Final Draft Report

Title:	Laboratory Evaluation of the PQI Model 300
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Problem Statement

During construction of hot-mix asphalt pavements, density measurements are taken at various stages to monitor the effect of the rollers and ensure proper compaction. The most commonly used method of measurement is the nuclear density gauge. The nuclear density gauge requires licensing, training, and specialized storage due to the radioactive source contained within the gauge. An alternative method that does not require a radioactive source is desired. The Pavement Quality Indicator (PQI) has the potential to be such method. Thus, research to determine the capabilities and accuracy of this non-nuclear gauge currently on the market is needed.

As a result of the increased interest in the use of the Pavement Quality Indicator (PQI) to measure in-place density of hot-mix asphalt, a pooled fund study was initiated by Maryland State Highway Administration (MDSHA) with participation from Pennsylvania, New York, Connecticut, Minnesota, and Oregon Department of Transportation. The objective of the pooled fund study was to evaluate the PQI using laboratory and field data.

Background

Work conducted at the Federal Highway Administration's Turner-Fairbank Highway Research Center in 1998 showed that the original PQI device (designated as Model 100) had serious problems when moisture was present in the mixture. A prototype version of a later model was also tested at that time. This prototype version showed promise in solving the problems associated with moisture. An updated version of the PQI device (Model 300) was introduced in late 1999 that incorporated advances from the 1998 prototype plus new algorithms based on a database collected by the manufacturers of the PQI device (TransTech Systems Inc, Albany, NY). It was decided that the PQI-300 device needed to be evaluated under controlled conditions in the laboratory and in the field before it could be used in the field with confidence.

Objectives

The objectives of this study are to: (1) measure the density of laboratory-prepared material using the PQI Model 300 and compare the results with those obtained by traditional methods; (2) document the conditions under which the device can be operated before proceeding with field trials.

This report documents the results obtained from testing the device in the laboratory under different conditions as explained in the experimental plan section.

Materials

The New York State Department of Transportation (NYSDOT) provided the materials used for this study. Aggregates from three different sources and gradations with three different nominal maximum aggregates sizes were used in this evaluation. While no specific mineral analysis was done on the aggregates, it is believed that the materials used represent a wide enough variety of aggregates used in hot-mix asphalt construction so that the conclusions are applicable to most conditions.

The different aggregates were mixed with an unmodified asphalt binder (PG 64-22) according to established job-mix formulas given by NYSDOT. The different mixes were compacted into slabs using a Linear Kneading Compactor. The slabs had final dimensions of 260-mm wide by 320-mm long with heights varying from 69 mm to almost 90 mm. Since all the slabs contained the same amount of material (by weight), different heights correspond to different densities.

Experimental Plan

The laboratory experimental plan consists of five factors. Each factor looks at a specific ability of the PQI-300 to determine the density of asphalt concrete under controlled conditions. This approach allows for easy evaluation of each factor. However, it does not allow for any assessment of the interactions that might exist between them (e.g., some gradations might be more susceptible to moisture changes than others). Such interactions could be further evaluated once the importance of the main factors is determined.

The factors investigated and the hypothesis used in their evaluation are described next.

> **Factor 1 – Density**: Changes in density of asphalt concrete produced with one aggregate source and one gradation should be proportional to the density measured using the PQI-300 device.
>
> **Factor 2 – Nominal Maximum Aggregate Size**: Changes in the nominal maximum aggregate size and the respective change in gradation properties can affect the ability of the PQI-300 to determine density of asphalt concrete**.**

Factor 3 – Aggregate Source: Changes in the aggregate source and the respective change in gradation properties can affect the ability of the PQI-300 to determine density of asphalt concrete**.**

Factor 4 – Temperature: Changes in temperature can affect the ability of the PQI-300 to determine the relative density of asphalt concrete. The internal algorithms inside the PQI device can account for these effects.

Factor 5 – Moisture: Moisture in the asphalt concrete can affect the ability of the PQI-300 to determine the relative density of asphalt concrete. The internal algorithms inside the PQI device can account for these effects.

Experimental Procedures

The experimental procedure consisted of making asphalt concrete slabs of 'known' density and comparing the accepted density to the density obtained from the PQI-300 when used according to the manufacturer's instructions. The experimental design for the five factors listed above is shown in table 1. The steps in the experiment are outlined next.

The first step consisted in the compaction of 18 slabs using limestone aggregates having a 12.5-mm nominal maximum aggregate size (NMAS) gradation and a maximum specific gravity of 2.480. Pairs of slabs were compacted to nine different heights ranging from 70.0 mm to 90.0 mm at 2.5-mm intervals.

For the next step, eight slabs were compacted to different heights using the same limestone aggregate but having a 19.0-mm NMAS gradation and a maximum specific gravity of 2.512. The height of these slabs ranged from 69.0 mm to 86.0 mm. This process was repeated with eight more slabs having a 25-mm NMAS gradation and a maximum specific gravity of 2.529. The height of these slabs ranged from 74.0 mm to 91.0 mm.

Another set of eight slabs was compacted to different heights using the gravel aggregate with a 12.5-mm NMAS gradation and a maximum specific gravity of 2.430. The height of this slabs ranged from 69.0 mm to 86.0 mm. The process was repeated with eight more slabs using the granite aggregate with a 12.5-mm NMAS and a maximum specific gravity of 2.478. The height of these slabs ranged from 74.0 to 91.0.

Since temperature is known to affect the conductivity of asphalt cement and thus the density readings from the PQI device, the first set of measurements was taken on one side of the slabs after they were compacted, while still relatively hot but out of the mold. This was meant to simulate the field process, where readings are taken during compaction of the hot asphalt pavement mat. The readings were taken using the average mode of the PQI-300 device (i.e., 5 measurements recorded and averaged internally by the device). In as much as possible, the device was moved within the slab to try to capture variations in density from the edge to the center. The data recorded was average density in kg/m^3, temperature in degree ºC, and phase angle (a relative measure of moisture, labeled in the PQI display as H2O reading).

The slabs were allowed to cool to room temperature. The PQI-300 was then used in the average mode (as explained earlier) and then in the continuous reading mode (i.e., three individual measurements recorded by the user) to obtain density measurements. During each measurement, the PQI was positioned on a different location throughout the slab. The data recorded in the continuous mode consisted of the density reading, the electrical signal in millivolts (strength of the electrical field measured by the device) and the phase angle (H2O reading). Since the depth of the electrical field is less than the height of the specimens (see figure 1) and the density is known to vary with depth, the process was repeated at both the top and the bottom of each slab and the density averaged into one single value.

After all the measurements were taken on the dry slabs, small quantities of surface moisture were applied on one side of each slab using a calibrated spray bottle with water. It was determined that approximately 6 grams of water would coat the surface of the slab. Data was collected using the continuous mode at three conditions: (1) before water was applied, (2) after applying 6 grams of water, (3) after applying 12 grams of water, and, in a few cases, after applying 18 grams of water. This was meant to simulate the condition in which the PQI-300 is used on a mat after a wet roller drives on it and not all moisture evaporates.

Once the data on surface moisture was collected, the density of the slabs was determined following the procedure in AASHTO T-166, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens. This procedure was carried out for two reasons, to obtain an estimate of density (besides mass divided by volume) and to allow water to enter the voids. Some of this water remained in the voids after the slab was submerged and then weighed in the saturated-surface dry condition. Three readings were taken using the PQI-300 on one side of these slabs. These readings were taken to approximate the condition in which internal moisture exists within the pavement. However, it is not clear how closely this last situation represents field conditions.

It is known that the results obtained from the procedure in AASHTO T-166 are not valid when the absorbed water exceeds 2 percent. Thus, to obtain a third estimate of the density (besides mass over volume and AASHTO T-166) the Corelock device was used. For this device to work, the slabs had to be sawn in half. After drying to constant weight, each half was placed inside a plastic bag where the air was removed using the Corelock vacuum method. The specific gravity (or density) was then calculated according to the procedures used in the

Corelock device. Attempts to measure slab density using a nuclear density gage were not successful because the imprint of the nuclear density gage was bigger than the size of the slabs. Comparisons between the nuclear gage and the PQI device should be done on the field portion of the study.

