CONSTRUCTION INDUSTRY COUNCIL
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QUALITY CONTROL AND QUALITY ASSURANCE OF ASPHALT PAVEMENT CONSTRUCTION USING INNOVATIVE NONDESTRUCTIVE METHODS

RESEARCH SUMMARY

Construction Industry Council
Quality Control and Quality Assurance of Asphalt Pavement Construction Using Innovative Nondestructive Methods
Research Summary

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FOREWORD

Although non-destructive pavement evaluation tools have been developed for years, the quality assurance is still doubtful and so it has yet common in Hong Kong. Before prompting this innovative tools, it is necessary to carry out a study on their overall performance. Hence, the Construction Industry Council (CIC) initiated the research by engaging a research team from The Hong Kong Polytechnic University to evaluate the feasibility of nondestructive methods and recommend the appropriate methods for asphalt pavement construction in Hong Kong.

The research team investigated the performance of three non-destructive tools. Laboratory tests and field evaluations have been conducted. Various factors which may affect the detection accuracy are studied. Measures have been suggested to improve the detection accuracy, and they are validated in the study. Based on the research findings, description on these non-destructive methods accuracy and reliability as well as limitations are summarised.

The research work presented in this report was funded by the CIC Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

The research work described in the report was carried out by a research team led by Dr. Zhen LENG from The Hong Kong Polytechnic University. The project cannot succeed without the dedicated effort of the research team. I would like to thank to all who took part in this valuable work.

Ir Albert CHENG
Executive Director of Construction Industry Council

PREFACE

In-situ asphalt mixture density is a critically important quality control (QC) and quality assurance (QA) index for flexible pavement construction, because density that is either too high or too low may cause early pavement failures. In current practice in Hong Kong, the QC/QA of in-situ asphalt mixture density is based on the coring method, i.e., cores are first extracted from the pavement, and then their densities are measured in the laboratory. Although this method provides accurate density measurement, it is a time-consuming method causing damages to the newly-built pavements. In addition, it can only provide discrete data at limited sampling locations, introducing risks in the QC/QA decisions.

Recent technology advancement has led to the development and applications of new nondestructive tools, such as electromagnetic (EM) density gauges, ground-penetrating radar (GPR) and infrared camera, for in-situ density or compaction uniformity measurement of asphalt pavement. These tools have shown various advantages, such as no damage to pavement, and fast and continuous data collection. However, the destructive coring method was still the dominant method for in-situ asphalt mixture density measurement in Hong Kong, while these innovative tools had been seldom studied and applied locally.

The main objectives of this study are to evaluate the feasibility and effectiveness of three non-destructive tools, namely EM density gauge, GPR, and infrared camera, as QC/QA tools for asphalt pavement construction, and recommend the most appropriate nondestructive method as well as the relevant testing protocol for in-situ asphalt mixture density measurement in Hong Kong. The investigator believes that the emerging non-destructive tools will ultimately replace or supplement the current destructive QC/QA method for asphalt pavement construction in Hong Kong, and significantly enhance the reliability and productivity of asphalt pavement construction QC/QA.

The investigator would like to express his sincere thanks to the CIC for support of this project.

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RESEARCH HIGHLIGHTS

This study aims to explore the feasibility of applying three nondestructive tools, namely Electromagnetic (EM) density gauges, ground penetrating radar (GPR), and infrared camera, as innovative quality control (QC) and quality assurance (QA) tools for asphalt pavement construction in Hong Kong. To achieve this objective, laboratory testing was first conducted to evaluate the effects of various factors on the performance of two common types of commercial EM density gauges, i.e., PQI 301 and PaveTracker 2701 B. Then, the on-site performance of three EM density gauges, including PQI 301, PQI 380, and PaveTracker 2701 B, and a 2-GHz air-coupled GPR system were investigated at four bituminous pavement construction sites. An FLIR T650sc infrared camera was also used at the construction sites to evaluate its performance in mapping the surface temperature of the asphalt pavements during construction.

The laboratory testing results indicated that the accuracy of the EM density gauges can be affected by various factors, including asphalt mixture gradation, asphalt content, and presence of paint and moisture, and appropriate calibration of the gauges is important to provide accurate density measurement. PQI 301 provides better testing repeatability than PaveTracker. The field testing results shows that: 1) temperature of asphalt mixture does not affect the density measurement using either GPR or EM density gauges; 2) GPR can be used for compaction monitoring during asphalt pavement construction and provide density and thickness profiles of asphalt mat with acceptable accuracy; and 3) infrared camera can be used for pavement surface temperature distribution monitoring and temperature segregation detection during asphalt pavement construction.

Overall, it is concluded that EM density gauges, GPR and infrared camera can all be used as effective quality control (QC) tools for asphalt pavement construction to improve the efficiency, accuracy and reliability of the current coring-based QC method. Corresponding guidelines on using these tools for QC purpose have been developed. However, these non-destructive tools are not considered accurate and reliable enough to be used as quality assurance (QA) tools yet. More field applications of these tools and development of user-friendly application software are recommended in the further study.

Remarks:
PQI: Pavement Quality Indicator

CONTENTS

1 INTRODUCTION

1.1 Background

In-situ asphalt mixture density is an important quality control (QC) and quality assurance (QA) index for flexible pavement construction, because density that is either too high or too low may cause early pavement failures.

Traditionally, two techniques have been widely used for asphalt pavement density measurement: laboratory testing on pavement cores and on-site testing using a nuclear density gauge. However, both methods have some limitations. Although the coring method provides accurate density measurement, it is a time-consuming method causing damages to the newly-built pavements. In addition, the coring method can only provide discrete data at limited sampling locations, introducing risks in the QC/QA decisions. On the other hand, the nuclear gauge method is a nondestructive method. However, it can only provide data at discrete locations. Furthermore, this method carries safety concerns because it uses radio-active material.

Very recently, new nondestructive tools, such as electromagnetic (EM) density gauges, ground-penetrating radar (GPR) and infrared camera, have entered the market as alternatives to the coring method and the nuclear density gauges. EM gauges, also known as nonnuclear gauges, use EM waves to measure in-place density of pavement materials (Figure 1). By avoiding the usage of radio-active material, these nonnuclear gauges have the advantages of completely bypassing the licenses, training, specialized storage, and safety risks associated with nuclear gauges (Romero & Kuhnow, 2002). However, some studies reported comparable or better performance of nonnuclear gauges compared to nuclear gauges (Sargand, Kim, & Farrington, 2005; Sebesta, Scullion, & Liu, 2005), while others reported the opposite (Rogge & Jackson, 1999).

(a) (b)

Figure 1 EM Density Gauge: (a) PaveTracker™ Model 2701-B Plus; (b) PQI™ Model 301

As Figure 2 illustrates, a GPR system is typically composed of an antenna (either air-coupled or ground-coupled), a data acquisition system, a distance measuring instrument (DMI), a survey vehicle or cart, and an optional GPS. As a density measurement tool, GPR has all the advantages of EM density gauges. Furthermore, it allows data collection at high speed (up to 100 km/h) and provides continuous density measurement. Some studies have shown that when used appropriately, the accuracy of GPR in predicting asphalt pavement density is comparable to, or better than, that of a nuclear density gauge (Leng, Al-Qadi, Shangguan & Son, 2012).

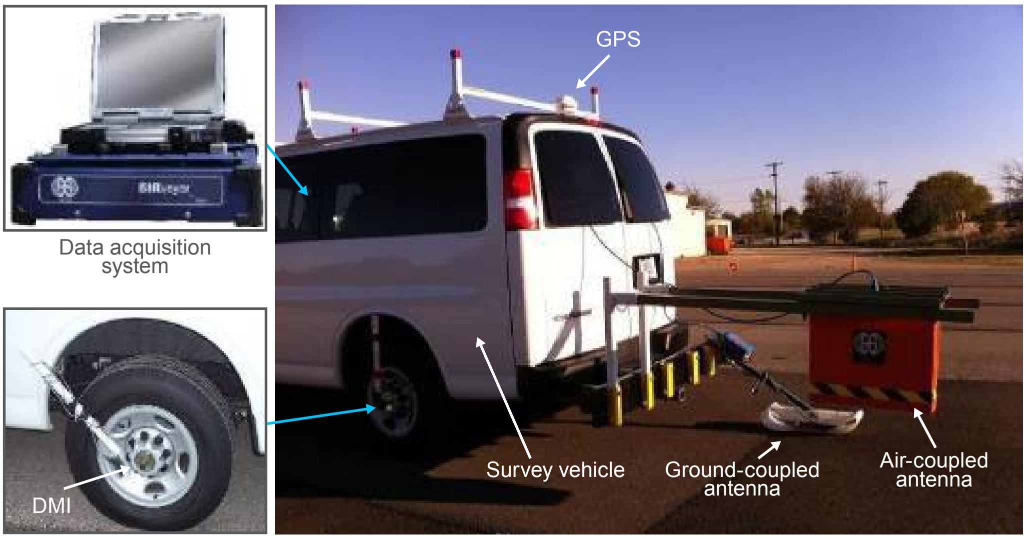


Figure 2 Ground Penetration Radar Measurement System

Temperature of asphalt mixture during construction is an important factor affecting its workability, thus its final density after compaction. In the current construction practice in Hong Kong, temperature measurement is carried out using thermal probes or infrared temperature guns. However, both these tools can only provide temperature data at discrete locations. To overcome such limitation, infrared cameras, which can provide temperature distribution data of asphalt mixture without physical contact, have been applied as a temperature measurement tool of asphalt mixture during construction. For example, Table 1 presents the imaging performance and the appearance of the FLIR® T650sc infrared camera used in this study for capturing the thermal images of asphalt pavements during construction.

Table 1 Imaging Performance and Appearance of FLIR® T650sc

Item	Value
Resolution	640×480 pixels
Thermal sensitivity	<20 mK at 30°C
Field of view (FOV) / Minimum focus distance	25°×19° / 0.25 m
Image frequency	30 Hz
Spectral range	7.5 to 13.0 μm

1.2 Aims and Objectives

The available research findings have shown the high potential of EM density gauge, GPR, and infrared camera as nondestructive QC/QA tools for asphalt pavement construction. However, the destructive coring method was still the dominant method for in-situ asphalt mixture density measurement in Hong Kong, while these innovative tools had been seldom studied and applied locally. Correspondingly, this study was conducted aiming to:

- Evaluate the feasibility and effectiveness of EM density gauge and GPR as a QC/QA tool for asphalt pavement construction in Hong Kong; and
- Recommend the most appropriate nondestructive method as well as the relevant testing protocol for in-situ asphalt mixture density measurement in Hong Kong.

2 RESEARCH METHODOLOGY

Figure 3 shows the research procedure of this study, which mainly includes the following four steps: literature review, testing (including laboratory evaluation and field testing), result analysis and summary.

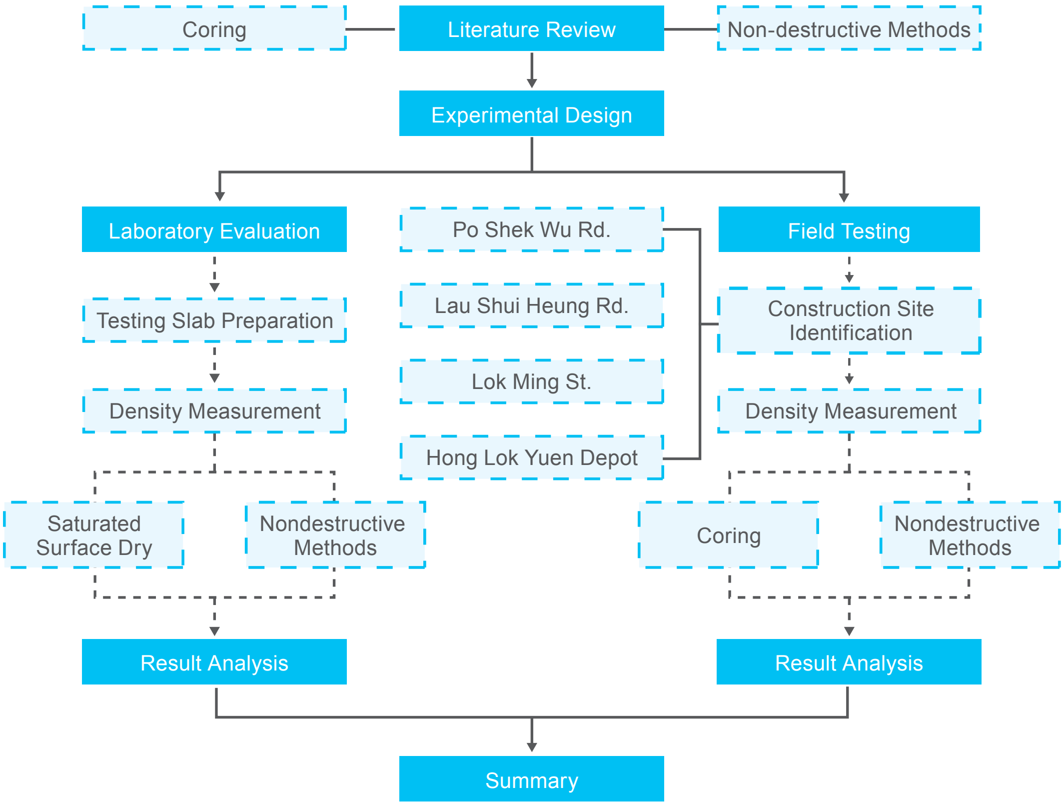


Figure 3 Research Flowchart

A comprehensive literature review was first conducted on the state-of-art and state-of-practice of nondestructive tools available for in-situ asphalt mixture density and temperature measurement. Specifically, the working mechanisms, advantages and disadvantages of each tool were reviewed and summarized.

To determine the effects of asphalt mixture compositions on the density gauge measurement accuracy, 36 hot mix asphalt (HMA) testing slabs with different compositions were prepared in laboratory. EM density gauge data were collected from these slabs using two common types of gauges, i.e., PQI 301 and PaveTracker™ Model 2701 B Plus (see Figure 1) and compared with their bulk densities measured by the standard saturated surface dry (SSD) method (see Figure 4). Table 2 shows the factors (including measurement direction, calibration method, asphalt mixture gradation, asphalt binder type, asphalt binder content and moisture condition) and their levels considered in this study.

