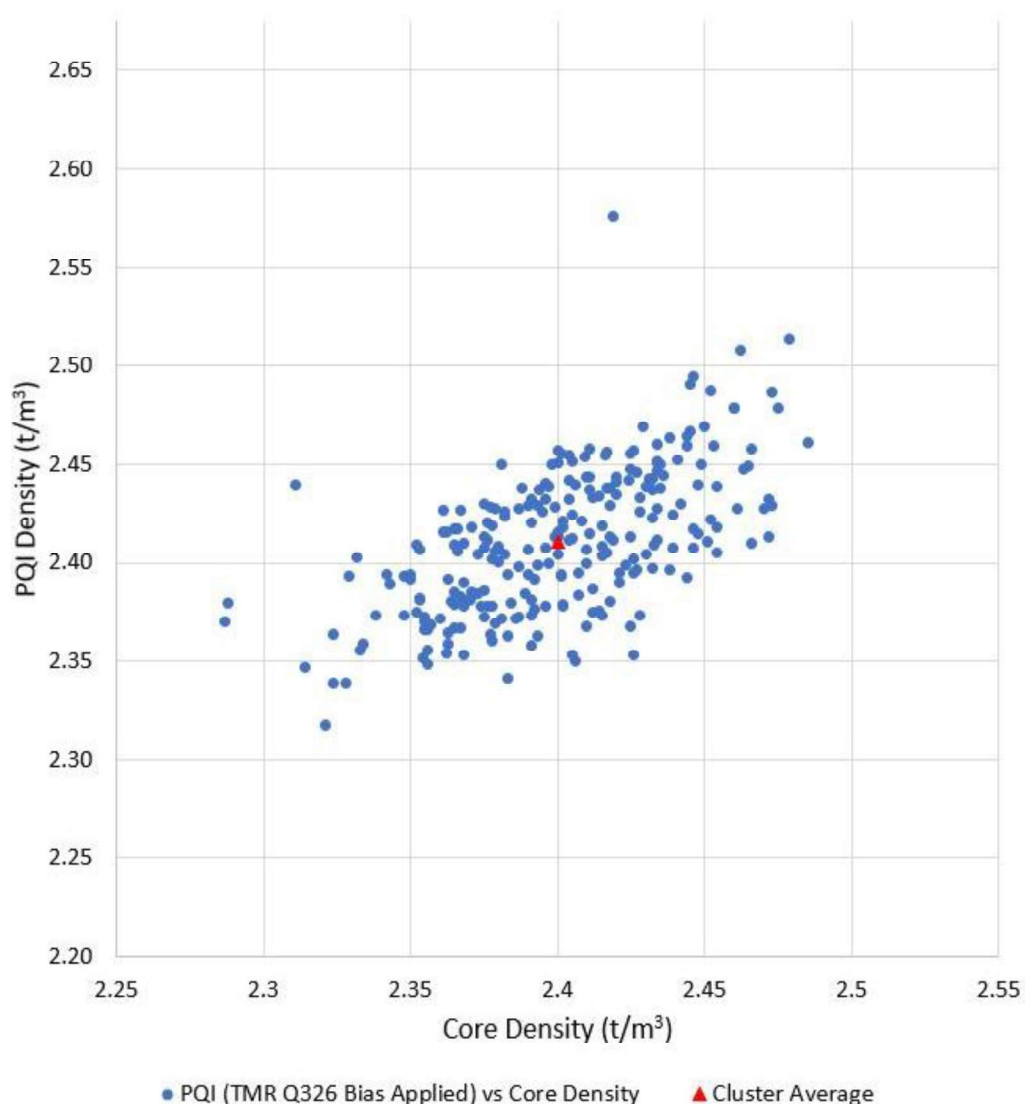


Table 5.3 provides a summary of the number of pass, fail and error types produced by the PQI device. Interestingly, there were no Type 1 errors observed using the PQI device whereas seven lots had Type 2 errors. In this case study, the PQI would therefore have identified 35% of the construction lots as conforming

to the specified compaction limits. This is contrary to the findings from the first case study, where the PQI device only produced Type 1 errors. The reason for this is not clear at the time of writing the report. It is however important to note that the data used in Case Study 2 were collected approximately 17 years ago prior to the development of the draft PQI test method Q326 and the PQI density readings appear to have been taken with an older PQI model that does not necessarily represent the latest technology. It is also unclear how the density bias was determined or applied to the data supplied by Contractor B.