Principle of Operation of PQI Device

A detailed description of the theory behind the development and operation of the PQI device is outside the scope of this report. In general terms, the PQI-300 operates on the principle of measuring changes in the electrical field resulting from the introduction of a dielectric (i.e., asphalt concrete). Whenever an electrical charge is applied to a conductor, an electrical field is produced. If a nonconductor, known as a dielectric, is introduced inside this electric field, the strength of the field is reduced. The amount by which this dielectric reduces the electrical field can be characterized by the dielectric constant. Dielectric constant values for different materials are shown in table 2. For most of materials used in asphalt concrete pavements, the dielectric constant is in the range of 1 to 6.

In order to use the dielectric constant as a measure of asphalt concrete density, the strength of an electrical field is measured. This measurement must first be taken on an asphalt concrete sample of known density. The constituents of asphalt concrete; asphalt binder, aggregates, air, and moisture, each have different dielectric constants. As the asphalt concrete is compacted (i.e., as the density increases), the ratio of the volume of air to that of the other components changes, causing a change in the dielectric constant of the system. The change in dielectric constant causes a change in the electrical signal. Since the amount and type of material remained constant (except for air), this change in the electrical signal must be proportional to changes in density. This implies that the density obtained from the PQI device is not an absolute value but a change from a known reference value.

Moisture is also present in most pavement systems. The dielectric constant for water is relatively high (~80) in comparison to other materials found in asphalt concrete. Thus, even a small amount of moisture can have a significant effect on the measurements. This problem, which was the downfall of the PQI-100, is addressed in the PQI-300 by measuring the lag in the electrical signal. This lag, or phase angle, is strongly related to moisture content, thus it is labeled on the PQI display as H2O reading. Through a combination of electrical theory and a regression equation that includes the phase angle, the electrical signal is corrected for moisture so that the value of density reported is less sensitive to changes in moisture content.

Other variables also affect the electrical signal measured by the PQI-300 device. These include the thickness and composition of the base plate (the bottom plastic plate that separates the inside of the PQI from the road surface), the gap between the device and the asphalt concrete due to roughness on the surface, and changes in temperature (which changes the dielectric constant of asphalt cement). These variables are also corrected through algorithms based both on electrical theory and regression analysis.

Results

A summary of all results obtained in this experiment is shown in tables A1 through A15 in Appendix A.

The first step in evaluating the results obtained from the PQI-300 was to determine what value should be used as the accepted slab density (see discussion on density of laboratory material in the next section). Figure 2 shows the density of the 12.5-mm NMAS Limestone measured using the three different methods. AASHTO T-166 is known to give unrealistic results for low-density (high voids) slabs, thus density obtained from this method cannot be used for comparisons. For high-void materials, the use of parafilm is recommended; however, it was not practical to use in slabs this big. Instead, the slabs were vacuum-sealed in a plastic bag by the Corelock device. Unfortunately, this method has not been approved as a specification method and its precision and bias is not known. Furthermore, in some tests, the vacuum-sealed bag was punctured allowing water to enter the bag and possibly affecting the results. Density obtained by dividing the mass over the volume is also flawed because it does not take into account the surface texture of low-density slabs. However, since the results obtained using this method closely matched those obtained using the Corelock device (as seen in figure 2), it was decided to use this density as the slab density.

The density of the slabs obtained from the PQI-300 was compared to the density obtained by dividing the mass over the volume (length x width x height). These results are shown in figures 3 and 4. The readings were taken at room temperature on both sides of the slabs (top and bottom) when they were completely dry. Of interest in these figures are the slope of the trend line and the correlation coefficient (R-squared) between both types of measurements. Ideally, both the slope and the R-squared should be close to 1. High values of R-squared would indicate that the PQI density is highly correlated to slab density by a simple straight line (i.e., slab density can be obtained by multiplying PQI density by a constant). A slope of 1 would indicate that the PQI density exactly matches the slab density at any density level (i.e., there would be no need to determine any constant it is unity).

Figure 3 shows that the slope for the 12.5-mm NMAS gradation is significantly different than the slopes for the gradations with the larger NMAS (0.59 vs 0.95 and 0.94). This might indicate that within one aggregate source and binder type there might be some changes in the dielectric constant. It must be noted, however, that the slabs with the 12.5-mm NMAS gradation were compacted in 1998, while the slabs with the other two gradations were compacted just a few weeks before taking the PQI measurements. This might be an indication of changes in the dielectric constant of the asphalt binder due to oxidative aging. To verify if the differences in the slope were the results of oxidative aging, a new set of slabs was compacted using ‘fresh’ asphalt binder. The data, also shown in figure 3, indicates that indeed, the slope of the relation increases while still showing a high correlation coefficient. Obviously, one set of data points is not enough to model the effects of aging of the mix. Nevertheless, it point to the fact that the PQI-300 measurements are sensitive to changes in material properties.

Figure 4 shows the relationship for the three different aggregates evaluated. The slope of the three lines is different and nowhere near the desired value of 1. This indicates that there is not one unique relationship between PQI density and slab density. Each aggregate (as well as each binder as suspected from the aging results shown above) has a slope that should be determined individually. Given that each material has its own dielectric characteristics, these results were expected.

Figure 5 shows how changes in temperature affect PQI density. In most cases, a decrease in temperature caused an increase in PQI density (i.e., the ‘cold’ slabs had higher density). This change was much as high as 70 kg/m^3. The temperature of the ‘hot’ slab was between 40 to 60 ºC. This range of temperature is similar to what might be seen in the field after compaction. The ‘cold’ slabs were at room temperature (25 ºC). This resulted in a temperature difference of about 25 ºC between hot and cold measurements. It can only be speculated that if the temperature difference were greater, so would the difference in density readings. As a reference for accepted differences in density measurements, AASHTO T-166 states that, in the laboratory, duplicate specific gravity results should not be considered suspect unless they differ by more than 0.02. If the density of water is taken as 1,000 kg/m^3, this translates into a difference of 20 kg/m^3 in density. Thus, changes caused by differences in temperature can be 2 to 4 times the accepted difference in measurement (note that if AASHTO T-166 were run at a different temperature, the density of water would change so a correction would have to be applied).

Figure 6 shows how the change in temperature affects the slope of the relation between PQI density and slab density. The PQI density measured on the ‘hot’ slabs had a lower slope than the density measured on the ‘cold’ slabs (0.60 vs. 0.69). It is noted that the correlation coefficient (R-squared) in figure 6 is similar to the ones in figures 3 and 4 where measurements were taken on both sides of the slabs (top and bottom). This is important since pavements can only be measured “from the top”. Further measurements on the slabs were taken only on one side.

Figure 7 show the different measurements obtained using the PQI-300 on the slabs after moisture had been introduced in the system. As the amount of surface moisture in the system increased, the slope of the relation decreased and so did the coefficient of correlation (R-squared). In the extreme case where internal moisture was present inside the slab, the PQI density did not match the value obtained under dry conditions resulting in a low values of R-squared (0.22). The figure shows that for the slabs with high density (greater than 2200 kg/m^3), the PQI density matched the density taken in dry conditions. In these higher density slabs, the amount of moisture retained after submerging the slab under water was less than 3 percent. The H2O number on the display when these measurements were recorded was less than 5 percent. The manufacturers of the PQI device recommend not taking measurements when the H2O number is high. While no specific guidelines are given to determine what constitutes a high H2O number, the data seems to suggest a number greater than 5.

Figure 8 shows how the signal reading and the H2O number change with different amounts of internal moisture. As long as the slab density was relatively high (>2250 kg/m^3), and only a small percentage of moisture was retained, the signal readings on the 'wet' slabs agree with the values obtained on the dry slabs. However, once the H2O number in the PQI-300 display was above 5.0, the difference between dry and moist readings increased dramatically.