(a) Mass in Air (b) Mass in Water (c) Surface Saturated-Dry Mass

Figure 4 Testing Slab Bulk Density Measurement

Table 2 Factors and Levels Table

Factors		Levels
Measurement Direction	1	Perpendicular to the compaction direction
	2	Parallel to the compaction direction
Calibration Method	1	Reference Only
	2	Reference and Offset
	3	Reference and Mix Calibration
Asphalt Mixture Gradation	1	Dense-graded
	2	Gap-graded
	3	Open-graded
Asphalt Binder Type	1	60/70
	2	PG 76
Asphalt Binder Content	1	4.2%-5.5%
	2	6-6.2%
	3	6.2%-8.2%
Moisture Condition	1	2.1
	2	4.1
	3	8.1

Following the laboratory testing, field data were collected from four construction sites, i.e., Po Shek Wu Road, Lau Shui Heung Road, Lok Ming Street and Hong Lok Yuen Depot of the Highways Department, which were identified by coordinating with the Highways Department. Gap-graded polymer modified stone mastic asphalt (PMSMA) were placed in the Po Shek Wu Road and the Hong Lok Yuen Depot as the surfacing material while dense-graded wearing course (WC) mixture were placed in the Lau Shui Heung Road and Lok Ming Street. The field testing mainly includes the following steps:

1) Mount the air-coupled GPR measurement system on a custom-designed PVC framework before conducting in-situ survey;

2) Collect the amplitude of the incident signal using a 1.0m by 1.2m steel plate because metal is a perfect reflector of GPR signals and will therefore reflect all GPR wave energy back to the receiving antenna;

3) Collect data using GPR and EM density gauges;

4) After data collection, cores were taken and sent to the public works laboratories for testing the SSD bulk densities and air void contents as a routine practice, which served as reference data to evaluate the performance of each non-destructive device.

GPR data were processed using Reflexw Software to obtain the amplitude profiles of the received signals. Then, the dielectric constant of the tested asphalt mixture was estimated from the amplitudes using the following equation:

$$\varepsilon_{AC} = \left[\frac{1 + \frac{A_o}{A_p}}{1 - \frac{A_o}{A_p}} \right]^2 \qquad (1)$$

where A_o is the amplitude of the surface reflection and A_p is the amplitude of the incident signal.

Equation 1 can also be written in another form to show the effect of the dielectric constant of asphalt pavement on the amplitude of surface reflection:

$$A_o = \left| \frac{1 - \sqrt{\varepsilon_{AC}}}{1 + \sqrt{\varepsilon_{AC}}} \right| A_p \qquad (2)$$

According to Equation 2, when the dielectric constant of the asphalt pavement, ε_{AC}, increases, the surface reflection amplitude A_o will also increase.

For each asphalt mixture, its density prediction model was built based on the laboratory measured bulk densities and the corresponding dielectric constant. Figure 5 presents the dielectric constant, predicted density data and the laboratory measured bulk density of three dense-graded wearing course core samples extracted from the construction sites at Lau Shui Heung Road, Kwan Tei, New Territories, as an example.

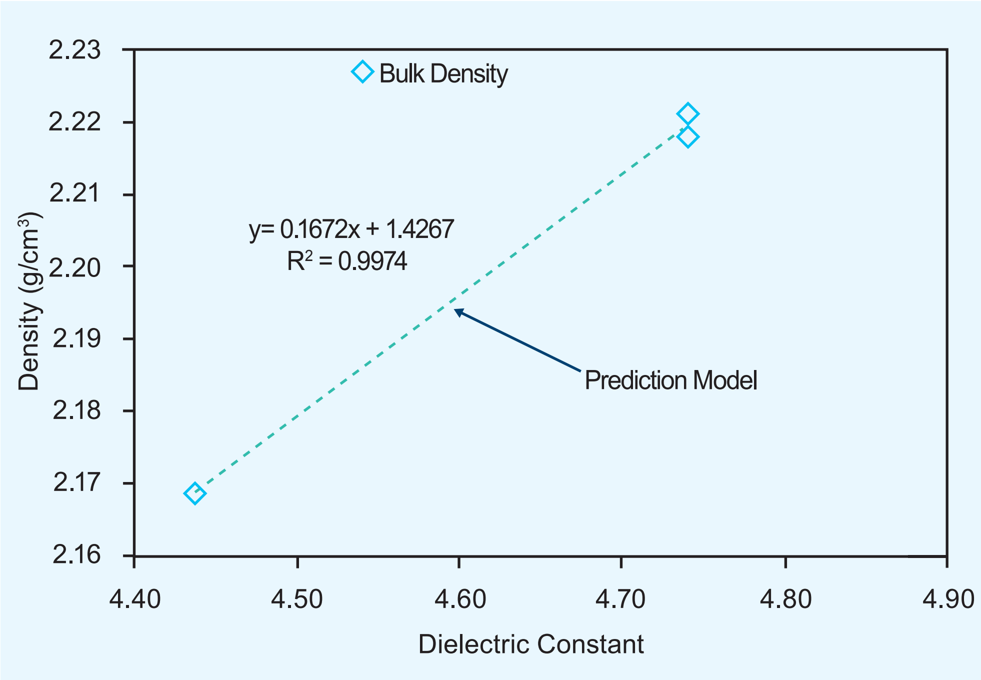


Figure 5 Density Prediction Model for Lau Shui Heung Rd.

To evaluate the feasibility and effectiveness of EM density gauge and GPR as a QC/QA tool for HMA density measurement. The test results of both laboratory and field tests were statistically analysed. Based on the analysed results the accuracy and variability of each device under different testing conditions was determined. In the analysis procedure, Analysis of Variance (ANOVA) and paired-t test were performed to evaluate the effect of the various factors. Based on the data analysis results, the factors which significantly affect the accuracy of density measurement were determined. The relationship between temperature and density were also studied.

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Laboratory Study Findings

The following sections summarise the findings on the effects of various factors on the HMA density measurement using EM density gauges from laboratory study.

Measurement Direction

To quantify the effect of measurement direction of density gauges, the density data of the 6 testing slabs with normal binder content were collected using PQI and PaveTracker at two perpendicular directions (Figure 6), i.e., parallel to the compaction direction and perpendicular to the compaction direction.

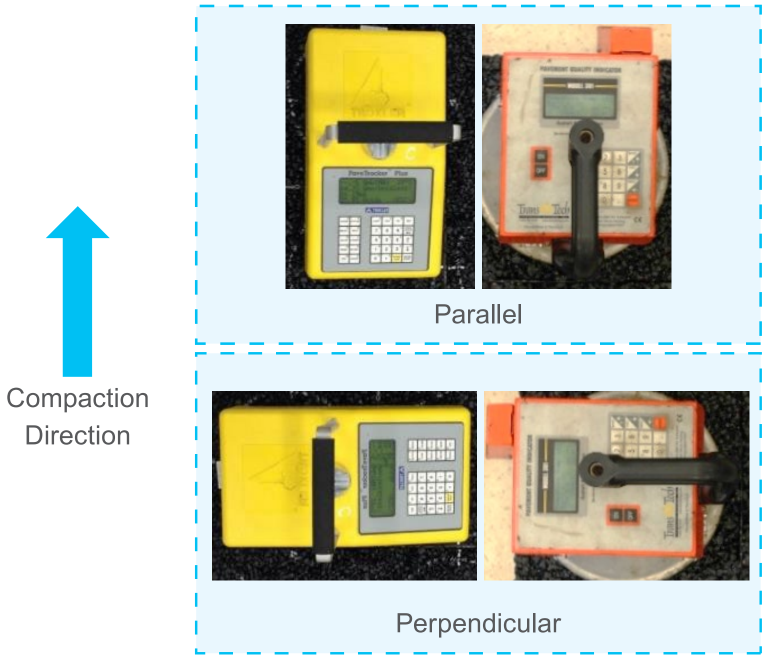
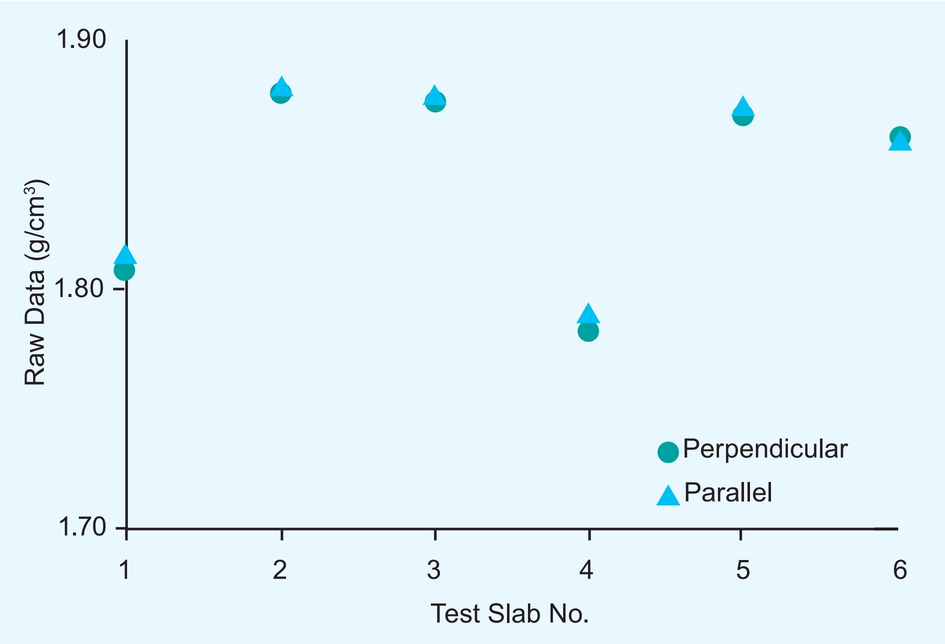
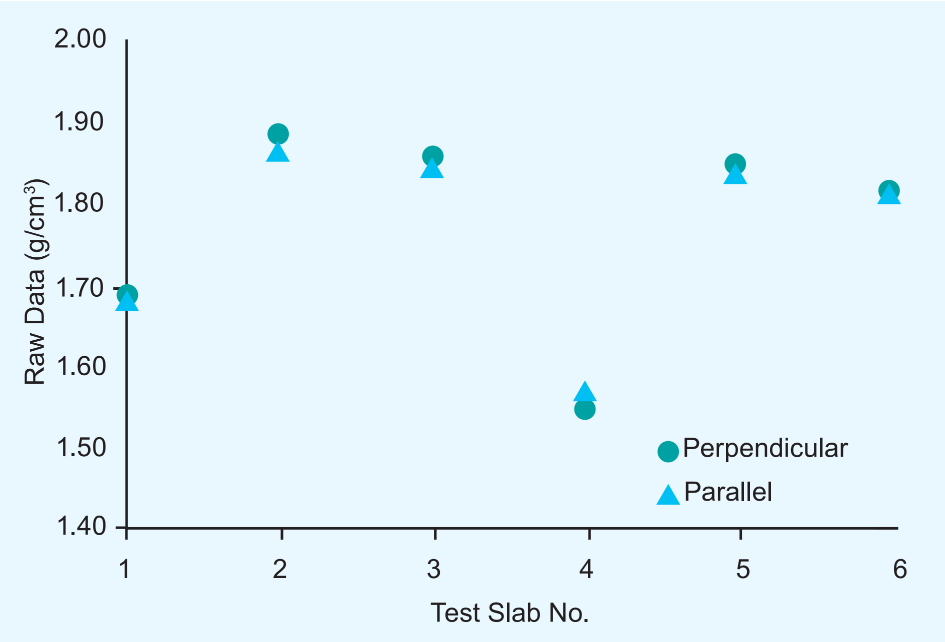


Figure 6 Measurement Directions

Figure 7(a) and 7(b) show the raw data collected at two directions by using PQI and PaveTracker, respectively. It can be seen that for both gauges, the measured densities at two directions were very close to each other. Student-t tests were further conducted to check the statistical difference in the measurement between the two directions. As expected, the test results showed that at 95% confidence level, the differences caused by variation of measurement direction are not statistically significant. Thus, it can be concluded that measurement direction does not significantly affect the measured results of both gauges.



(a) PQI collected raw data



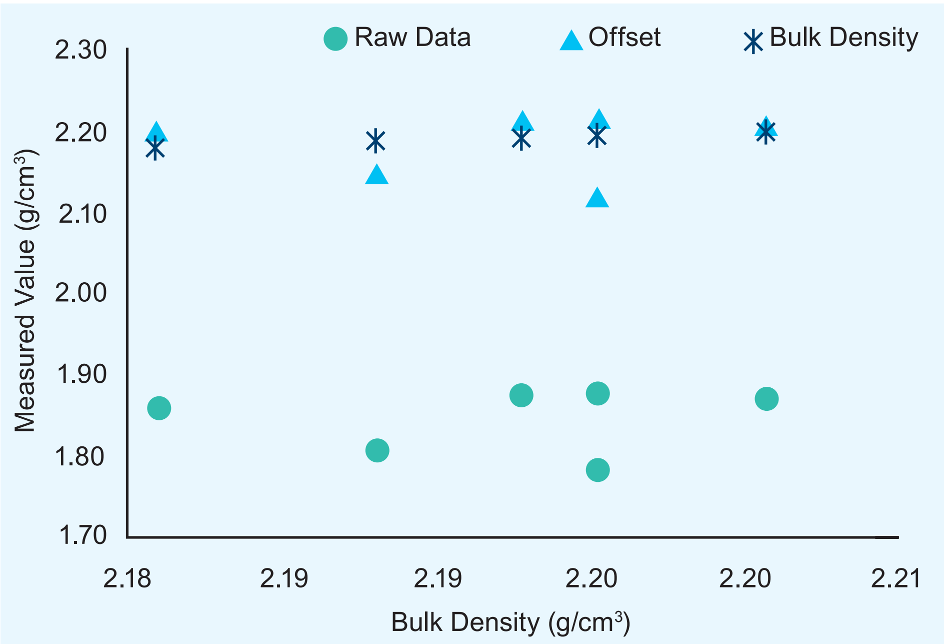
(b) PaveTracker collected raw data

Figure 7 Raw Data Collected at Two Directions

Calibration Method

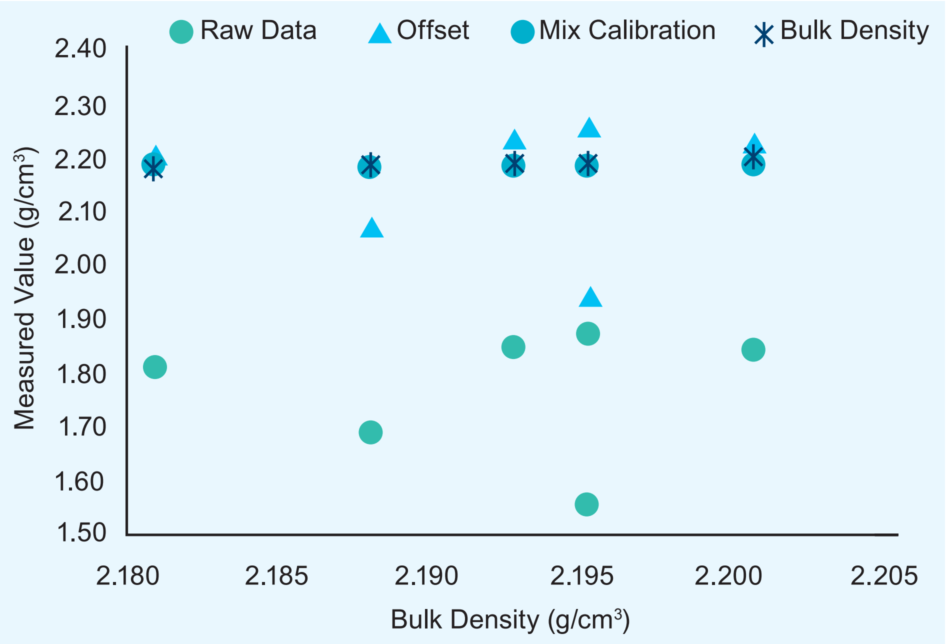
To identify the effects of calibration methods, the raw data of each measurement and their corresponding calibrated data were compared.