Table 5.3: Summary of Case Study 2 results – SM14 mix

Mix type	Number of lots	Number of pass results	Number of fail results	Total Type 1 errors	Total Type 2 errors	Average residual (t/m ³)
SM14	20	4	9	0	7	0.027

Given that the data used for the second case study already had a density bias applied by the contractor, an analysis using an updated bias was not carried out on the SM14 results.

5.3 SUMMARY OF CASE STUDIES

Table 5.4 summarises the results of the case studies presented in Section 5.1 and 5.2.

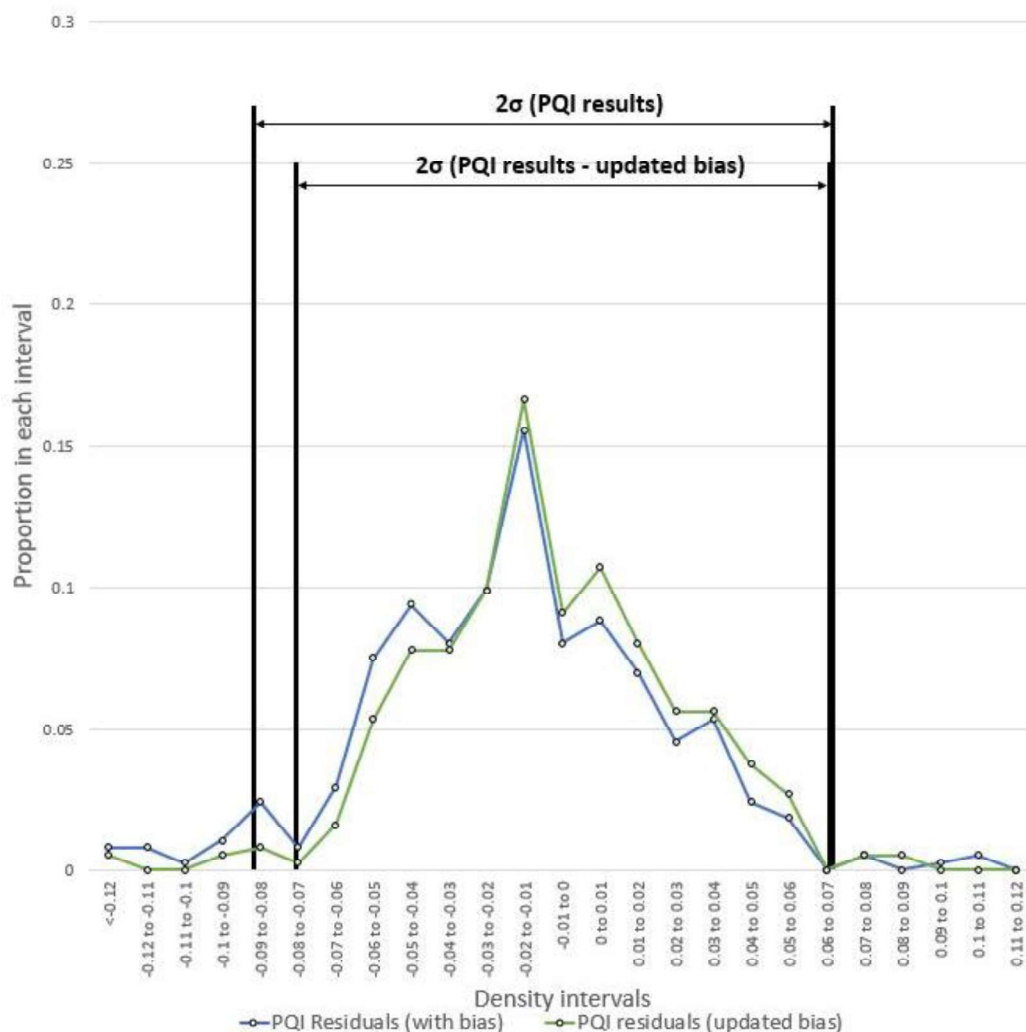
Table 5.4: Summary of the case study results