Figures 7 and 8 indicate that, the PQI-300 device can account for small amounts of moisture. However, to obtain consistent (and accurate) density values using this device, the amount of moisture present must be relatively low and consistent. The H2O number shown in the display seems to be a good indicator of moisture level. Figure 9 shows that there is a relation between the H2O number and the percent of water retained after submerging the slabs under water during T-166 tests. Failure to keep track of this number could lead to the wrong conclusion.

Discussion

Density of Laboratory Materials

The density of any solid material is defined in AASHTO M132 (ASTM E12) as the mass of a unit volume of material at a specified temperature. Since asphalt concrete is not a completely solid material (i.e., it contains voids), the term bulk density is often used instead. While the concept of density might be easy to define, determining the "right" value is not, as discussed next.

As was previously stated, the bulk density of asphalt concrete can be measured in different ways. By knowing the dimensions of the sample (l x w x h) and its mass, the bulk density can be determined. This assumes smooth surfaces and thus, a small error is introduced in low-density or coarse samples. Another common method to determine the bulk density is to use AASHTO T-166: Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens. However, if the percent of water absorbed is high (greater than 2 percent), this method is not recommended. Other methods, such as AASHTO T-275: Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-

Coated Specimens, or the new CoreLock vacuum-sealing device, can be used with high void (high absorption) specimens. Unfortunately, practical limitations on the size of the test equipment and sample handling problems preclude the use of these methods with large slabs. For example, in this work, slabs had to be cut in half to fit inside the CoreLock bags without puncturing them. Furthermore, the density of laboratory specimens, like that of field samples, is not uniform. Density gradients can be found from the top the bottom of the slabs, and from the edge to the middle making it difficult to arrive at an absolute value.

In summary, while the concept of bulk density of asphalt concrete is well defined, the actual measurement carries some uncertainty, especially at lower densities. Throughout this paper, comparisons of bulk density obtained through different methods were made. However, given that no absolute values can be established, no one measurement can be considered as the absolute standard.

Applicability of PQI-300 to Asphalt Concrete Pavement Density

The results presented above indicate that the PQI-300 device can be used to determine the density of asphalt concrete pavements. However, as with any other device, the user must be aware of the principles of operation as well as the limitations of the device. The readings provided by the PQI device are not absolute. They are relative measurements based on a given known value. Thus, it is necessary to ‘calibrate’ the device (or adjust the reference point) with a pavement section (or slab) of known density and made from of the exact same material as the one where density measurements are desired.

Changes in gradation, aggregate source, and temperature between the reference material and the pavement being measured can affect the accuracy of the readings. Moisture levels must not only remain constant but also be below certain value (H2O reading less than 5 for this study) to obtain meaningful density measurements. Furthermore, the fact that each aggregate and gradation had different slopes when compared to the slab densities indicates that both slope and intercept (offset) need to be determined on a reference material. In the next phase of this study, field trials need to be performed to determine if these factors can be controlled and kept constant to obtain actual pavement density.

An example of the applicability of the PQI-300 to asphalt pavements operations for the 12.5-mm NMAS mixture is shown in figure 10. This figure shows the PQI-300 readings corrected under dry conditions at approximately 90% Gmm (i.e., an offset was applied so that PQI readings and the asphalt concrete density match at 2,230 kg/m^3). Normally, the target density in the field is 92% Gmm or 2,280 kg/m^3 for this mix. After compaction, there is moisture on the pavement from the rollers. Thus, the PQI density follows the wet curve. Since the same correction factor developed for dry conditions is applied to the wet curve (i.e, no new calibration is done), the reading corresponds to a density of approximately 2340 kg/m^3 or about 94% Gmm. By not correcting for moisture, an error of 60 kg/m^3 that translates to 2.5% air voids was introduced.

Conclusions

Based on the evaluation of the PQI-300 device at the Bituminous Mixtures Laboratory using asphalt mixtures with limestone, gravel, and granite aggregates the following conclusions were obtained:

1. Based on the high R-squared values, the PQI-300 device can be used to determine relative changes in density of asphalt concrete under constant temperature and humidity conditions for a single mixture.
2. Changes in nominal maximum aggregate size produced only small changes in the density relations (slope) between the PQI and the slab density. Thus, it might be possible to use the same proportionality constant (slope) for different aggregate size as long as the same asphalt binder is used.
3. The relationship between PQI readings and density is different for different aggregate sources. It is therefore necessary to calibrate (i.e., determine both slope and offset) the device for individual mixtures.
4. Small amounts of surface moisture in the asphalt concrete do not affect the ability of the PQI-300 device to provide a relative measure of density as long as the moisture remains constant. Thus, determination of any calibration constants must be done under similar moisture levels.
5. The H2O values in the display panel can be used to monitor changes in moisture.
6. High contents of internal moisture continue to provide problems with the density determined using the PQI-300 device. However, the H2O value displayed is an indication of when problems are likely to occur.

Recommendations

Based on the results obtained on this research, the following recommendations

1. The slope and intercept need to be determined during calibration. Current procedures allow only the intercept (called offset) to be determined.
2. Moisture levels need to be monitored and recorded when measuring density using the PQI device.
3. Field trials need to be performed to determine if these factors can be controlled and kept constant to obtain actual pavement density.

Acknowledgements

The following people were involved on this research: Tom Harman, FHWA Asphalt Pavements Team Leader; Scott Parobeck, Frank Davis, Don Wilbanks, from SaLUT Inc.; and Jaret Morse from TransTech Systems, Inc. Kevin Stuart and Terry Mitchell from FHWA provided valuable comments. New York State

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Disclaimer

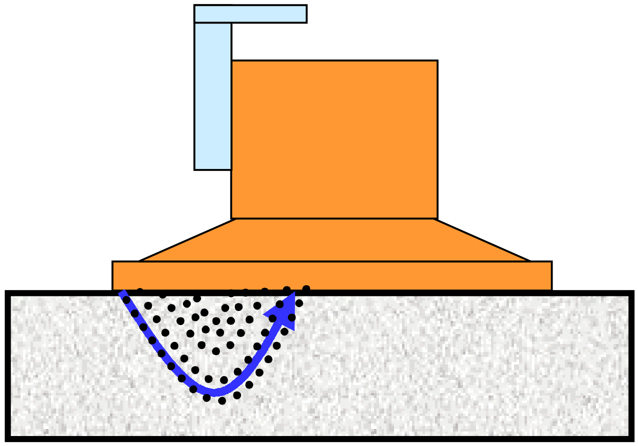
The opinions and conclusions presented in this document are those of the author(s) only and do not necessarily represent those of the Federal Highway Administration or any State Highway Agency.

Table 1. Factor Levels Used in This Study

Factor	**Level**
Density	From 1 839 kg/m^3 to 2 436 kg/m^3
Aggregate Size	12.5-mm, 19.0-mm, and 25.0-mm NMAS
Aggregate Source	Limestone, Granite, Gravel
Temperature	Hot (~50 ºC) and room temperature (~25 ºC)
Moisture	No moisture
	Two levels of surface Moisture
	Internal moisture

Table 2. Dielectric Constant of Some Common Materials.