Figure 8 presents the raw gauge data, calibrated gauge data and the laboratory measured bulk density of 6 slabs prepared with SMA with normal binder content, as an example. The measurements from slabs prepared with other mixtures showed similar trend. The average error percentages, which were calculated by Equation 3, are presented in Figure 8c. Regardless of the gauge type, there are considerable differences between the raw data and the bulk density. After calibration, according to Figure 8a and 8b, the accuracies of the density measurement using both gauges were significantly increased. As Figure 8a shows, compared with the uncalibrated data, PQI measured raw data after offset calibration are closer to the bulk density. Similarly, offset is also a feasible method to increase the accuracy of PaveTracker. From Figure 8c, it can be found that although offset can effectively decrease the error percentages of both PQI and PaveTracker, the error percentages of PaveTracker are higher than those of PQI. It is worth noting that PaveTracker with mix calibration provides the most accurate results.

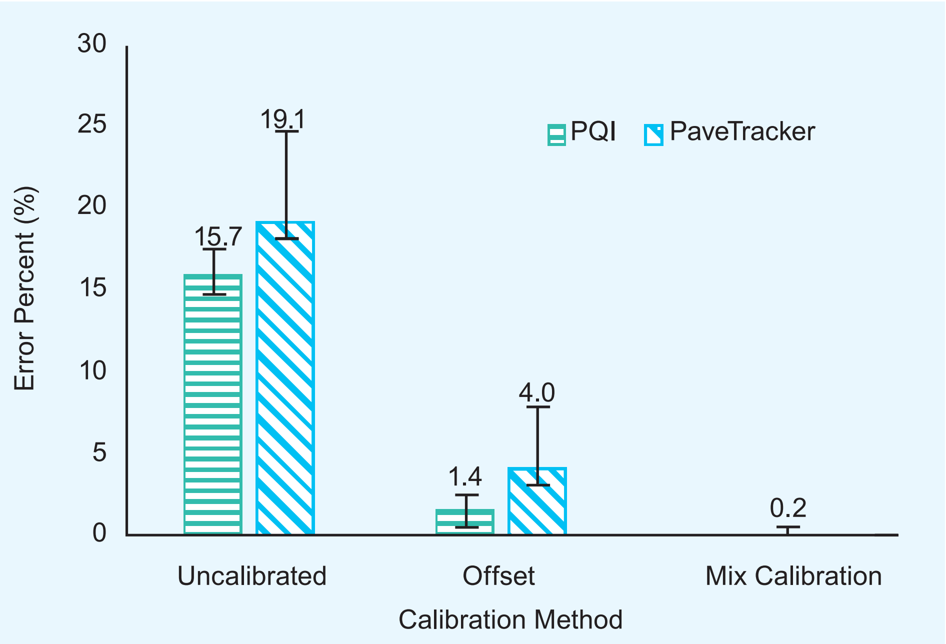


(a) Changes in the PQI measured data

Figure 8 Influence of Calibration Method on the Accuracy of EM Density Gauges



(b) Changes in the PaveTracker measured data



(c) Error Percent of Different Calibration Methods

Figure 8 Influence of Calibration Method on the Accuracy of EM Density Gauges

$$\text{Error Percent} = \frac{\textit{Measured Value - Laboratory Measured Bulk Density}}{\textit{Laboratory Measured Bulk Density}} \times 100\% \qquad (3)$$

To evaluate the effect of calibration method on density measurement using EM density gauges, Analysis of Variance (ANOVA) was performed on the raw data and calibrated data. As expected, significant differences at 95% confidence level were concluded between the bulk density and raw data. It indicates the raw data of EM density gauges cannot be directly used without calibration.

Paired-t tests were further performed on the calibrated data to verify the effectiveness of various calibration methods. As Table 3 shows, regardless of the gauge type and calibration method, all P-values are larger than 0.05 (i.e., the null hypothesis is accepted), indicating that there is no statistical difference between the calibrated data and bulk density. Based on the data presented in Table 3, it can be concluded that the accuracy of the gauges can be significantly improved by calibration.

Table 3 Results of Paired-t Test for Calibration Methods

			PaveTracker		PQI
			Offset	**Mix Calibration**	**Offset**
			P-Value	P-Value	P-Value
Wearing Course			0.312	0.303	0.292
Stone Mastic Asphalt (SMA)	Lower Binder Content		0.235	0.262	0.339
	Normal Binder Content	Dry Surface	0.545	0.696	0.693
		H_2O index 4.1^	0.316	0.605	0.795
		H_2O index 8.1	0.113	0.256	0.484
	Higher Binder Content		0.362	0.990	0.125
Friction Course			0.695	0.938	0.580

^ H_2O index was measured by PQI

Asphalt Binder Content

Figure 9 shows the air void contents, as well as the measurement error percentages of PMSMA test slabs with different asphalt binder contents. It can be observed that the air void contents of the slabs decreased with the increase of binder content. Meanwhile, the error percentages of both PQI and PaveTracker vary among different asphalt contents, although they show different tendencies. The t-test results on the differences of error percentage indicate that these differences are significant at 95% confidence level. However, it cannot be concluded that asphalt content affects the accuracy of EM density gauges, because it might also be caused by the change of air void content.

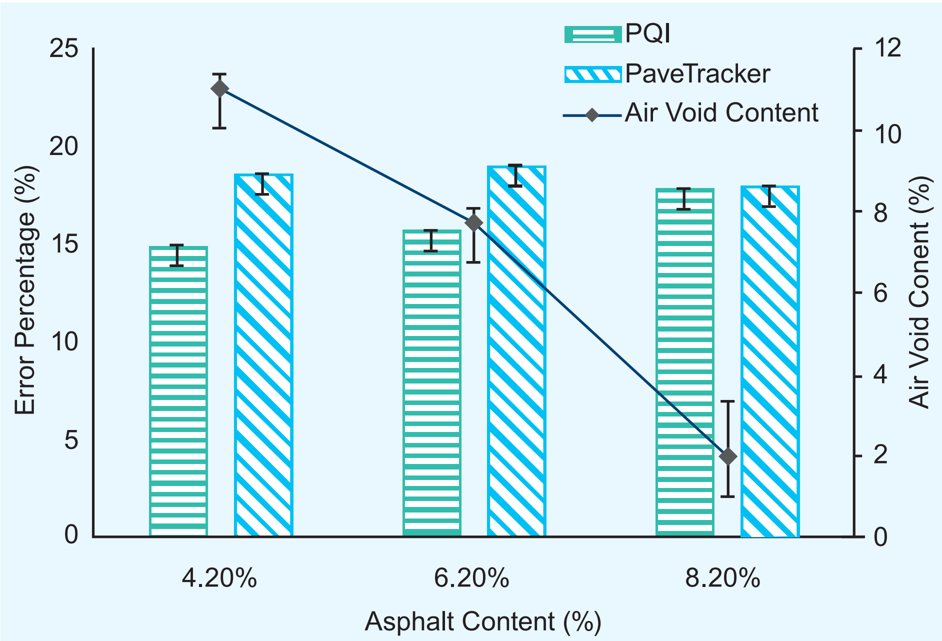


Figure 9 Relationship between Error Percentage, Air Void Content and Binder Content

Moisture Condition

During the construction process, water is often sprayed on the asphalt pavement surface to prevent asphalt mixture from sticking on the compactor rollers, which may affect the EM density gauge measurement. To explore the relationship between the moisture level and the EM density gauge data, different amounts of water were manually sprayed on the surface of the prepared testing slabs before testing.

The PQI device reports the H_2O index as an indicator of moisture level, whereas the PaveTracker does not. Therefore, the H_2O index reported by the PQI is used for both the PQI and PaveTracker, although the TransTech does not indicate the relation between moisture condition and the H_2O index.

H_2O index data collected during the construction of Po Shek Wu Road, Sheung Shui, Hong Kong using PQI indicated that the H_2O indexes of the pavement during compaction process were from 4.7 to 7.9 (Figure 10). Based on this observation, density data at three different H_2O index levels (2.1, 4.1, and 8.1) were collected to investigate the influence of moisture on density measurement.

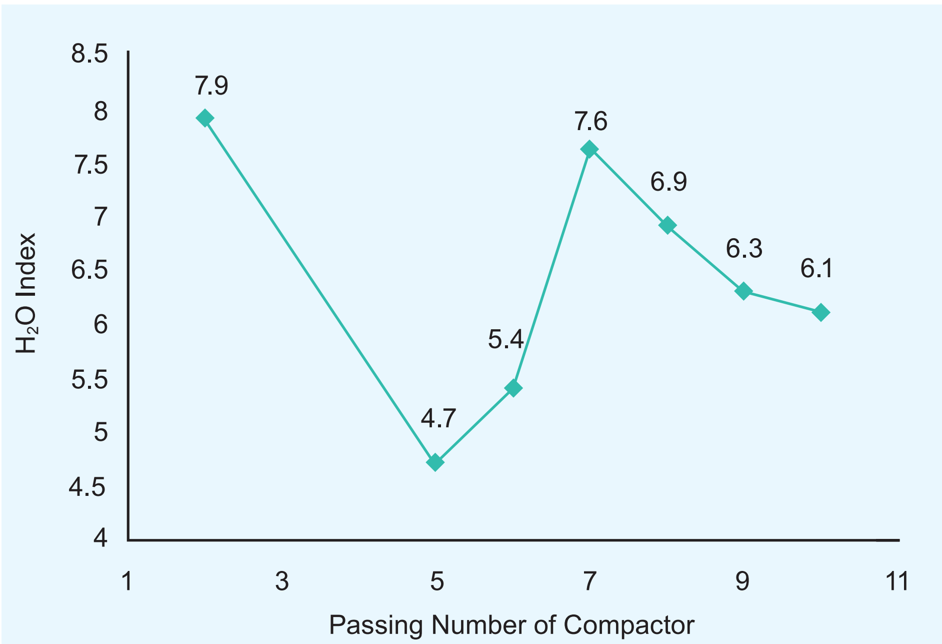


Figure 10 Relationship between Passing Number of Compactor and H_2O Index

Figure 11 shows the relationship between H_2O index and the raw data measured by PQI and PaveTracker. It is clear that the PQI measured data stays constant within the moisture range of 2.1 to 8.1, implying that within the testing moisture range. The moisture effect can be ignored when PQI is used. On contrary, raw density data from PaveTracker increase with the increasing H_2O index. It can also be noticed that the density data collected from PaveTracker, after mix calibration, become constant. Therefore, it is recommended that mix calibration should be applied to PaveTracker when data is collected under wet conditions.

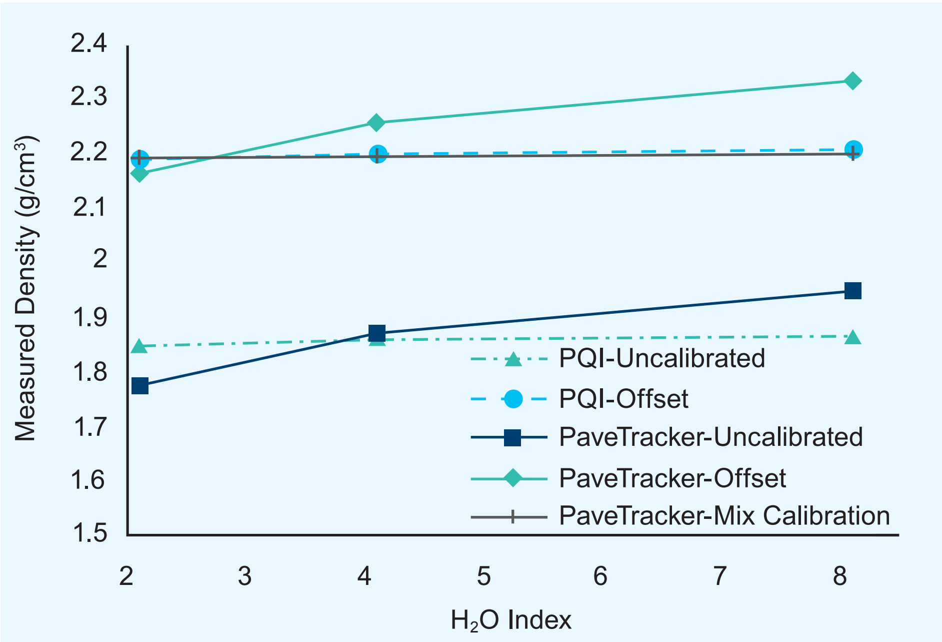


Figure 11 Relationship between H_2O Index and Measured Density

Paint

During the construction process, reference locations are selected based on the EM density gauge data followed by making it on the pavement surface for QC purpose. EM density gauge data are collected from these spots to adjust the compaction number. However, the presence of paint may affect the accuracy of density estimation since the dielectric constant of the liquid phase in paint is higher than that of asphalt mixture. In this study, the change in the collected data with different painting area and volatilization time were captured. Circular painting area with three different diameters: 3cm, 5cm and 7cm, were manually sprayed on the surface of the prepared testing slabs to explore the relationship between painting area diameter and EM density gauge data (Figure 12). To evaluate the effect of the volatilization of the liquid phase in the paint, EM density gauge data were collected at 0 minute and 30 minutes later after spraying.