Case Study	Number of lots	Number of pass results	Number of fail results	Total Type 1 errors	Total Type 2 errors	Average residual density (t/m ³)
Case Study 1 (with single bias)	14	6	0	8	0	0.043
Case Study 1 (with updated bias)	14	10	0	4	0	0.032
Case Study 2	20	4	9	0	7	0.027

The analysis showed that by applying multiple density bias updates to the PQI readings used in the first case study significantly reduced the number of Type 1 errors and the average residual density for the PQI and asphalt cores.

Figure 5.6 also shows a probability distribution of the residual density values resulting from applying an updated density bias to PQI readings for the two asphalt mixes included in the case studies. The vertical lines shown on the graph represent the 95th per cent confidence interval (i.e., two standard deviations). An updated bias decreased the standard deviation and average residual density values of the PQI readings resulting in more accurate measurements.

Figure 5.6: Probability distribution of residuals (bias and updated bias)



However, of particular concern is the number of Type 2 errors observed in the second case study, given that a significant number of lots would have been incorrectly identified as conforming to the specified compaction limits if only the PQI device was used for compliance testing. As mentioned previously, the data used in the second case study should be treated with caution given that it was obtained in 2003 and may not necessarily represent the latest in PQI technology or testing standards.

6 BENEFITS OF USING THE PQI DEVICE

The PQI (and similar non-destructive density testing devices) offers the ability to determine the density of asphalt layers without the need for destructive testing (e.g., asphalt cores). It is however unlikely that the need for asphalt cores will be eliminated anytime soon, but the use of non-destructive devices such as the PQI could reduce the number of asphalt cores required for compliance testing if these devices were found to be a reliable measure of density.

Furthermore, non-destructive test methods (if reliable) can provide the following additional construction benefits:

- Reduced cost and time associated with the quality control and assurance of asphalt layers during construction.
- Asphalt cores (if not properly reinstated) can introduce a weak spot in newly constructed asphalt layers that increases the risk of moisture entry and/or localised surface defects. This risk is removed with the use of non-destructive test methods.
- Realtime density measurements obtained from non-destructive devices can be used to optimise compaction processes and take pre-emptive correction actions to avoid potential non-conformances during construction.
- Non-destructive testing generally allows for more tests over a larger area to be undertaken compared to asphalt cores. This larger testing coverage allows for a better representation of the actual density and uniformity achieved throughout construction lots.
- The larger sample size obtained from non-destructive testing allows for a more robust and statistically significant assessment of density compliance during construction.
- Together with Intelligent Compaction technology can improve the uniformity of asphalt compaction during construction.

Electromagnetic density measurement devices also do not have the same occupational health and safety risks that are associated with using an NDG.

The appropriate application of a project-specific density bias should result in the average of several PQI measurements being a more accurate representation of the density, but it cannot guarantee that a test in a specific location is an accurate measurement of the density at that location. The difference between more widespread testing and accurate spot measurements should be kept in mind when considering how the PQI results are interpreted and how the device is implemented in the field.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The purpose of this project was to evaluate the suitability of the PQI device as a density conformance test for asphalt layers during construction. This was done by evaluating the correlation between PQI and core density measurements from side-by-side testing undertaken by two contractors. The effect of asphalt mix type, temperature, layer thickness and measuring pattern on the PQI readings was also assessed.

The data showed that the PQI–core density relationship was closely clustered around the average density values which indicates that PQI is a measure of density. The decision to implement the device for density compliance testing should therefore be based on how closely the performance (i.e., precision and accuracy) of the PQI matches the performance of other acceptable non-destructive test methods such as the NDG.

A comparison between the PQI device, NDG and asphalt cores found that the standard deviation of the density values were similar for the datasets with comparable sample sizes, which suggest that a similar level of precision exists between the three methods of density measurements. However, preliminary indications are that the NDG may be more accurate than the PQI device. This finding is however based on a limited dataset and did not include any side-by-side testing using both devices. It is therefore recommended that further investigations be undertaken to determine the relative performance of the PQI device against the NDG in a controlled study.