Material	**Dielectric Constant**
Vacuum	1
Air	1.00054
Paraffin	~2
Plexiglas	3.4
Transformer Oil	~3
Mica	~6
Porcelain	6-7
Distilled Water	80
Metal	Infinity



(a)

(b)

Figure 1 -- (a) Sketch of the PQI device showing the path of the electrical field
(b) Picture of the PQI-300 device on top of a slab

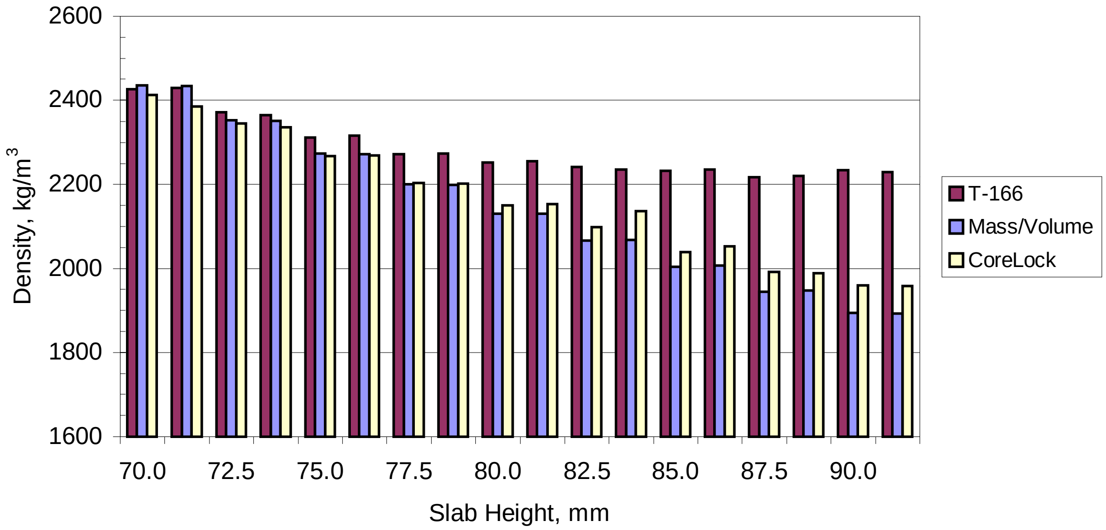


Figure 2 – Slab density obtained by three different methods for the limestone aggregates with the 12.5 NMAS gradation.

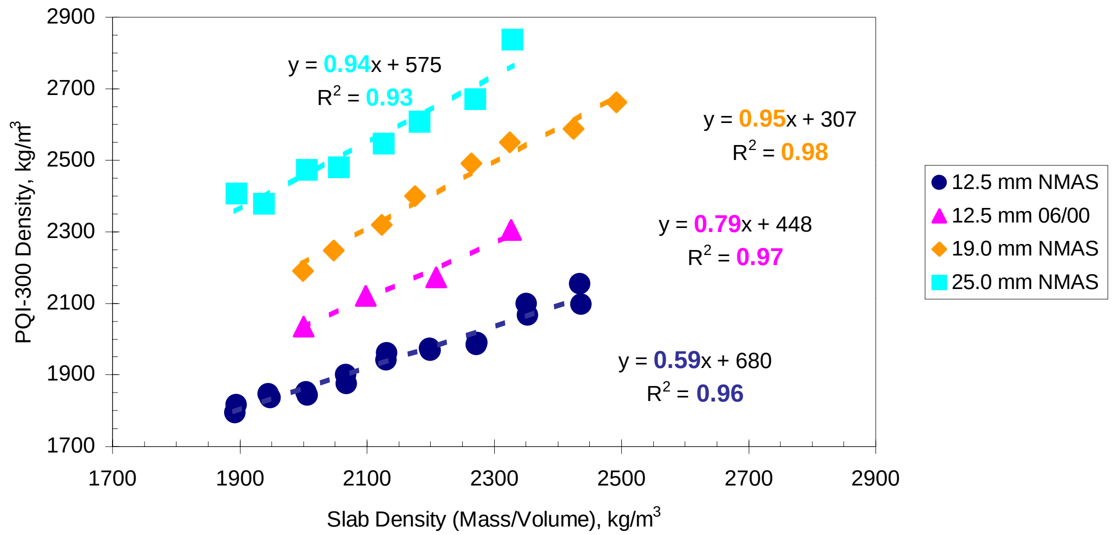


Figure 3 – Comparison between PQI-300 density readings and density of slabs prepared with limestone aggregate using gradations with 3 different NMAS (Vertical scale has been separated for clarity).

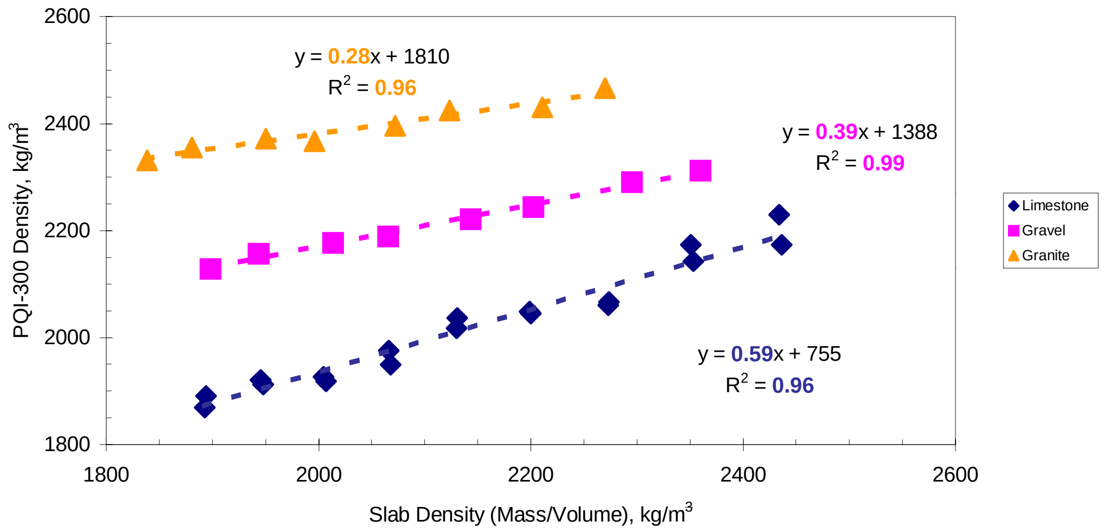


Figure 4 – Comparison between PQI-300 density readings and density of slabs prepared using gradations with 12.5-mm NMAS and three different aggregates (Vertical scale has been separated for clarity).

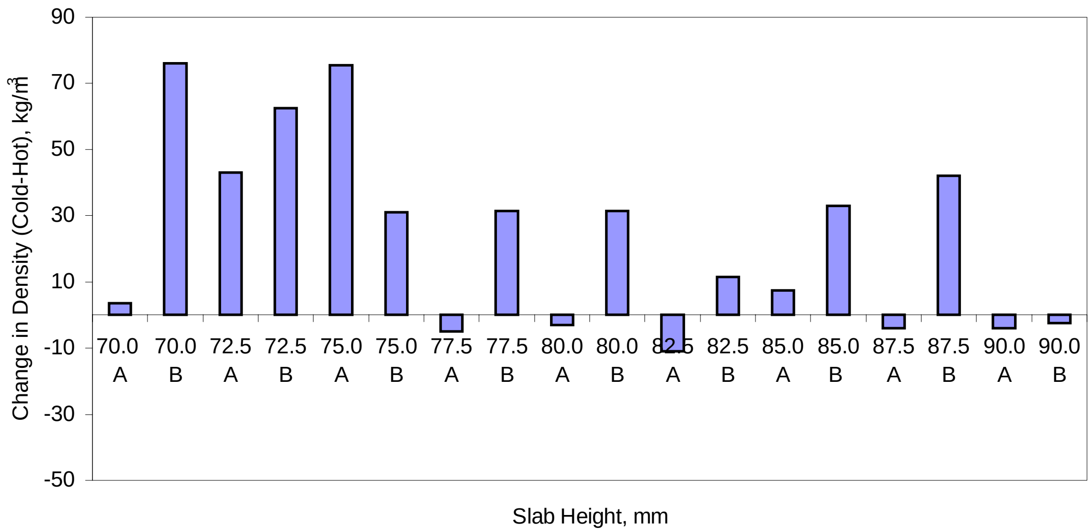


Figure 5 – Change in PQI-300 density reading resulting from a change in temperature from approximately 50 ºC to room temperature for the limestone aggregate with the 12.5-mm NMAS gradation.