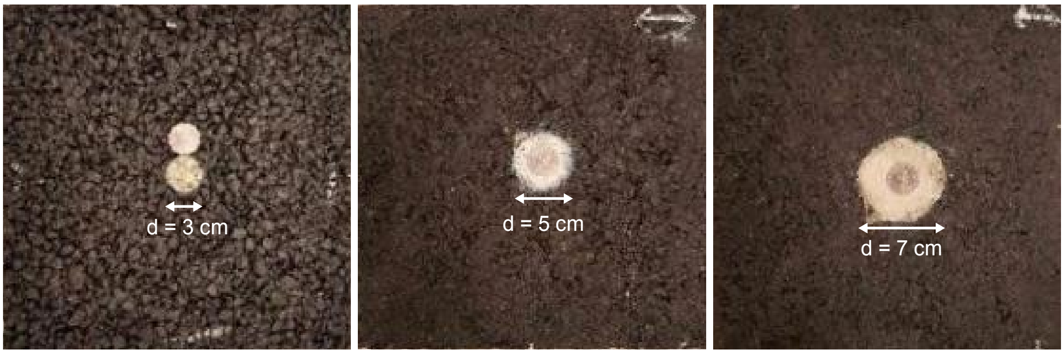


Figure 12 Circular Painting Area with Three Diameters

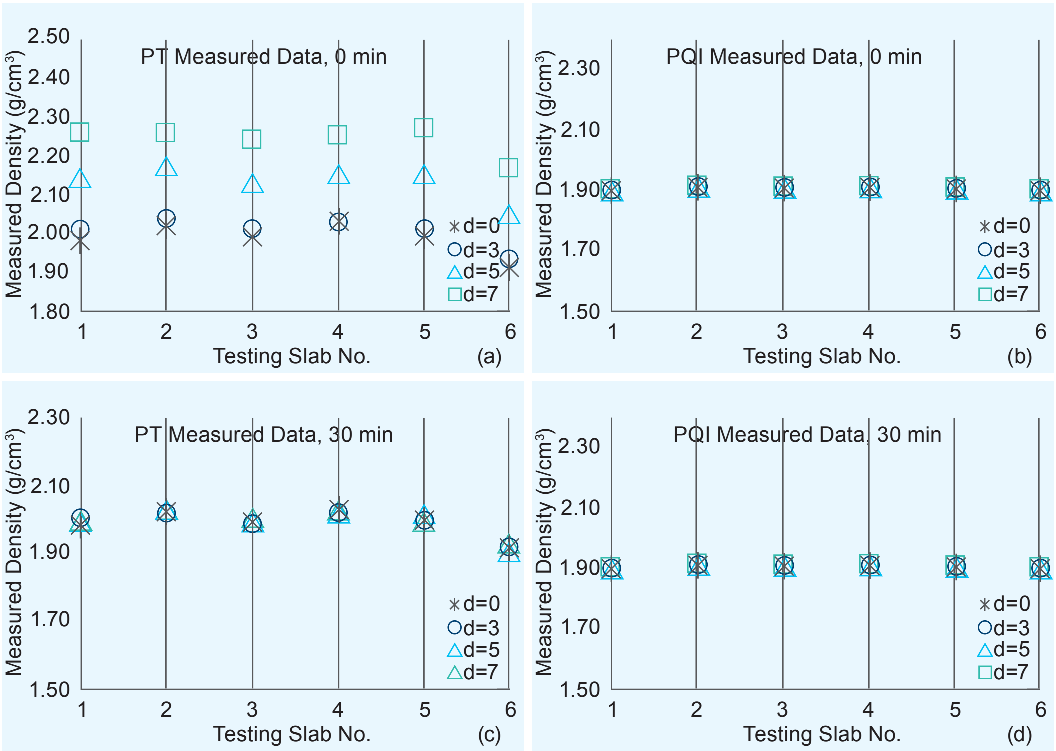


Figure 13 Effect of Painting Area and Volatilization Time on EM Density Gauge Data

Figure 13 illustrates the changes in EM density gauge data at different conditions. As shown in Figure 13(b) and Figure 13(d), regardless of volatilization time, PQI measured data stays constant within the dimeter range of 0 cm to 7 cm. On contrary, raw density data from PaveTracker highly depends on the volatilization time and painting area. The PaveTracker-measured raw data increases with the increasing of painting area when the painting area is still wet. After 30 minutes, no significant difference is observed. Therefore, it is recommended that when PaveTracker is used, data collection should be conducted after the paint becomes dry.

Underlying Layer

To evaluate the effect of underlying layer material, the performances of EM density gauges on six pavement structures with three different underlying layers were characterized (Figure 14). These pavement structures are labelled as S, SW, SF, W, WS and WF, representing structures presented in Figure 14.

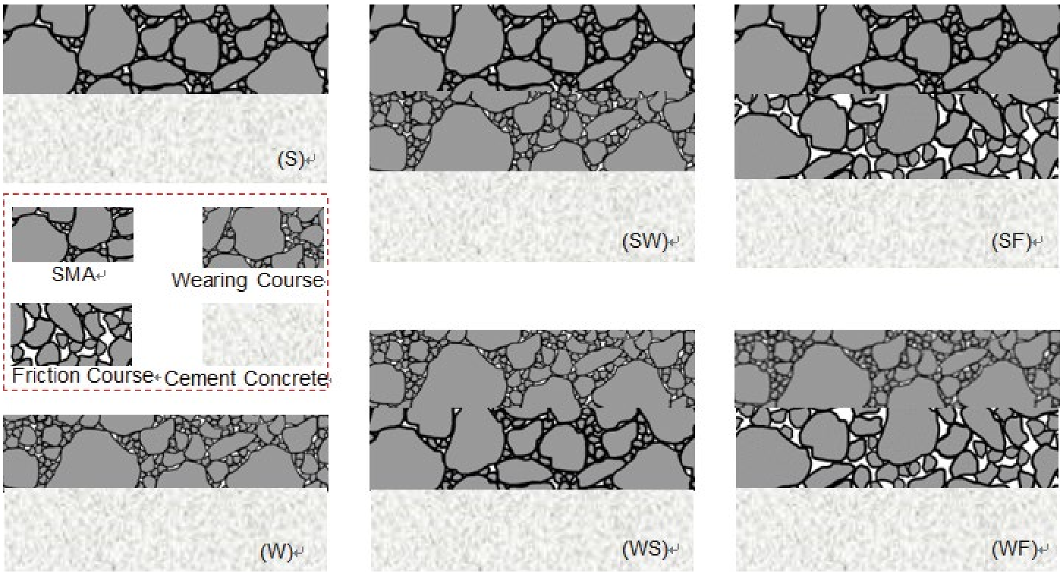


Figure 14 Description of Different Structures

Figure 15 shows the EM density gauge data collected from different structures with three different underlying layers. Regardless of the structure composition, those data stay constant. It can be concluded that the underlying layer of the measured layer may not affect the accuracy of the density measurement using EM density gauges. However, it should be noticed that the thickness of the surface layer in this study is 5cm, and when the thickness of the surface layer is smaller than 5cm, this conclusion might not be valid.

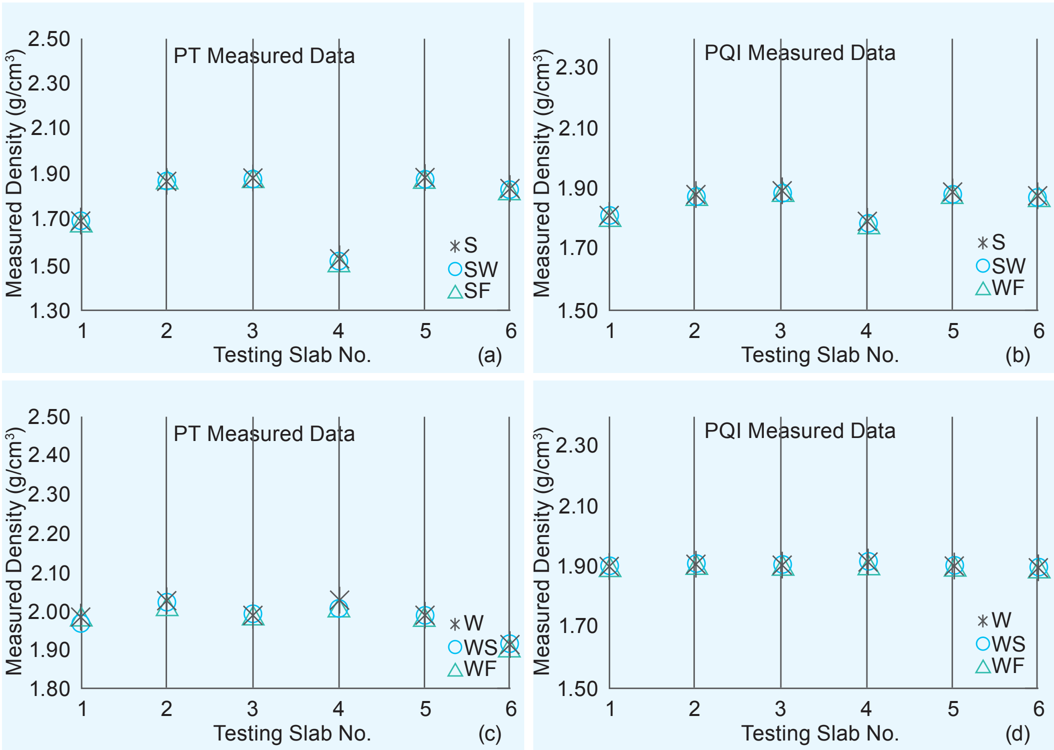


Figure 15 Effect of Underlying Layer on EM Density Gauge Data: (a) PT collected raw data from S, SW, and SF, (b) PQI collected raw data from S, SW, and SF, (c) PT collected raw data from W, WS, and WF, and (d) PQI collected raw data from W, WS, and WF

General Liner Model Analysis

General linear model was applied to determine the effects of gradation and thickness of testing slabs on EM density gauge measurement. In this model, asphalt binder type, moisture condition, asphalt binder content, air void content, and thickness of the testing slabs were independent variables, while error percentage of PQI and PaveTracker measurements were depended variables. From Table 4, it can be observed that the accuracy of PQI measurement can be affected by the changes in gradation of asphalt mixture. In order to exclude the influence given by the presence of moisture, the PaveTracker must be mix calibrated.

Table 4 General Linear Model Analysis Results

	Gradation	Binder Type	Binder Content	Air Void Content	Moisture Condition	Thickness
PQI	Y	N/A	N	N	N	N
PQI-Offset	Y	N/A	N	N	N	N
PaveTracker	N	N/A	N	N	Y	N
PaveTracker-Offset	N	N/A	N	N	Y	N
PaveTracker-Mix Calibration	N	N/A	N	N	N	N

Y = Significantly different

N = Not significantly different

Repeatability

To verify the repeatability of the two common types of EM density gauges, the data collection process was repeated 10 times at the same location. In each collection process, EM density gauges were lifted around 30 cm and then placed back at the same location. Figure 16 presents the coefficient of variation of the EM density gauge measured raw data, which shows that the coefficient of variation of the PaveTracker collected raw data is around 0.4%, which is much higher than PQI (0.04%). It indicated that the PQI provided better repeatability than PaveTracker.

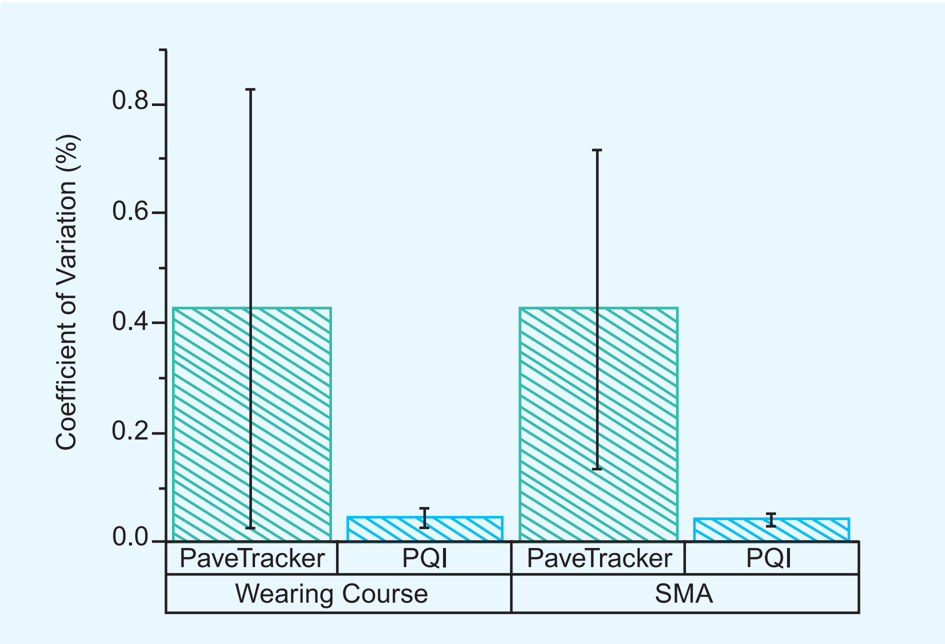


Figure 16 Coefficient of Variation of the EM Density Gauge Data

Summary of Findings

The laboratory study investigated the accuracies of two common types of EM density gauges, PQI and PaveTracker, for asphalt pavement density measurement under different conditions. The following summarizes the major findings of the laboratory tests:

- The effect of measurement direction on EM density gauge measurement is insignificant;
- The accuracy of EM density gauges can be considerably increased by calibration. For the slabs prepared in this study, the error percentages of PQI and PaveTracker were reduced from 15% to 1.5% and from 19% to 0.2%, respectively;
- After mix calibration, the effect of the presence of moisture on measurement accuracy is insignificant for both PQI and PaveTracker. But the accuracy of PaveTracker can be affected by moisture if the gauge is not calibrated or calibrated by the offset method;
- Asphalt content may affect the accuracy of EM density gauge measurement;
- The effect of asphalt mixture gradation on density measurement using PQI cannot be ignored;
- The effect of underlying layer on EM density gauge measurement is insignificant;
- Painting may affect the accuracy of PaveTracker, but not that of PQI;
- PQI provides better repeatability than PaveTracker.