Case studies (using the data provided) were also undertaken to assess the impact of using the PQI for density compliance on two construction projects. The PQI readings were compared to the densities obtained from asphalt cores at the same location, and the number of false negative (Type 1) and false positive (Type 2 errors) PQI results were determined. Type 2 errors present the greatest risk to TMR as this type of error represent density results that are incorrectly identified as complying with the specified compaction criteria. Although Type 1 errors still present a risk (especially to the contractor), this type of error will likely be retested using conventional asphalt cores.

The first case study used PQI data obtained from a recent construction project in accordance with draft test method Q326. The analysis resulted in four Type 1 errors and zero Type 2 errors, suggesting that the PQI device could be suitable for density compliance testing. However, the second case study resulted in zero Type 1 errors and seven Type 2 errors. The reason for the difference between the two case studies is not clear, however, it is important to note that the data used in the second case study were collected prior to the development of the draft PQI test method Q326 and the PQI density readings appear to have been taken with an older PQI model that does not necessarily represent the latest technology.

It was found that mix type does have an influence on the PQI readings and that a mix-specific density bias is required.

For the range of layer thickness included in the study, layer thickness showed little effect on the PQI readings; furthermore, the limited variation in pavement thicknesses expected to occur during construction would limit much of the effect the thickness has on the PQI readings. The data evaluated clustered around thicknesses of 100 mm and 50 mm; however, no clear change in the PQI readings was observed. This is possibly due to the layer thickness being entered as an input parameter into the device prior to testing. The minimal influence of thickness suggest that the density of the underlying layer is not influencing the PQI readings, however this was not investigated as part of the study.

The data showed that temperature appears to have a weak but important influence on the PQI readings. Although the relationship is weak, the effect may be significant enough over typical pavement temperature ranges to warrant further investigation into the effect of temperature variations during testing. In the interim, a requirement should be included in test method Q326 to determine the density bias at temperature ranges typical of the temperatures that will be experienced while taking measurements with the PQI during

construction. Density measurements for compliance testing outside of these typical temperature ranges should not be allowed.

The effect of moisture was not included in the study. However, White (2019) indicated that moisture did influence the PQI readings and recommended that the density testing be undertaken on the day following construction to limit the influence of moisture and temperature on the PQI readings.

The effect of the density measurement pattern (i.e., cloverleaf vs single position readings) was also assessed and preliminary indications are that the cloverleaf pattern did not necessarily provide any additional benefit, other than perhaps ensuring the device is seated properly. The requirement for cloverleaf pattern measurements in draft test method Q326 should therefore be investigated further.

The procedure for determining the density bias included in test method Q326 is similar to the method specified by TMR for NDG devices, except for the need to update the density bias during construction and the removal of uncharacteristic data pairs. The study clearly demonstrated the need for monitoring and updating the PQI density bias throughout a project. It is therefore recommended that the requirement in the current NDG method be adopted as an interim measure to check the PQI density bias for every 10,000 tonnes of asphalt placed. It is also recommended to remove any uncharacteristic PQI–core data pairs when determining the density bias (similar to the procedures specified in the NDG method).

In all the analyses the R squared values were relatively low. The cause for this may be that other variables such as moisture and texture depth affect the results; further investigation is required. It is recommended that investigation of the cloverleaf pattern is also done to evaluate the effect this has on the accuracy and repeatability of the PQI while being able to determine whether the device was properly seated during testing.

The case studies showed that the device has the potential to be used as a conformance test. The proportion of Type 2 errors is typically low; however, the results were not conclusive as only one case study had complete data. The data provided showed that changes to the bias are necessary throughout a project and that regular coring should be done to ensure that the bias being applied, and therefore the PQI, remain accurate. It is therefore recommended that a procedure for updating the bias with regular calibration cores be included in the Q326 method.