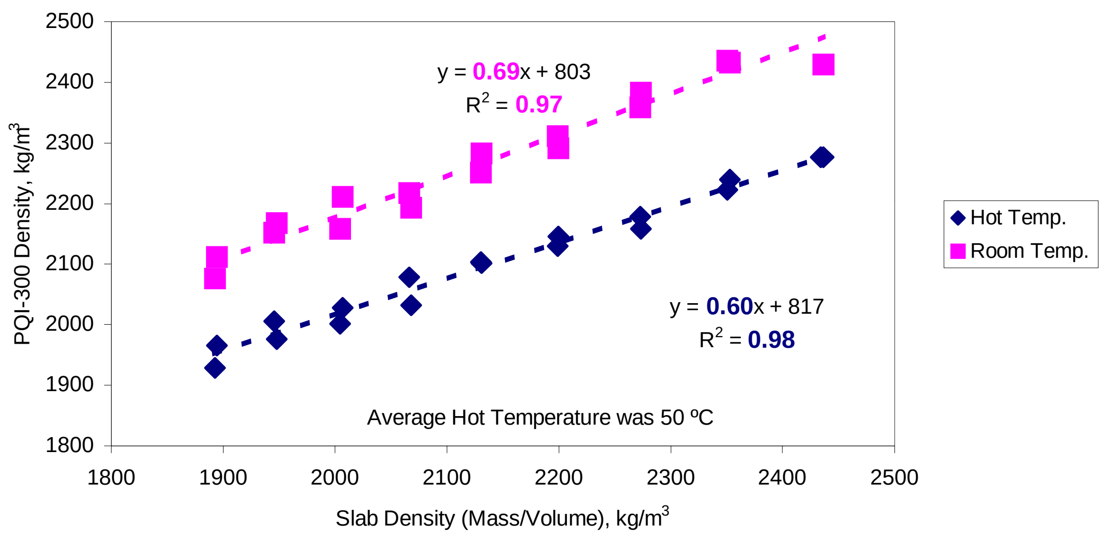


Figure 6 – Effect of changes in temperature on the relation between PQI-300 density readings and the density of slabs for the limestone aggregates with the 12.5-mm NMAS gradation (vertical scale has been separated for clarity).

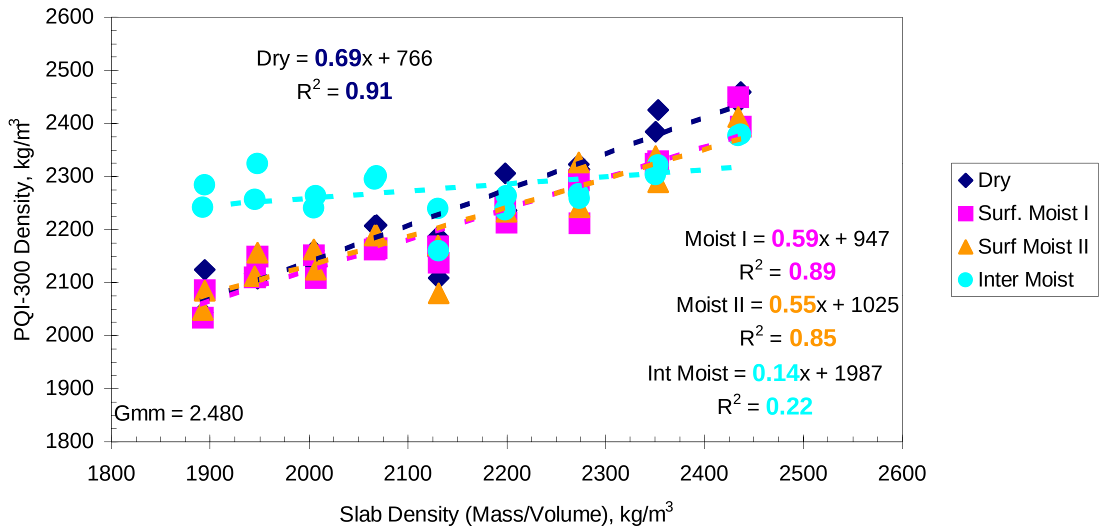


Figure 7 – Comparison of PQI-300 density readings after different levels of moisture for the limestone aggregate with the 12.5-mm NMAS gradation.

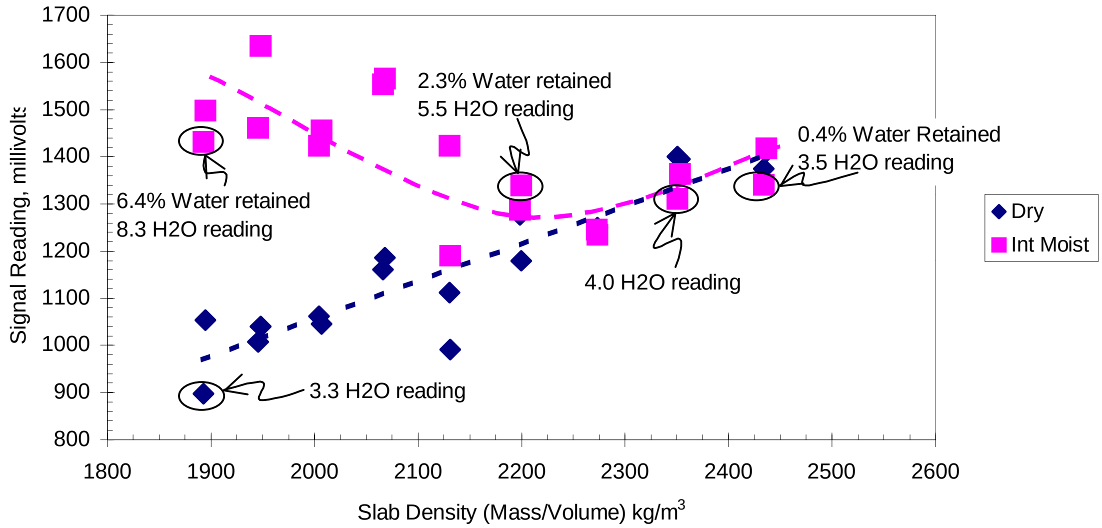


Figure 8 – Effect of internal moisture on the electrical signal reading of the PQI-300 for slabs of different densities prepared using the limestone with the 12.5-mm NMAS gradation.

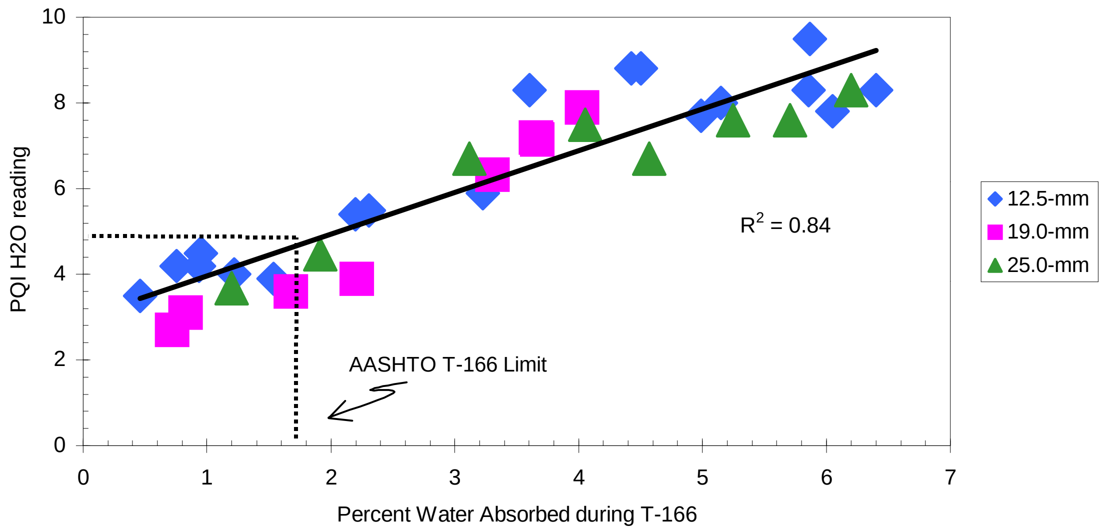


Figure 9 – Relation between the PQI-300 H2O number and the percent of water absorbed during AASHTO T-166 for the slabs prepared with limestone aggregates of different maximum nominal size.