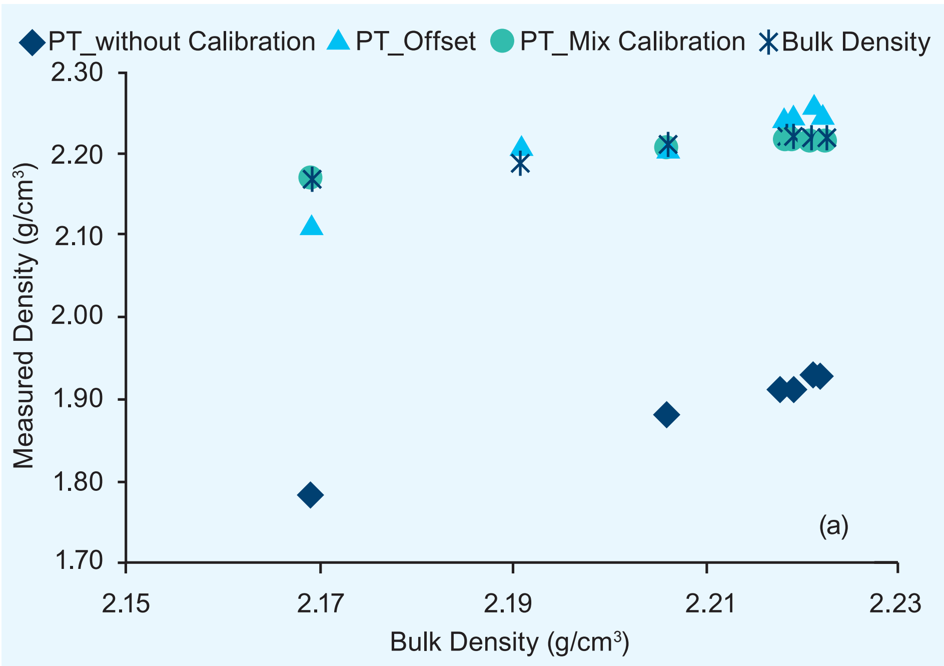
3.2 Field Evaluation Findings

In field study, three EM density gauges (PQI 301, PQI 380, PaveTracker 2701 B), a 2-GHz air-coupled GPR, and an infrared camera were evaluated at four asphalt pavement construction sites. At each construction site, data were collected using at least two EM density gauges and a GPR. Then, cores were taken and sent to public works laboratories for testing the air void content, and reference was made to these test results to evaluate the performance of each non-destructive device.

Calibration Method

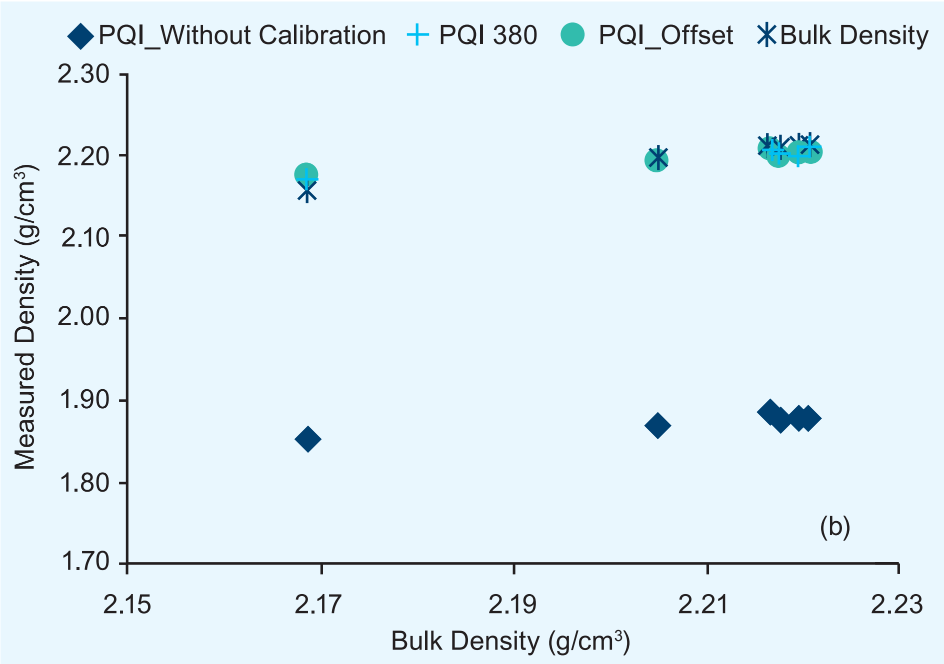
EM density gauge data was calibrated by two types of calibration methods as described before. As for GPR, the density data was estimated by prediction model.

Figure 17 to Figure 19 present the results for Lau Shui Heung Road, Lok Ming Street, and Hong Lok Yuen Depot, respectively. It can be seen that calibration can significantly increase the measurement accuracy of EM density gauges, and in most cases, mix calibration could provide a more accurate result. In addition, it was found that the accuracy of the GPR prediction model is comparable to that of EM density gauge. The error percentages are presented in Figure 20. From Figure 20, it can be observed that although offset can effectively decrease the error percentages of both PQI and PaveTracker, the error percentage of PaveTracker is higher than that of PQI. It is also clear that the performance of the EM density gauges and GPR vary from project to project. Besides, GPR can provide acceptable prediction accuracy.

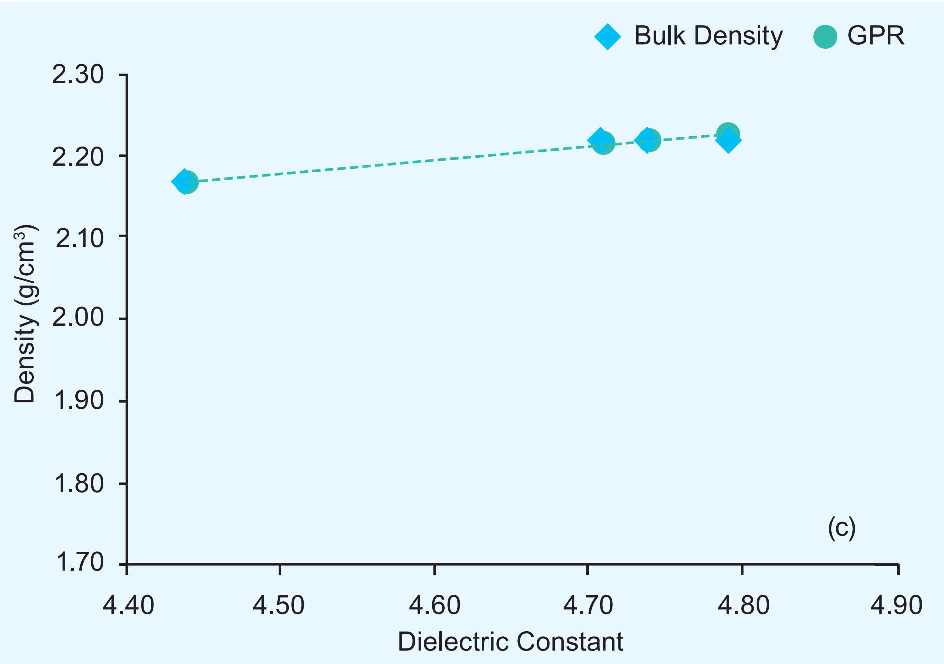


(a) PaveTracker Measured Data

Figure 17 Nondestructive Device Measured Data at Lau Shui Heung Rd.

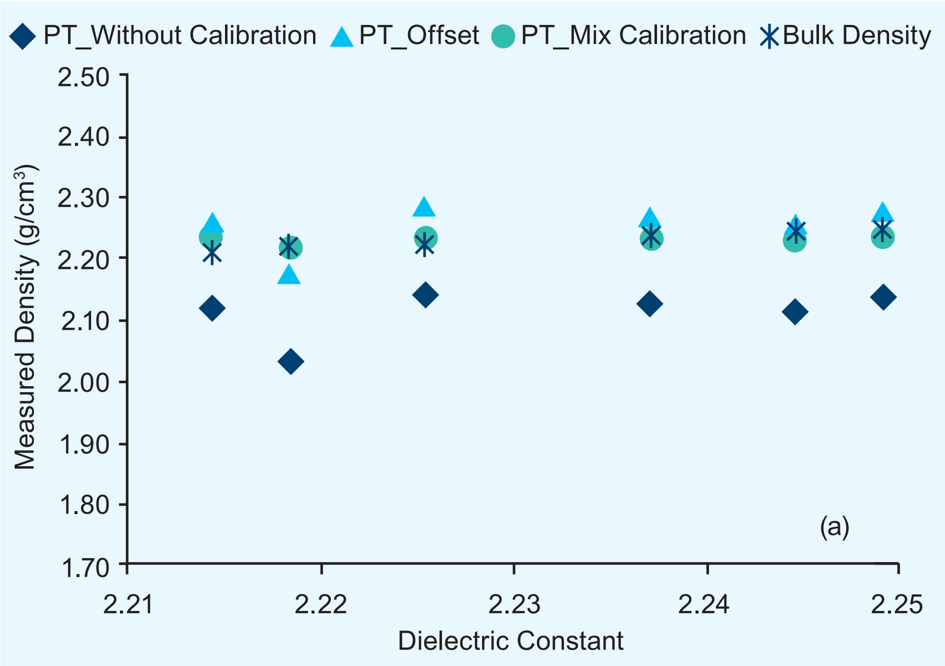


(b) PQI Measured Data

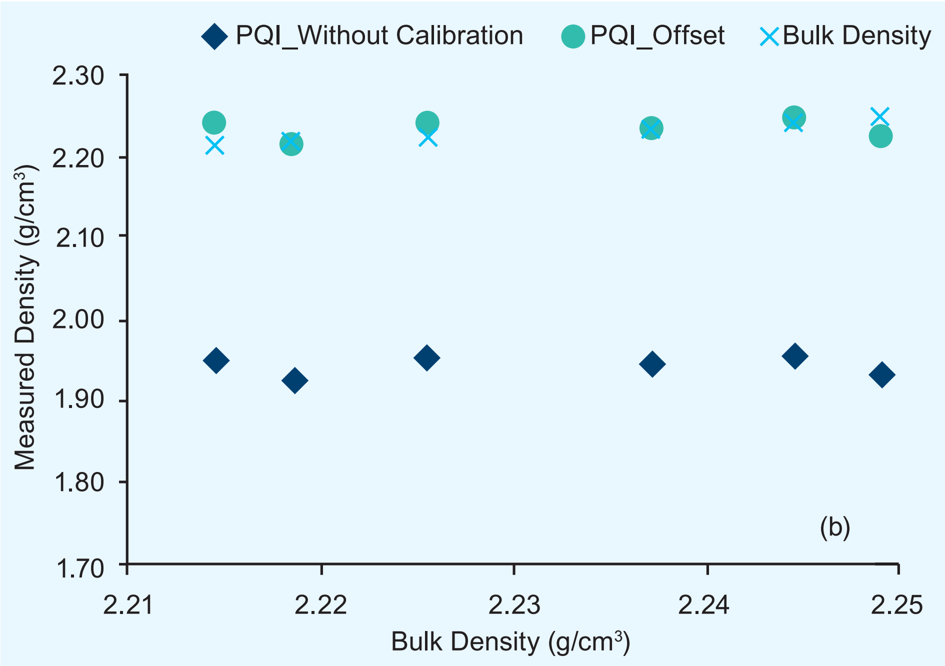


(c) GPR Predicted Data

Figure 17 Nondestructive Device Measured Data at Lau Shui Heung Rd.

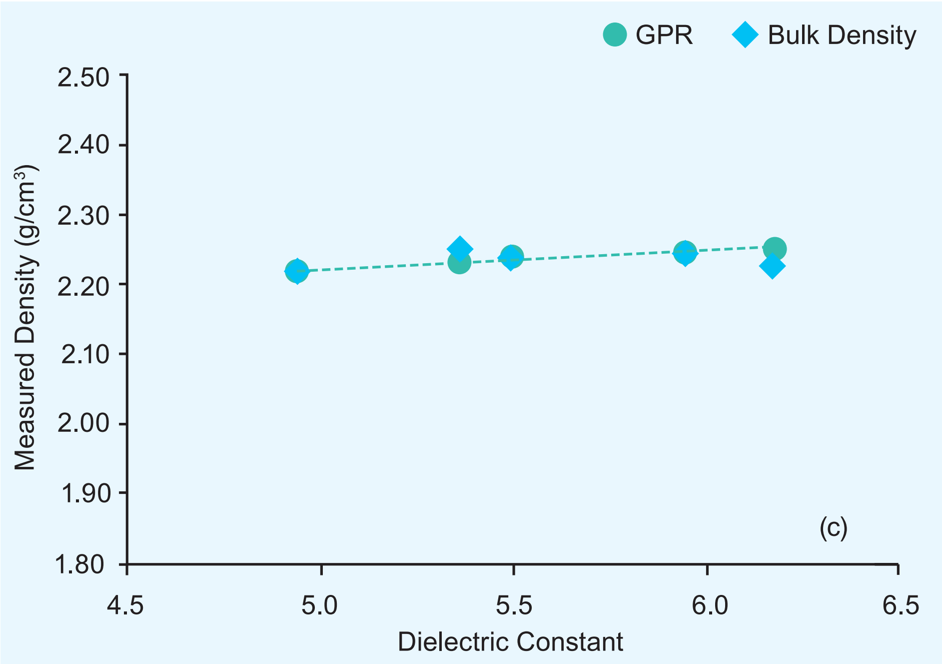


(a) PaveTracker Measured Data



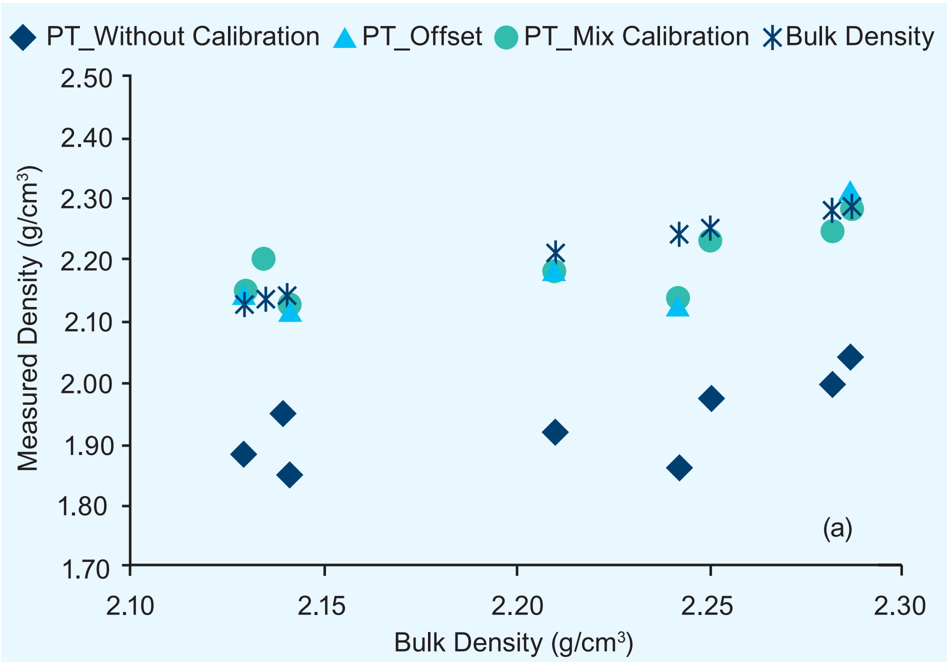
(b) PQI Measured Data

Figure 18 Nondestructive Device Measured Data at Lok Ming St.