7.2 RECOMMENDATIONS

Based on the findings of the study, it is recommended that the following updates be included in the draft test method Q326:

- a procedure to check and update the bias during construction
- a note to avoid using the PQI when any moisture is present on the surface
- a procedure to remove uncharacteristic values from the dataset used to calculate the density bias
- limitations on the pavement temperature while carrying out PQI testing
- possible replacement of the cloverleaf pattern with repeated testing at a single position, pending outcomes from further studies.

It is also recommended that a controlled study be undertaken to assess the proposed updates to test method Q326 and the relative performance of the PQI device against the NDG.

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DRAFT TEST METHOD Q326

Draft Test Method Q326: Compacted density of asphalt – electromagnetic surface contact device

1 Source

This method is based on ASTM D7113: Density of bituminous paving mixtures in place by the electromagnetic surface contact methods.

2 Scope

This method sets out the procedure for the determination of the compacted density of asphalt using an electromagnetic surface contact device. The device measures changes in the electromagnetic field resulting from the compaction process.

An adjustment is made to the output of the device in the form of density bias as determined from a comparison between the electromagnetic surface contact density and core compacted density results.

3 Apparatus

The following apparatus is required:

- 3.1 Electromagnetic surface contact device capable of accommodating surface moisture and temperature variation in the range typically encountered in paving applications (Note 11.1).
- 3.2 Reference block (standardisation plate), as supplied by the manufacturer with the device and traceable to the device. This block/plate is usually part of the carry case.
- 3.3 Straightedge.
- 3.4 Brush.
- 3.5 Crayon for marking test locations.

4 Calibration and biasing

4.1 Manufacturer calibration

The device must be calibrated at least once every year for density measurement as detailed in the relevant manufacturer's manual (Note 11.2).

4.2 Asphalt density bias

A density bias for the particular asphalt mix and device must be determined as follows:

- 4.2.1 Select at least 10 test sites within the lot under consideration using Random Stratified Sampling: Selection of Location – Available Area (unless otherwise specified) as detailed in Test Method Q050 (Note 11.3). Number each test site consecutively in chronological order.
- 4.2.2 At each test site, undertake the following:
- 4.2.3 Measure the compacted density as detailed in Steps 6.1 to 9.1, except that no asphalt density bias is applied. This density is referred to as the device density. Record the device density values to the nearest 0.001 t/m³, for all locations (Note 11.4).
- 4.2.4 Obtain a 150 mm diameter core sample centrally within the site in accordance with Test Method AS 2891.1.2.
- 4.2.5 Measure the compacted density of the core sample as detailed in Test Method Q306B or Q306C as appropriate (Note 11.5).

4.2.6 Determine the average device density for each site by averaging the corresponding device density values (Note 11.4).

4.2.7 Calculate the asphalt density bias to the nearest 0.001 t/m³ as follows:

$$B_p = \bar{D}_c - \bar{\rho}_D$$

where B_p = asphalt density bias (t/m³)

$\bar{D}_c$ = average core compacted density for the test sites (t/m³)

$\bar{\rho}_D$ = average device density for the test sites (t/m³)

4.2.8 This bias is to be determined again whenever there is a change to the mix design.

5 Operational checks

To ensure that the device is operating normally, an operational check is to be undertaken daily as follows:

- 5.1 Turn the device on and allow readings to stabilise, this will usually take 15 minutes.
- 5.2 Place the device in the carry case and follow the manufacturer's instructions to perform a daily standardisation/reference check. Record any readings and outcome of the operational check (pass/fail) (Notes 11.6 and 11.7).
- 5.3 If the device fails the daily operational check, remove the device from service and have it repaired by a licensed service agent.

6 Configuration

On each day of use, configure the device before testing by setting or checking test parameters appropriate to the asphalt mix design as follows:

- 6.1 Check or set user definable test parameters as detailed in the manufacturer's instructions for entering project and mix details (Notes 11.8 and 11.9).

7 Test site selection and preparation

Determine test locations and prepare each test site as follows:

- 7.1 Use Random Stratified Sampling: Selection of Location – Available Area (unless otherwise specified) as detailed in Test Method Q050 to determine each test location.
- 7.2 At a designated test location, use the straightedge to define a test site which is flat and free from depressions.
- 7.3 Brush all loose material from the test site.