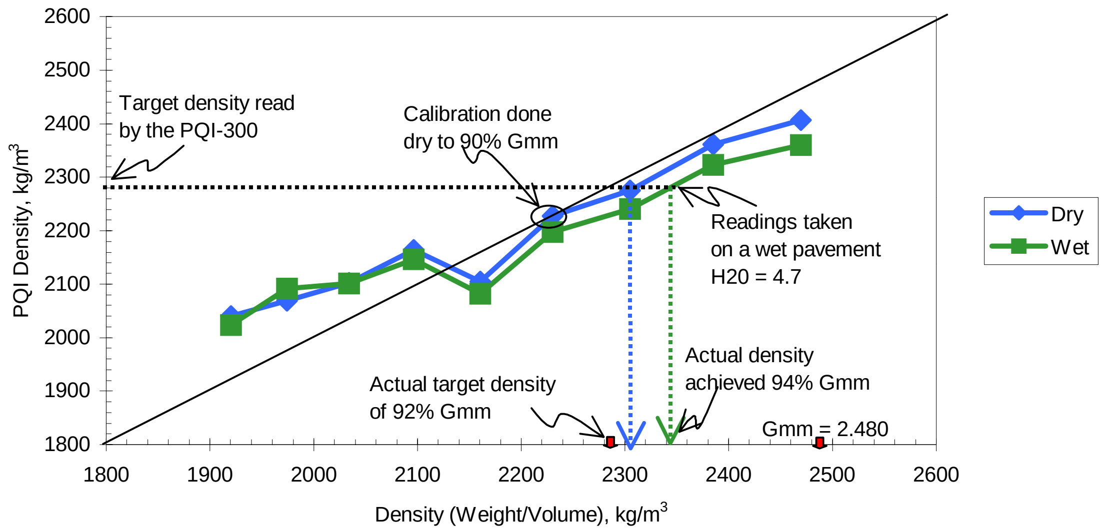


Figure 10 – Possible example of PQI-300 use.

Appendix A

Summary of Results

Table A1 – Density of Slabs Compacted using Limestone with the 12.5-mm Nominal Maximum Aggregate Size Gradation and having a Maximum Density of 2 480 kg/m^3.

Sample Height (mm)	Dry mass (g)	Mass/Volume(1) (kg/m^3)	T-166(2) (kg/m^3)	Wat Abs(3) %	Corelock(4) (kg/m^3)
70.0 A	14 190	2 436	2 426	0.75	2 413*
70.0 B	14 176	2 434	2 429	0.46	2 385*
72.5 A	14 193	2 353	2 371	0.95	2 345*
72.5 B	14 180	2 351	2 365	0.93	2 336*
75.0 A	14 187	2 274	2 312	1.22	2 268*
75.0 B	14 182	2 273	2 316	1.54	2 269
77.5 A	14 184	2 200	2 273	2.31	2 204*
77.5 B	14 177	2 199	2 274	2.20	2 202
80.0 A	14 179	2 130	2 252	3.60	2 150
80.0 B	14 183	2 131	2 255	3.23	2 153
82.5 A	14 183	2 066	2 242	4.43	2 099*
82.5 B	14 194	2 068	2 236	4.51	2 136
85.0 A	14 175	2 004	2 232	5.15	2 039
85.0 B	14 192	2 007	2 235	4.99	2 053*
87.5 A	14 161	1 945	2 218	5.86	1 992
87.5 B	14 181	1 948	2 220	5.87	1 989
90.0 A	14 185	1 894	2 234	6.05	1 959*
90.0 B	14 172	1 893	2 229	6.40	1 958*

* Indicates cases where at least in one of the tests the vacuum was lost, which might affect the results.

Notes:
(1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the bulk specific gravity of the slab measured according to AASHTO T-166.
(3) Water absorbed during AASHTO T-166 procedure.
(4) Density obtained from the bulk specific gravity of the slab vacuum-sealed in a plastic bag using the CoreLock device.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A2 – PQI-300 Density Readings Obtained under Dry Conditions for Slabs Compacted Using the Limestone with 12.5-mm Nominal Maximum Aggregate Size Gradation

Sample Height (mm)	Density (m/v)[(1)] (kg/m^3)	PQI-300 Density[(2)] (kg/m^3)	Signal Strength (mV)	Phase Angle (H2O Value)	Change In Density[(3)] Cold-Hot (kg/m^3)
70.0 A	2 436	2 299	1 388	3.5	+3.5
70.0 B	2 434	2 355	1 405	3.1	+76.0
72.5 A	2 353	2 268	1 342	3.4	+43.0
72.5 B	2 351	2 299	1 373	3.4	+62.5
75.0 A	2 274	2 191	1 278	3.7	+75.5
75.0 B	2 273	2 185	1 267	3.7	+31.0
77.5 A	2 200	2 170	1 234	3.6	-5.0
77.5 B	2 199	2 174	1 239	3.5	+31.5
80.0 A	2 130	2 143	1 176	3.3	-3.0
80.0 B	2 131	2 161	1 193	3.2	+31.5
82.5 A	2 066	2 100	1 166	3.9	-11.0
82.5 B	2 068	2 075	1 124	3.7	+11.5
85.0 A	2 004	2 052	1 075	3.6	+7.5
85.0 B	2 007	2 043	1 082	3.9	+33.0
87.5 A	1 945	2 046	1 062	3.4	-4.0
87.5 B	1 948	2 037	1 072	3.9	+42.0
90.0 A	1 894	2 016	1 035	3.8	-4.0
90.0 B	1 893	1 994	991	3.6	-2.5

Notes: (1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the average of six measurements, three on top and three on the bottom of the slabs at room temperature.
(3) Densities obtained from the average of five measurements, all on the top. Average hot temperature was 51 ºC.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A3 – PQI-300 Density Readings Obtained under Different Levels of Moisture for the for Slabs Compacted using the Limestone with the 12.5-mm Nominal Maximum Aggregate Size Gradation

Sample Height (mm)	Dry (1) (kg/m³)	PQI H2O(2)	Surface Moisture I(3) (kg/m³)	PQI H2O	Surface Moisture II(4) (kg/m³)	PQI H2O	Internal Moisture(5) (kg/m³)	PQI H2O
70.0 A	2 459	3.3	2 394	3.8	2 395	4.6	2 379	4.2
70.0 B	2 440	3.1	2 450	3.1	2 412	3.5	2 377	3.5
72.5 A	2 425	3.5	2 329	4.2	2 395	4.8	2 321	4.5
72.5 B	2 384	3.8	2 324	4.3	2 338	4.9	2 303	4.2
75.0 A	2 313	3.3	2 212	4.3	2 242	4.7	2 259	4.0
75.0 B	2 323	3.1	2 293	3.4	2 326	3.6	2 267	3.9
77.5 A	2 236	3.5	2 213	3.7	2 234	4.1	2 264	5.5
77.5 B	2 306	3.7	2 247	4.0	2 248	4.6	2 237	5.4
80.0 A	2 187	3.6	2 169	4.1	2 170	4.8	2 240	8.3
80.0 B	2 109	3.5	2 137	3.7	2 080	4.6	2 160	5.9
82.5 A	2 207	4.0	2 162	4.4	2 189	4.6	2 295	8.8
82.5 B	2 208	4.2	2 165	4.5	2 190	4.6	2 301	8.8
85.0 A	2 160	3.4	2 152	3.7	2 163	3.8	2 241	8.0
85.0 B	2 129	3.8	2 108	3.7	2 125	3.8	2 264	7.7
87.5 A	2 117	3.6	2 110	3.7	2 112	3.9	2 256	8.3
87.5 B	2 107	4.6	2 150	4.0	2 157	4.1	2 324	9.5
90.0 A	2 124	4.3	2 085	4.2	2 085	4.2	2 284	7.8
90.0 B	2 043	3.8	2 033	4.1	2 048	4.1	2 242	8.3

Notes: (1) Density obtained from the average of three PQI measurements on top of the specimen.
(2) Phase angle, labeled as H2O value.
(3) Density obtained from the average of three PQI measurements on top of the specimen after approximately 6 g of water had been sprayed on the surface.
(4) Density obtained from the average of three PQI measurements on top of the specimen after approximately 12 g of water had been sprayed on the surface.
(5) Density obtained from the average of three PQI measurements on top of the specimen after the specimen had been submerged underwater for specific gravity measurements (AASHTO T-166).