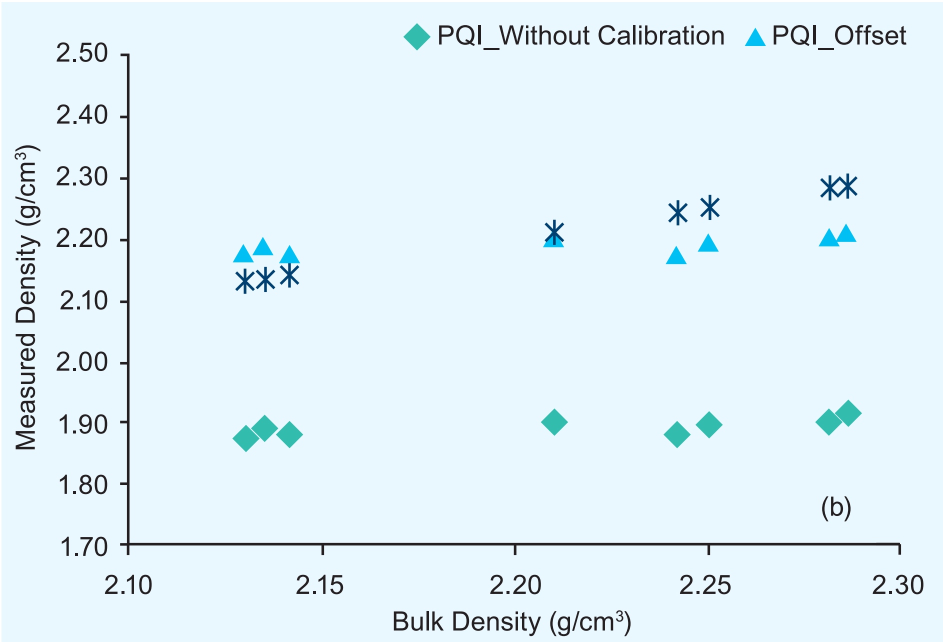
(c) GPR Predicted Data

Figure 18 Nondestructive Device Measured Data at Lok Ming St.

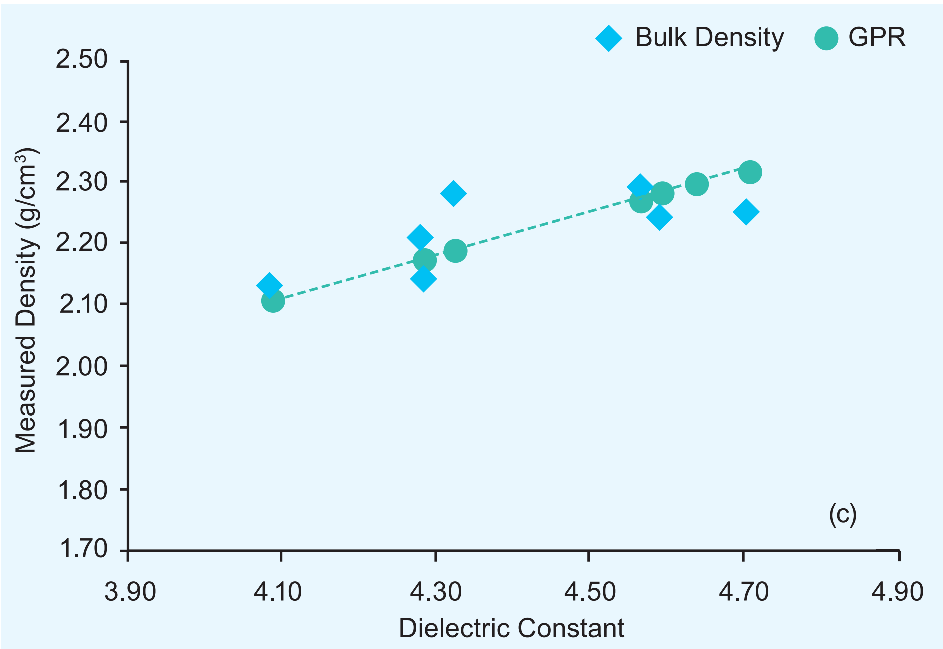


(a) PaveTracker Measured Data

Figure 19 Nondestructive Device Measured Data at Hong Lok Yuen Depot

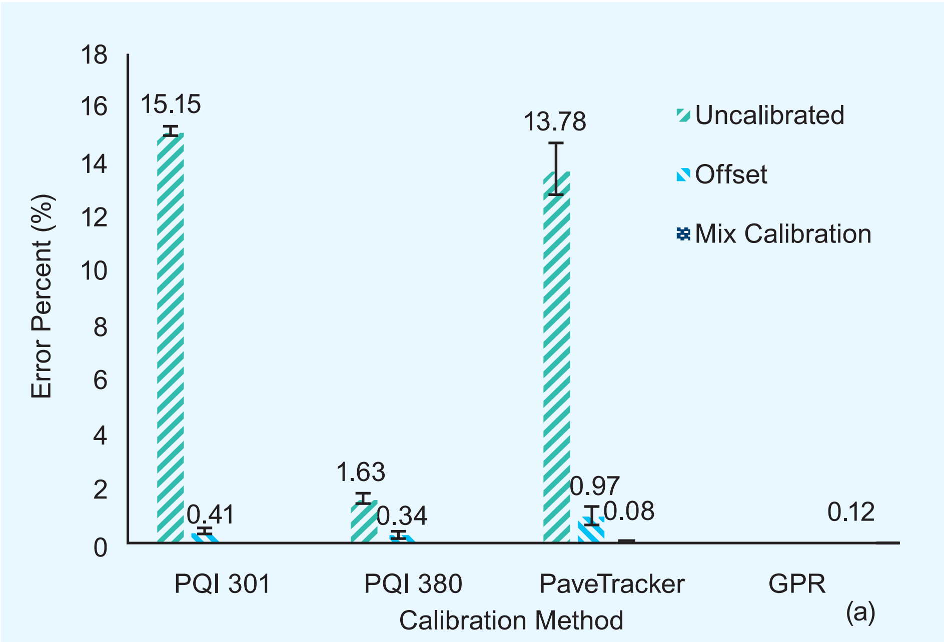


(b) PQI Measured Data

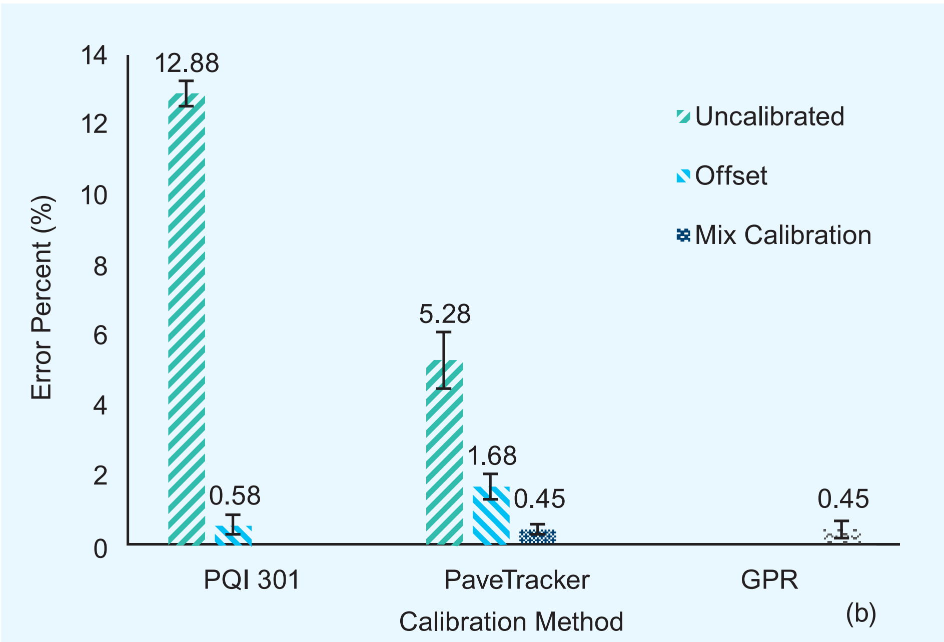


(c) GPR Predicted Data

Figure 19 Nondestructive Device Measured Data at Hong Lok Yuen Depot

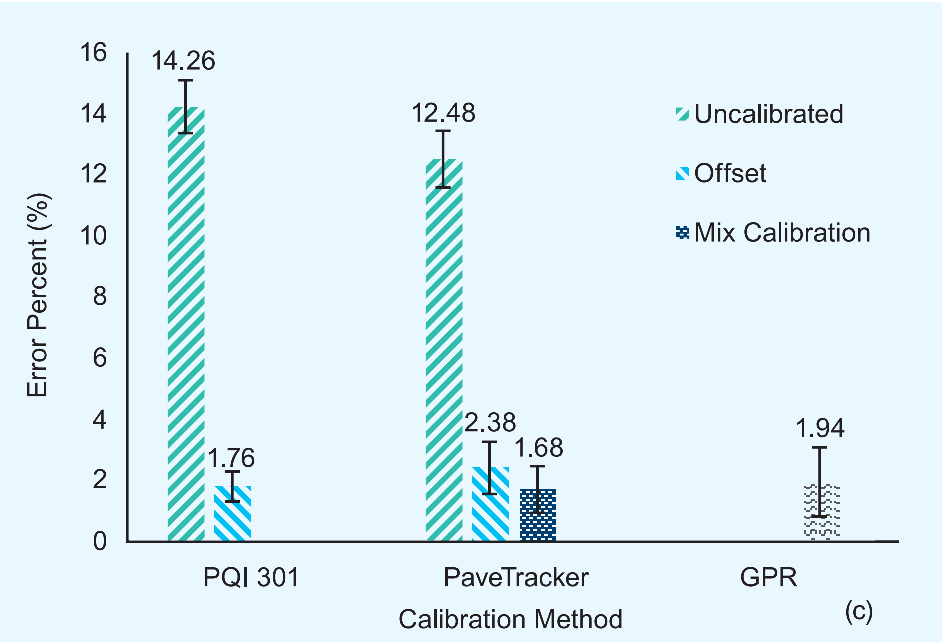


(a) Lau Shui Heung Rd



b) Lok Ming St.

Figure 20 Error Percent of Different Density Measurement Methods at Three Construction Sites

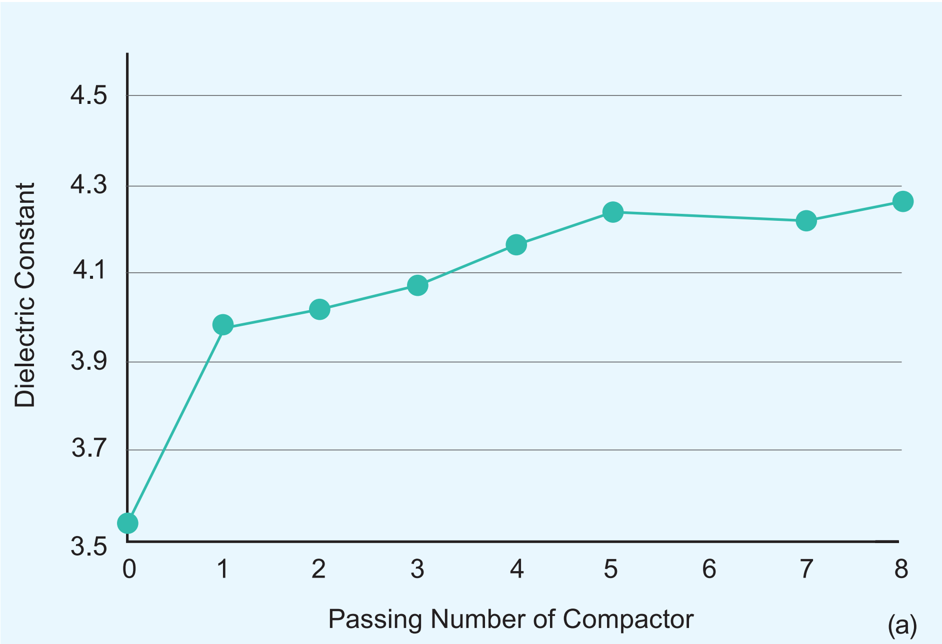


(c) Hong Lok Yuen Depot

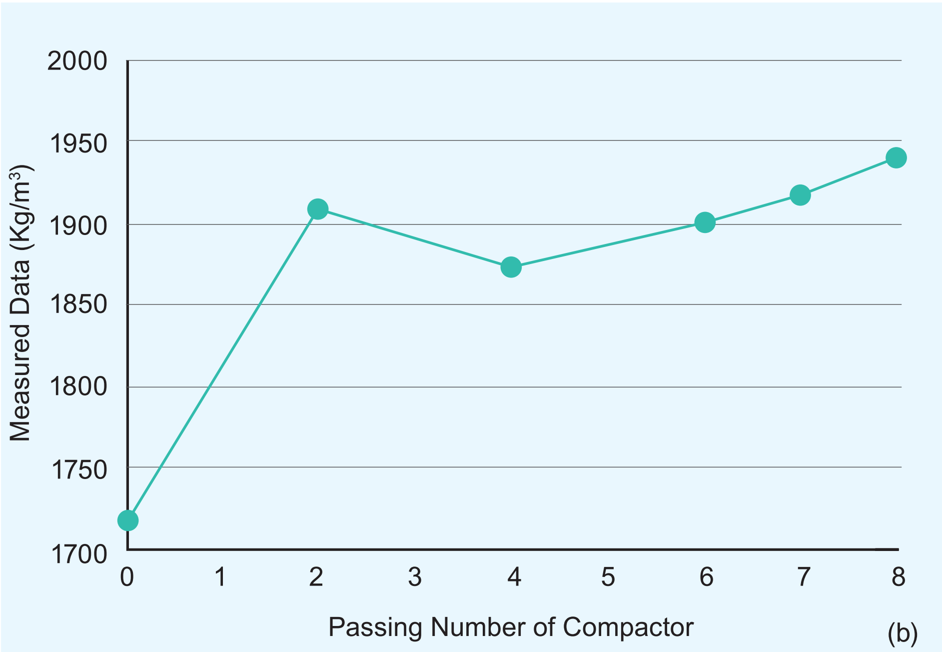
Figure 20 Error Percent of Different Density Measurement Methods at Three Construction Sites

Compactor Passing Number

In-situ survey was conducted to determine if the non-destructive devices could accurately characterize the effect of each compaction pass on the density of the asphalt mixture. Figure 21 and Figure 22 show the raw EM density gauge data and the dielectric constant collected at construction site at Po Shek Wu Rd. and Lau Shui Heung Rd., respectively, after each compactor pass. From Figure 21(a), it can be seen that the dielectric constant of the asphalt mixture increased dramatically after the first compaction pass, and then increased at reduced rates. This is reasonable because the asphalt mixture was much easier to compact when it was in a loose state. After five compaction passes, the dielectric constant increased much less, which indicates that the density of the asphalt mixture did not increase much. A similar trend was observed in Figure 22. The first four compaction pass increased the dielectric constant significantly, and then the following four compaction passes contributed much less.