8 Testing

- 8.1 Place the device on the prepared test site such that the longitudinal axis of the device is parallel to the direction of rolling and use a crayon or at least three dots of paint around the perimeter of the base plate to mark the first measurement position for the test location.
- 8.2 Confirm that the device is firmly seated without rocking (Note 11.10).
- 8.3 Using the appropriate measurement mode take readings as detailed in the manufacturer's instructions (Note 11.11). Record the reading mode, compacted density and temperature of the asphalt.

- 8.4 Move the device to the next measurement position (refer to Figure 1). Repeat Steps 8.2 to 8.3 until readings have been recorded for all five measurement positions.

9 Calculations

- 9.1 Determine the compacted density for the test site to the nearest 0.001 t/m³ by averaging the density values obtained from each measurement position.
- 9.2 Where the asphalt density bias has not been applied via the device microprocessor, adjust the compacted density calculated in Step 9.1 as follows:

$$D_C = \bar{\rho}_D + B_p$$

where D_C = compacted density (t/m³)

$\bar{\rho}_D$ = average device density (t/m³)

B_p = asphalt density bias (t/m³)

10 Reporting

Report the density bias as follows:

- 10.1 Asphalt density bias to the nearest 0.001 t/m³.
- 10.2 Source and type of the asphalt together with the mix code number and nominal layer depth.
- 10.3 A tabulation containing the device density and core compacted density data used to determine the bias, together with the date tested, lot number, test site number, and chainage and offset.

Report test results as follows:

- 10.4 Compacted density to the nearest 0.001 t/m³.
- 10.5 Date tested, measurement mode, lot number, test site number, and chainage and offset.
- 10.6 Source and type of the asphalt together with the mix code number and nominal layer depth.

11 Notes on method

- 11.1 A device such as the TransTech Pavement Quality Indicator (PQI 380) has been found to be suitable.
- 11.2 The device must be recalibrated following any major repair or component replacement.
- 11.3 In order to determine an asphalt density bias, which is representative of the lot, sampling locations must be distributed throughout the lot.
- 11.4 The test area is formed by a cloverleaf pattern over the surface of the asphalt at each test location (Refer to Figure 1) with the numbers of the five measurement positions shown.
- 11.5 For stone mastic asphalt the core sample compacted density must be determined in accordance with Test Method Q306C and for open graded asphalt in accordance with Test Method Q306D. For dense graded asphalt, the core sample may be tested in accordance with Test Method Q306B rather than Test Method Q306C, provided that its air void content is not less than the minimum specified level. The same compacted density method must be used for both the bias determination and bias checks.
- 11.6 A location away from sources of electromagnetic interference such as high voltage power lines, large metal objects and mobile phones.

- 11.7 A record is to be kept for each device to record operational check data and the date of measurement.
- 11.8 The scope of user definable test parameters is dependent on the make and model of device. Such parameters may include:
- a) project name and location
 - b) mix identification, layer thickness/depth, nominal mix size
 - c) maximum density (maximum theoretical density)
 - d) asphalt density bias (offset).
- 11.9 Varying composition of the underlying layer and fluctuations in the final layer thickness can lead to inconsistency in results. For this reason, the asphalt depth entered into test parameters on the device is to be set lower than the nominal thickness. For sound and even underlying surfaces (which will encompass most applicable projects), set the asphalt depth in the device to 10 mm less than the nominal layer thickness. On rough and uneven surfaces (that is, a base material or roughly profiled asphalt surface with variability), set the asphalt depth in the device to 20 mm less than the nominal layer thickness.
- 11.10 If the device cannot be firmly seated, prepare a new test site immediately adjacent to the original site.
- 11.11 Some devices including the PQI380 allow recordings to be taken in 'Average Reading' mode. The PQI does not store individual readings when using 'Average Reading' mode, therefore it is recommended that all readings are taken in 'Single Reading' mode and averaged manually on a worksheet or through the logged individual data at a later time.

Figure 1 – Cloverleaf measurement pattern