To convert from kg/m³ to lbs/ft³ multiply by 0.0624.

Table A4 – Density of Slabs Compacted using Limestone with the 19.0-mm Nominal Maximum Aggregate Size Gradation and having a Maximum Density of 2 512 kg/m^3

Sample Height (mm)	Dry mass (g)	Mass/Volume[(1)] (kg/m^3)	T-166[(2)] (kg/m^3)	Wat Abs[(3)] %	Corelock[(4)] (kg/m^3)
69.0	14 303	2 491	2 444	0.72	2 424
71.0	14 319	2 424	2 414	0.83	2 392
74.0	14 315	2 325	2 354	1.68	2 318*
76.0	14 318	2 264	2 322	2.21	2 262
79.0	14 302	2 176	2 282	3.65	2 184
81.0	14 308	2 123	2 279	4.03	2 154
84.0	14 309	2 047	2 294	3.30	2 093
86.0	14 306	1 999	2 285	3.66	2 059*

* Indicates cases where at least in one of the tests the vacuum was lost, which might affect the results.

Notes:
(1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the bulk specific gravity of the slab measured according to AASHTO T-166.
(3) Water absorbed during AASHTO T-166 procedure.
(4) Density obtained from the bulk specific gravity of the slab vacuum-sealed in a plastic bag using the CoreLock device.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A5 – PQI-300 Density Readings Obtained under Dry Conditions for Slabs Compacted Using the Limestone with 19.0-mm Nominal Maximum Aggregate Size Gradation.

Sample Height (mm)	Density (m/v)(1) (kg/m^3)	PQI-300 Density(2) (kg/m^3)	Signal Strength (mV)	Phase Angle (H2O Value)	Change In Density(3) Cold-Hot (kg/m^3)
69.0	2 491	2 462	1 499	2.3	
71.0	2 424	2 387	1 468	2.5	
74.0	2 325	2 350	1 422	2.4	
76.0	2 264	2 292	1 378	2.4	N/A
79.0	2 176	2 200	1 317	2.5	
81.0	2 123	2 120	1 272	2.6	
84.0	2 047	2 048	1 221	2.8	
86.0	1 999	1 991	1 158	2.8	

Notes: (1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the average of six measurements, three on top and three on the bottom of the slabs at room temperature.
(3) Densities obtained from the average of five measurements, all on the top.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A6 – PQI-300 Density Readings Obtained under Different Levels of Moisture from the for Slabs Prepared with the 19.0-mm Nominal Maximum Aggregate Size Gradation

Sample Height (mm)	Dry (1) (kg/m^3)	PQI H2O(2)	Surface Moisture I(3) (kg/m^3)	PQI H2O	Surface Moisture II(4) (kg/m^3)	PQI H2O	Internal Moisture(5) (kg/m^3)	PQI H2O
69.0	2 860	2.3	2 535	2.6	2 663	2.6	2 573	2.7
71.0	2 757	2.5	2 481	3.0	2 474	3.1	2 583	3.1
74.0	2 554	2.3	2 501	2.6	2 463	3.0	2 460	3.6
76.0	2 516	2.4	2 442	2.6	2 323	3.2	2 367	3.9
79.0	2 340	2.5	2 284	2.8	2 302	2.9	2 284	7.2
81.0	2 271	2.5	2 236	2.8	2 259	3.0	2 282	7.9
84.0	2 365	2.7	2 321	2.7	2 295	3.0	2 374	10.0
86.0	2 313	2.7	2 280	2.8	2 285	3.0	2 364	9.8

Notes: (1) Density obtained from the average of three PQI measurements on top of the specimen.

(2) Phase angle, labeled as H2O value.

(3) Density obtained from the average of three PQI measurements on top of the specimen after approximately 6 g of water had been sprayed on the surface.

(4) Density obtained from the average of three PQI measurements on top of the specimen after approximately 12 g of water had been sprayed on the surface.

(5) Density obtained from the average of three PQI measurements on top of the specimen after the specimen had been submerged underwater for specific gravity measurements (AASHTO T-166).

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A7 – Density of Slabs Compacted using Limestone with the 25.0-mm Nominal Maximum Aggregate Size Gradation and having a maximum density of 2 529 kg/m^3

Sample Height (mm)	Dry mass (g)	Mass/Volume(1) (kg/m^3)	T-166(2) (kg/m^3)	Wat Abs(3) %	Corelock(4) (kg/m^3)
74.0	14 340	2 329	2 386	1.20	2 235
76.0	14 355	2 270	2 347	1.91	2 282*
79.0	14 348	2 183	2 317	3.12	2 206
81.0	14 332	2 127	2 304	4.05	2 211*
84.0	14 364	2 055	2 305	4.57	2 103
86.0	14 350	2 006	2 296	5.25	2 058
89.0	14 348	1 938	2 293	5.71	1 994*
91.0	14 342	1 894	2 285	6.20	1 946*

* Indicates cases where at least in one of the tests the vacuum was lost, which might affect the results.

Notes: (1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the bulk specific gravity of the slab measured according to AASHTO T-166.
(3) Water absorbed during AASHTO T-166 procedure.
(4) Density obtained from the bulk specific gravity of the slab vacuum-sealed in a plastic bag using the CoreLock device.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A8 – PQI-300 Density Readings Obtained under Dry Conditions for Slabs Compacted Using the Limestone with 25.0-mm Nominal Maximum Aggregate Size.

Sample Height (mm)	Density (m/v)(1) (kg/m^3)	PQI-300 Density(2) (kg/m^3)	Signal Strength (mV)	Phase Angle (H2O Value)	Change In Density(3) Cold-Hot (kg/m^3)
74.0	2 329	2 386	1 398	2.3	-67.5
76.0	2 270	2 221	1 330	2.8	-17.0
79.0	2 183	2 157	1 241	2.6	+78.0
81.0	2 127	2 097	1 188	2.6	-34.0
84.0	2 055	2 031	1 156	3.1	-38.0
86.0	2 006	2 024	1 120	2.8	-5.5
89.0	1 938	1 928	1 015	3.0	0.0
91.0	1 894	1 957	1 054	3.0	+11.5

Notes: (1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the average of six measurements, three on top and three on the bottom of the slabs at room temperature.
(3) Densities obtained from the average of five measurements, all on the top. Average hot temperature was 46 ºC.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A9 – PQI-300 Density Readings Obtained under Different Levels of Moisture for the for Slabs Compacted using the Limestone with the 25.0-mm Nominal Maximum Aggregate Size Gradation

Sample Height (mm)	Dry [(1)] (kg/m^3)	PQI H2O[(2)]	Surface Moisture I[(3)] (kg/m^3)	PQI H2O	Surface Moisture II[(4)] (kg/m^3)	PQI H2O	Internal Moisture[(5)] (kg/m^3)	PQI H2O
74.0	2 652	2.3	2 357	2.9	2 349	3.4	2 428	3.7
76.0	2 480	2.6	2 324	2.9	2 285	3.4	2 342	4.5
79.0	2 430	2.5	2 288	3.6	2 303	4.1	2 269	6.7
81.0	2 342	2.6	2 175	3.2	2 178	3.5	2 229	7.5
84.0	2 264	3.0	2 224	3.0	2 229	3.4	2 281	6.7
86.0	2 239	2.8	2 220	3.1	2 203	3.4	2 295	7.6
89.0	2 158	2.9	2 168	3.3	2 165	3.4	2 297	7.6
91.0	2 203	2.9	2 133	3.5	2 113	3.7	2 325	8.3

Notes:
(1) Density obtained from the average of three PQI measurements on top of the specimen.
(2) Phase angle, labeled as H2O value.
(3) Density obtained from the average of three PQI measurements on top of the specimen after approximately 6 g of water had been sprayed on the surface.
(4) Density obtained from the average of three PQI measurements on top of the specimen after approximately 12 g of water had been sprayed on the surface.
(5) Density obtained from the average of three PQI measurements on top of the specimen after the specimen had been submerged underwater for specific gravity measurements (AASHTO T-166).