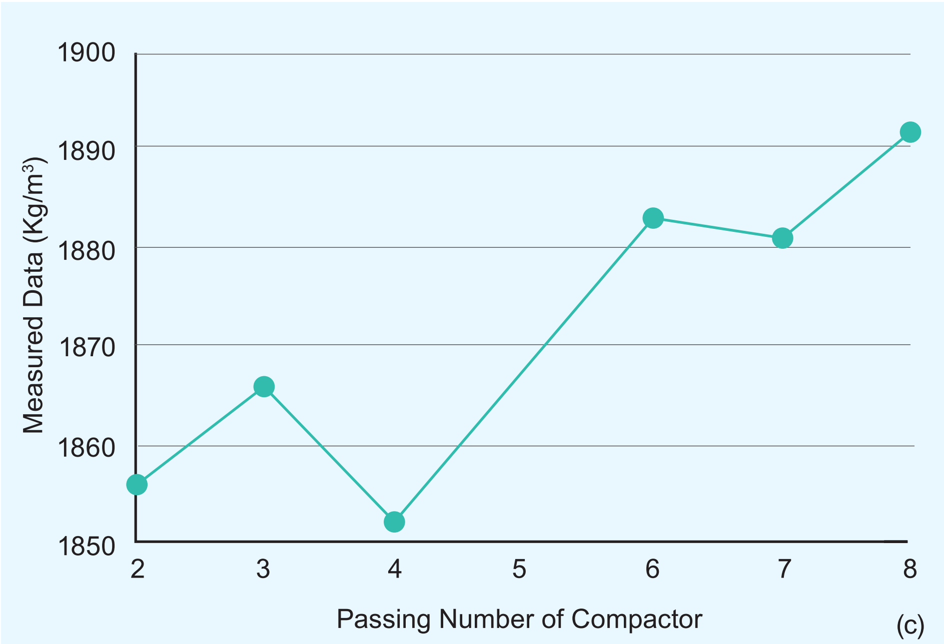


(a) Dielectric constant



(b) PaveTracker collected raw data

Figure 21 Raw EM Density Gauge Data and Dielectric Constant versus Passing Number of Compactor (Po Shek Wu Rd.)



(c) PQI 301 collected raw data

Figure 21 Raw EM Density Gauge Data and Dielectric Constant versus Passing Number of Compactor (Po Shek Wu Rd.)

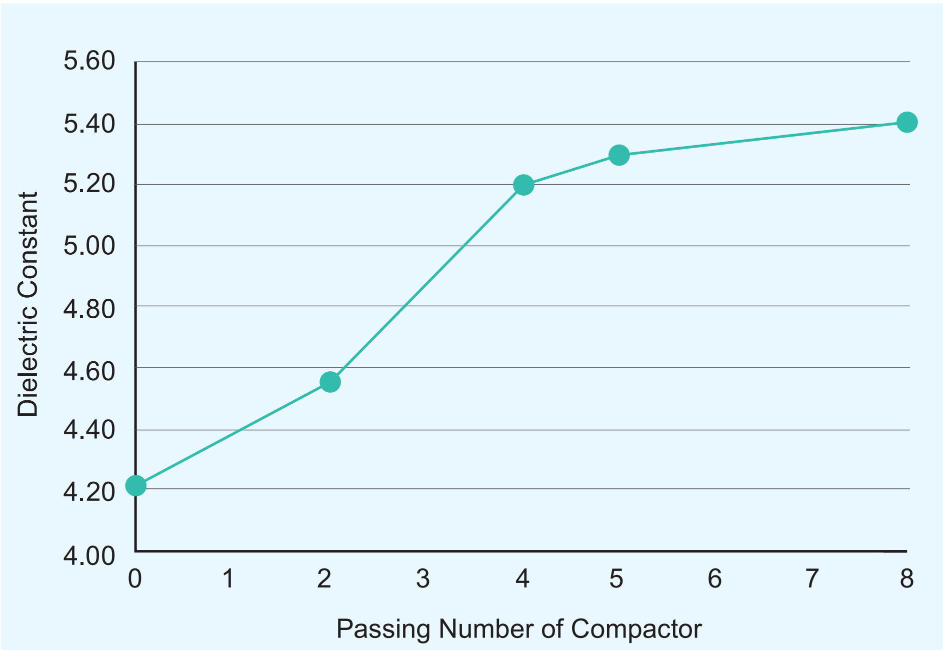


Figure 22 Dielectric Constant versus Passing Number of Compactor (Lau Shui Heung Rd)

It is recommended that the dielectric constant versus passing number of compactor curves could provide the compactor operator with useful information on monitoring compaction status to achieve better quality control. And both the EM density gauges and GPR can be used as a quality control tool since they are sensitive to the change in asphalt mixture caused by the change of compactor passing number.

Pavement Temperature

Figure 23 plots the processed dielectric constant of the gap-graded SMA pavement surface layer placed at Po Shek Wu road at different temperatures. It is clear in this figure that, except for some random fluctuation, the dielectric constant stays constant within the temperature range of 40°C to 70°C, which indicates that within the testing temperature range, the temperature effect can be ignored when using the GPR prediction model to estimate the asphalt mixture density.

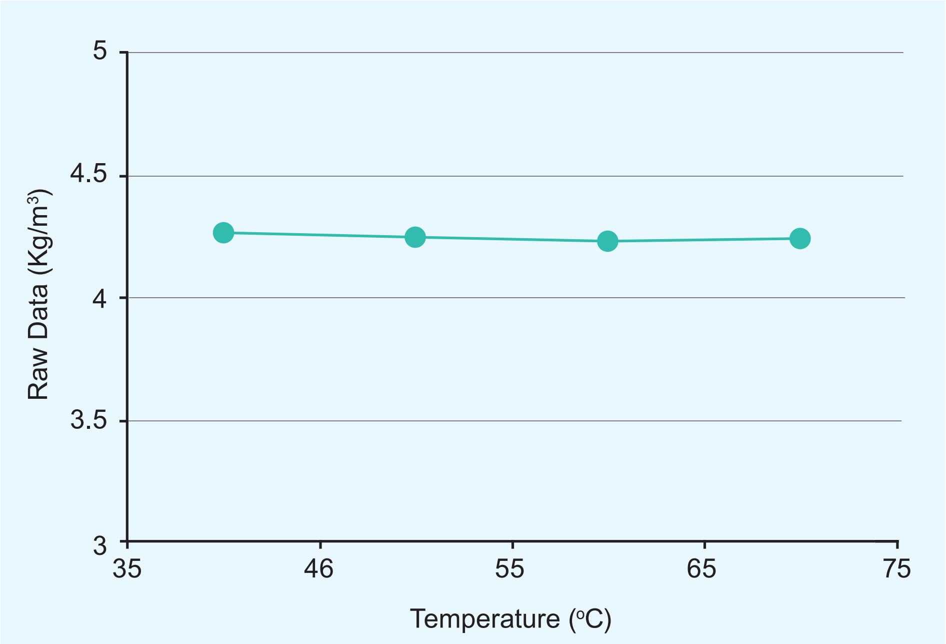


Figure 23 Relationship between the Dielectric Constant and Temperature

Figure 24 illustrates the change in EM density gauge data within the temperature range of 40°C to 70°C collected from the gap-graded SMA pavement at Po Shek Wu road. Similar as dielectric constant, EM density gauge data stays constant within this temperature range.

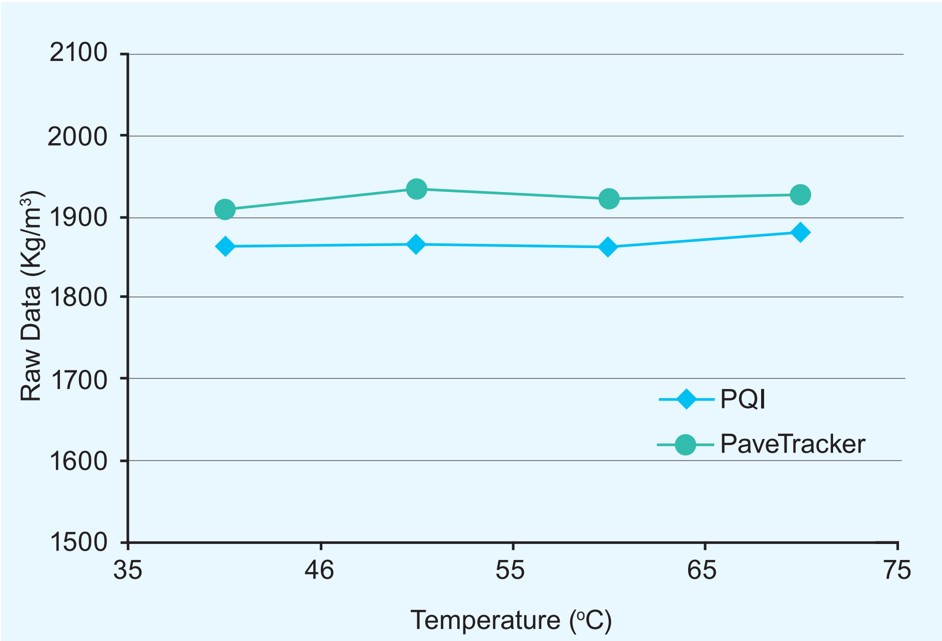


Figure 24 Relationship between the EM Density Gauge Data and Temperature

Repeatability

To verify the repeatability of the EM density gauges at each location, data collection process were repeated 5 times at the construction site at Lok Ming Street. Figure 25 presents the collected raw data. It can be observed that the PQI provided a very good repeatability while that of PaveTracker was much poorer.

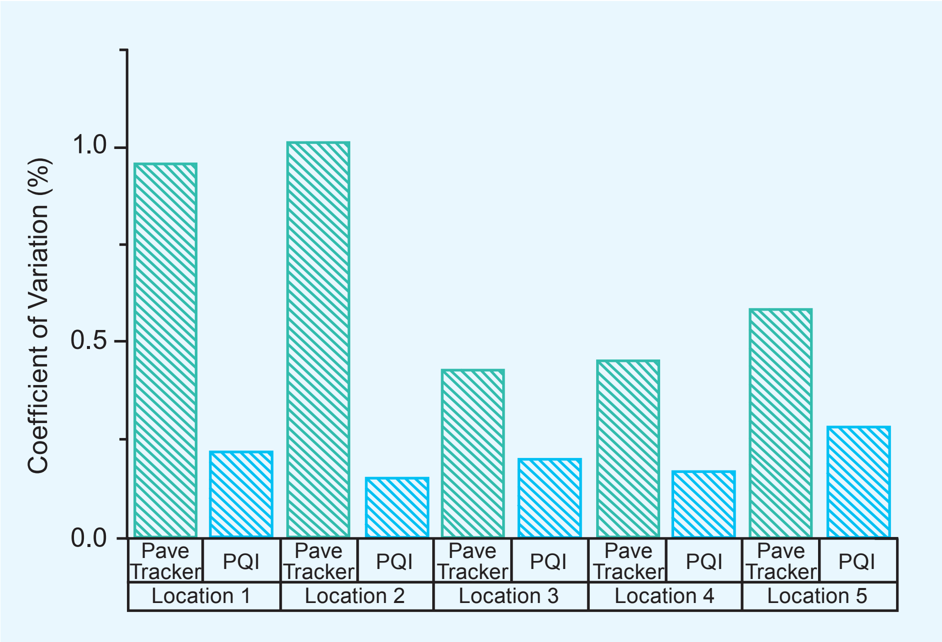


Figure 25 Coefficient of Variation of EM Density Gauge Data at Different Locations

Thickness Measurement

Layer thickness measurement is by far the most common and successful application of GPR in pavement survey. As described above, once the GPR data are collected, the GPR signal travel time within the pavement layer and can be obtained. Then the thickness of the pavement layer can be calculated by Equation 4.

$$d_1 = \frac{ct_1}{2\sqrt{\varepsilon_{r,1}}} \tag{4}$$

Where t_1 is the two-way travel time of an electromagnetic wave within the surface layer, which can be obtained from the GPR signal, and d_1 is the thickness of the surface layer.

Table 5 presents the GPR-measured t_{AC} and thickness at each core location, with the thickness of the core samples as reference. It can be seen that when predicting the thickness of asphalt mat, GPR works better at Hong Lok Yuen Depot than at Lok Ming Street. The prediction accuracy at Hong Lok Yuen is considered acceptable with the average error percent of 2.37%.

Table 5 Comparison of GPR-predicted and Vernier calliper Measured Thickness

Core #		Core Thickness (mm) Average	COV* (%)	Predicted Thickness (mm)	Thickness Prediction Error (%)
Hong Lok Yuen Depot	1	55.85	2.98	55.66	0.33
	2	57.45	1.85	54.09	5.84
	3	50.91	1.56	52.64	3.39
	4	51.15	1.03	52.67	2.98
	5	53.04	0.84	54.14	2.09
	6	50.68	1.17	51.85	2.32
	7	53.50	1.18	54.34	1.57
	8	54.09	3.21	53.86	0.42
Lok Ming Street	2	48.78	3.18	46.22	9.73
	4	51.73	1.77	47.59	10.78
	5	49.66	0.67	45.27	15.54
	7	45.29	1.13	53.77	4.75
	9	54.66	1.10	51.00	14.93

*COV represents coefficient of variation

Density and Layer Thickness Profiles

Once the pavement had cooled enough to withstand traffic, GPR and EM gauges were used to measure density from a selected 2.5m × 9m area at the construction site at Lau Shui Heung Road (Figure 26). The density and thickness profile provided by GPR were obtained through data processing using the corresponding density predict model and a custom-made program developed by the researchers.