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A10 – Density of Slabs Compacted using Gravel with the 12.5-mm Nominal Maximum Aggregate Size Gradation and having a maximum density of 2 430 kg/m^3

Sample Height (mm)	Dry mass (g)	Mass/Volume(1) (kg/m^3)	T-166(2) (kg/m^3)	Wat Abs(3) %	Corelock(4) (kg/m^3)
69.0	13 543	2 360	2 352	0.38	2 333*
71.0	13 560	2 296	2 314	0.43	2 289
74.0	13 560	2 202	2 247	0.77	2 214
76.0	13 551	2 143	2 211	1.14	2 160
79.0	13 574	2 065	2 190	2.03	2 085*
81.0	13 569	2 013	2 156	2.79	2 049*
84.0	13 582	1 943	2 140	3.45	1 982
86.0	13 581	1 898	2 133	3.78	1 925

* Indicates cases where at least in one of the tests the vacuum was lost, which might affect the results.

Notes:
(1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the bulk specific gravity of the slab measured according to AASHTO T-166.
(3) Water absorbed during AASHTO T-166 procedure.
(4) Density obtained from the bulk specific gravity of the slab vacuum-sealed in a plastic bag using the CoreLock device.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A11 – PQI-300 Density Readings Obtained under Dry Conditions for Slabs Compacted Using the Gravel with 12.5-mm Nominal Maximum Aggregate Size.

Sample Height (mm)	Density (m/v)(1) (kg/m^3)	PQI-300 Density(2) (kg/m^3)	Signal Strength (mV)	Phase Angle (H2O Value)	Change In Density(3) Cold-Hot (kg/m^3)
69.0	2 360	2 213	1 131	3.4	+0.5
71.0	2 296	2 191	1 109	3.5	+10.0
74.0	2 202	2 145	1 057	3.8	-6.5
76.0	2 143	2 122	1 027	3.9	+25.0
79.0	2 065	2 089	992	4.4	+22.0
81.0	2 013	2 077	977	4.4	+20.5
84.0	1 943	2 057	957	5.4	+9.5
86.0	1 898	2 028	910	5.1	+23.0

Notes: (1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).

(2) Density obtained from the average of six measurements, three on top and three on the bottom of the slabs at room temperature.

(4) Densities obtained from the average of five measurements, all on the top. Average hot temperature was 46 ºC.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A12 – PQI-300 Density Readings Obtained under Different Levels of Moisture for the for Slabs Compacted using the Gravel with the 12.5-mm Nominal Maximum Aggregate Size Gradation

Sample Height (mm)	Dry (1) (kg/m³)	PQI H2O(2)	Surface Moisture I(3) (kg/m³)	PQI H2O	Surface Moisture II(4) (kg/m³)	PQI H2O	Internal Moisture(5) (kg/m³)	PQI H2O
69.0	2 248	3.0	2 216	3.6	2 130	7.1	2 189	4.9
71.0	2 212	3.4	2 208	3.8	2 198	4.2	2 191	5.0
74.0	2 153	3.6	2 158	3.8	2 156	4.3	2 141	6.5
76.0	2 129	3.7	2 136	4.0	2 137	4.1	2 138	6.4
79.0	2 117	3.6	2 116	4.3	2 098	5.7	2 157	10.2
81.0	2 089	3.8	2 092	4.0	2 095	4.2	2 233	12.7
84.0	2 072	5.0	2 069	4.2	2 077	4.2	2 254	11.6
86.0	2 029	4.2	2 033	4.5	2 037	4.5	2 263	13.3

Notes: (1) Density obtained from the average of three PQI measurements on top of the specimen.
(6) Phase angle, labeled as H2O value.
(7) Density obtained from the average of three PQI measurements on top of the specimen after approximately 6 g of water had been sprayed on the surface.
(8) Density obtained from the average of three PQI measurements on top of the specimen after approximately 12 g of water had been sprayed on the surface.
(9) Density obtained from the average of three PQI measurements on top of the specimen after the specimen had been submerged underwater for specific gravity measurements (AASHTO T-166).

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A13 – Density of Slabs Compacted using Granite with the 12.5-mm Nominal Maximum Aggregate Size Gradation and having a maximum density of 2 478 kg/m^3

Sample Height (mm)	Dry mass (g)	Mass/Volume(1) (kg/m^3)	T-166(2) (kg/m^3)	Wat Abs(3) %	Corelock(4) (kg/m^3)
74.0	13 974	2 270	2 276	0.99	2 234
76.0	13 981	2 211	2 248	1.44	2 194
79.0	13 956	2 123	2 210	2.41	2 128
81.0	13 965	2 072	2 167	3.08	2 053*
84.0	13 951	1 996	2 141	3.86	2 012*
86.0	13 955	1 950	2 127	4.35	1 980*
89.0	13 928	1 881	2 099	5.11	1 922*
91.0	13 921	1 839	2 072	5.74	1 873*

* Indicates cases where at least in one of the tests the vacuum was lost, which might affect the results.

Notes:
(1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the bulk specific gravity of the slab measured according to AASHTO T-166.
(3) Water absorbed during AASHTO T-166 procedure.
(4) Density obtained from the bulk specific gravity of the slab vacuum-sealed in a plastic bag using the CoreLock device.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A14 – PQI-300 Density Readings Obtained under Dry Conditions for Slabs Compacted Using the Granite with 12.5-mm Nominal Maximum Aggregate Size.

Sample Height (mm)	Density (m/v)(1) (kg/m^3)	PQI-300 Density(2) (kg/m^3)	Signal Strength (mV)	Phase Angle (H2O Value)	Change In Density(3) Cold-Hot (kg/m^3)
74.0	2 270	2 116	976	3.4	+36.5
76.0	2 211	2 080	951	4.1	+15.0
79.0	2 123	2 074	922	3.7	+34.5
81.0	2 072	2 046	882	3.9	+62.5
84.0	1 996	2 017	853	4.6	+29.5
86.0	1 950	2 022	844	3.5	+42.0
89.0	1 881	2 006	820	4.2	+19.5
91.0	1 839	1 982	777	4.4	+26.0

Notes: (1) Density obtained by dividing the mass over the volume (volume = 260 mm x 320 mm x sample height).
(2) Density obtained from the average of six measurements, three on top and three on the bottom of the slabs at room temperature.
(5) Densities obtained from the average of five measurements, all on the top. Average hot temperature was 46 ºC.

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.

Table A15 – PQI-300 Density Readings Obtained under Different Levels of Moisture for the for Slabs Compacted using the Granite with the 12.5-mm Nominal Maximum Aggregate Size Gradation

Sample Height (mm)	Dry (1) (kg/m^3)	PQI H2O(2)	Surface Moisture I(3) (kg/m^3)	PQI H2O	Surface Moisture II(4) (kg/m^3)	PQI H2O	Internal Moisture(5) (kg/m^3)	PQI H2O
74.0	2 115	3.4	2 046	4.9	2 049	5.5	2 094	7.7
76.0	2 079	4.0	2 080	4.9	2 082	5.5	2 100	7.0
79.0	2 093	3.5	2 078	5.3	2 072	6.6	2 154	12.2
81.0	2 055	3.8	2 048	5.8	2 053	6.1	2 225	14.4
84.0	2 022	4.5	2 039	6.4	2 050	6.6	2 256	15.8
86.0	2 030	2.8	2 041	6.2	2 049	6.3	2 274	14.8
89.0	2 013	4.1	2 023	6.1	2 031	6.2	2 249	15.1
91.0	1 980	4.2	1 987	6.3	1 995	6.3	2 251	14.4

Notes: (1) Density obtained from the average of three PQI measurements on top of the specimen.
(10) Phase angle, labeled as H2O value.
(11) Density obtained from the average of three PQI measurements on top of the specimen after approximately 6 g of water had been sprayed on the surface.
(12) Density obtained from the average of three PQI measurements on top of the specimen after approximately 12 g of water had been sprayed on the surface.
(13) Density obtained from the average of three PQI measurements on top of the specimen after the specimen had been submerged underwater for specific gravity measurements (AASHTO T-166).

To convert from kg/m^3 to lbs/ft^3 multiply by 0.0624.