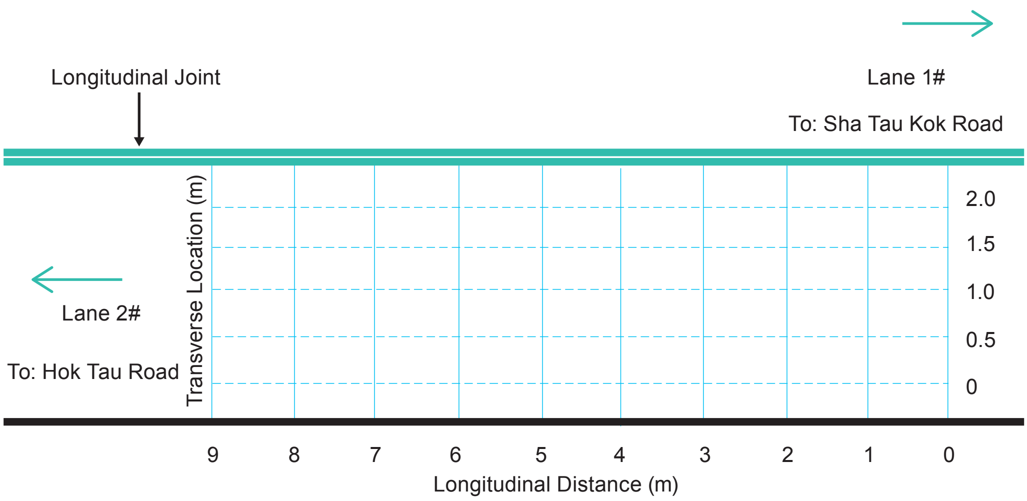


Figure 26 Testing Area Schematic at Lau Shui Heung Road

Figure 27 presents the density colour maps based on the data collected from GPR and two common types of EM density gauge. Obviously, GPR density map offers more details on the asphalt pavement density. Between the two EM density gauges, PQI is less sensitive to the density change. However, despite the above differences, it can be observed from all the maps that the density at locations with the transverse location of 0.5m and 1.5m are higher than the other parts of the pavement. Figure 28 shows that the thicknesses of this testing area are between 5.8cm and 4.4cm.

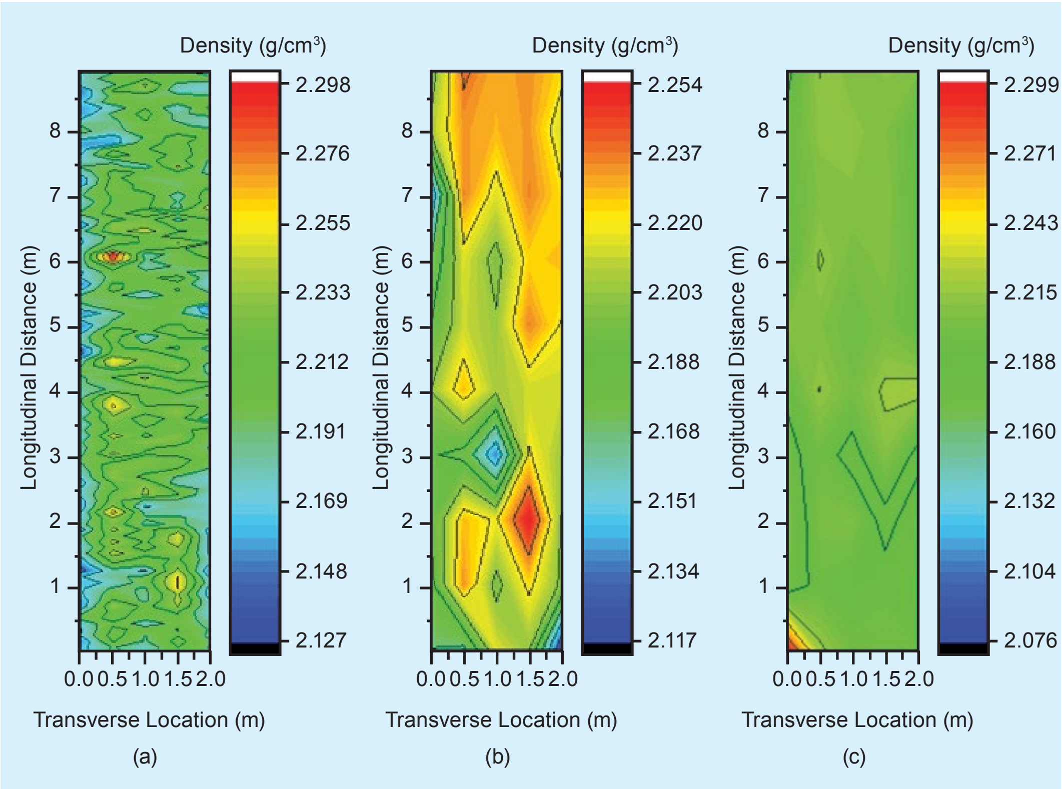


Figure 27 Density Map of Lau Shui Heung Road: (a) GPR, (b) PaveTracker, and (c) PQI

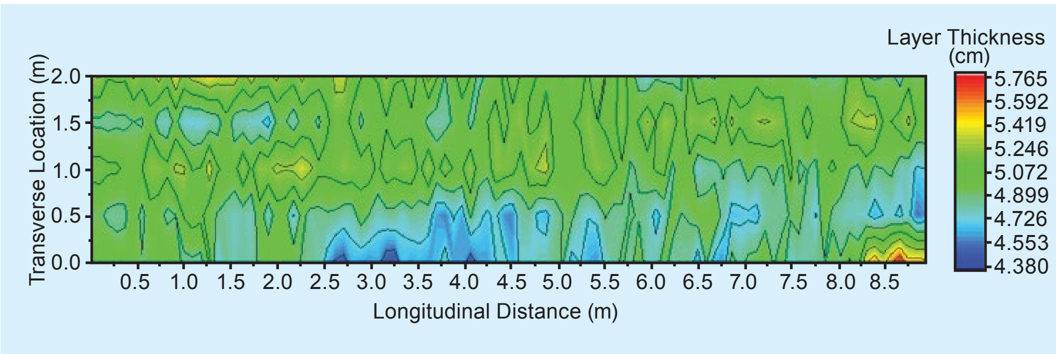


Figure 28 Layer Thickness Map of the Testing Area at Lau Shui Heung Road

Summary of Findings

The in-situ testing investigated the accuracies of two common types of EM density gauges, PQI and PaveTracker, and GPR for asphalt pavement density measurement at four construction sites. The following summarizes the major findings of the in-situ survey:

- The accuracy of EM density gauges can be considerably increased by calibration;
- GPR can provide a comparable performance to EM density gauges;
- The effect of asphalt mat temperature on EM density gauges and GPR are insignificant;
- GPR can be successfully used for compaction monitoring during construction while EM density gauges cannot;
- PQI presents an excellently repeatability while PaveTracker does not;
- GPR can also be applied to measure the thickness after the compaction continuously, rapidly, and nondestructively;
- GPR can be implemented as an effective tool to provide density and thickness profile of asphalt pavement while EM density gauges cannot.

3.3 Temperature Monitoring

An infrared camera was used to monitor the temperature of asphalt mixture during the construction process at Pok Shek Wu Road and Lau Shui Heung Road.

Temperature Monitoring

Figure 29 presents the temperature of the asphalt mixture in paver hopper before paving. As can be seen, the temperature of the asphalt mixture at hopper bottom was higher than that at top with a temperature differential of around 60°C. It was caused by the uniformity of temperature in haul trucks. Asphalt mixture with higher temperature, namely lower viscosity and adhesion, were dumped at the bottom of the paver hopper. Conversely, lower temperature asphalt mixture was placed at the top.

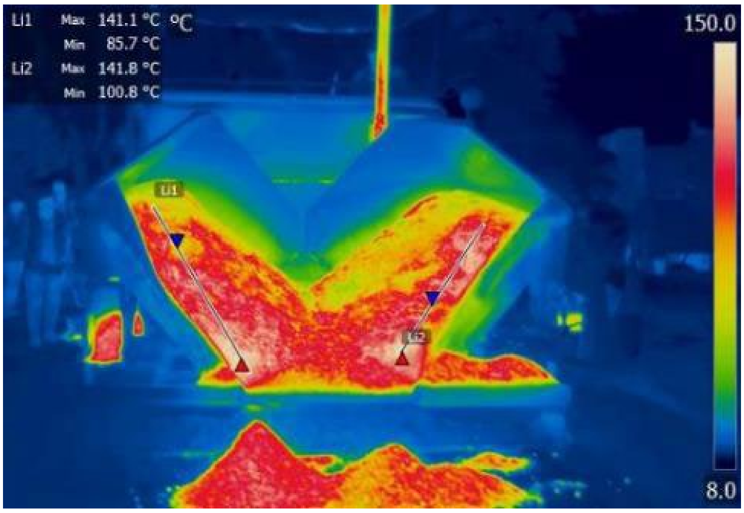


Figure 29 Temperature Monitoring Before Paving

Figure 30 shows a thermal image taken at the time of placement. Based on the data presented by this figure, it can be found that there was a low-level temperature segregation at the surveyed location.

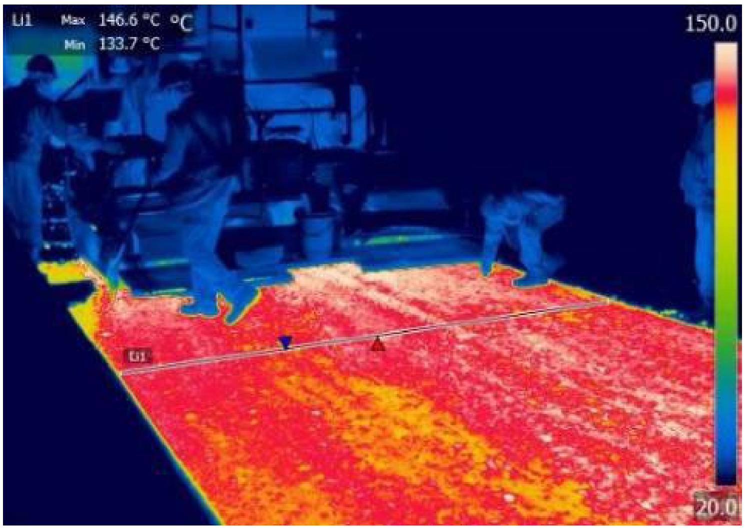


Figure 30 Temperature Monitoring During Paving

Figure 31 presents the typical thermal images and conventional digital picture of pavement compaction. As Figure 31(a) shows, there is significant surface temperature difference (approximately 50^{o}C) between the loose mixture area and the compacted mixture area, which was mainly caused by cooler roller and water spraying. In Figure 31(b) and Figure 31(c), the spots marked as Sp1 to Sp5 are locations where the paver stopped and restarted. Although these spots are invisible in the conventional pictures (Figure 31 (c)), they can be easily located in thermal image. Thus, the temperature differentials caused by the compaction makes infrared camera a potential tool for monitoring the compaction uniformity.

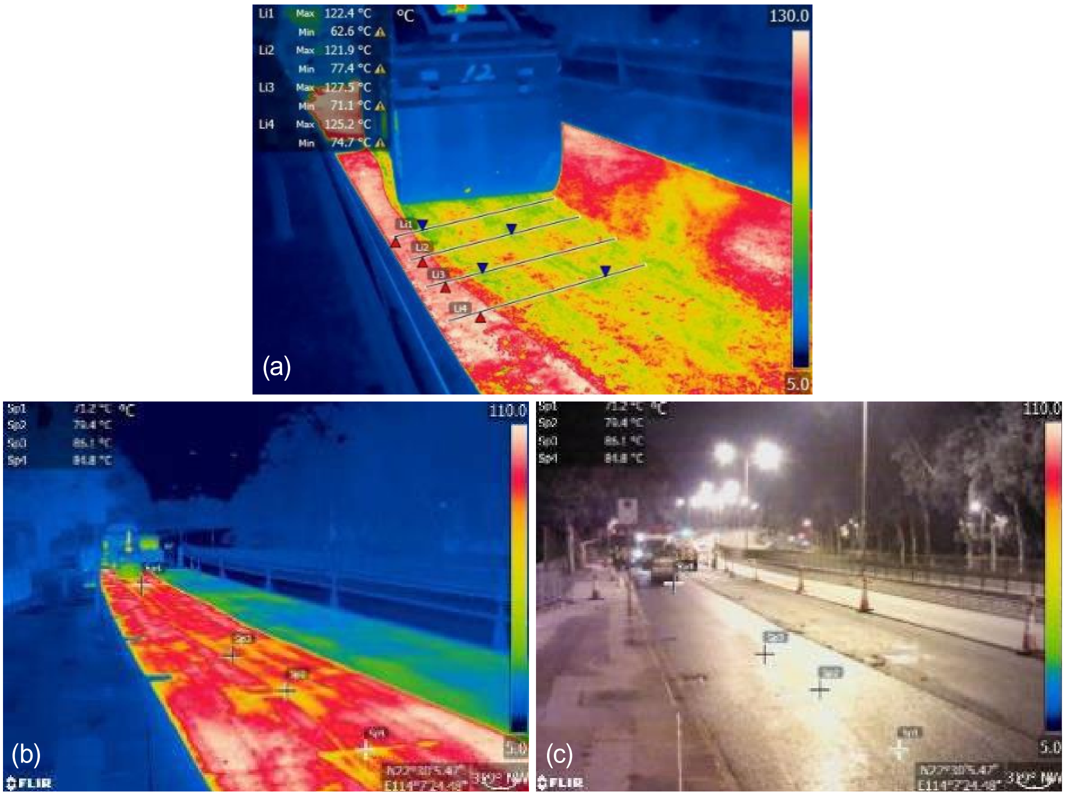


Figure 31 Temperature Monitoring During Compaction

Figure 32 illustrates the surface temperature distribution of the asphalt pavement after construction. Based on the real-time full-coverage temperature information provided by the thermal image, the appropriate traffic opening time can be determined.

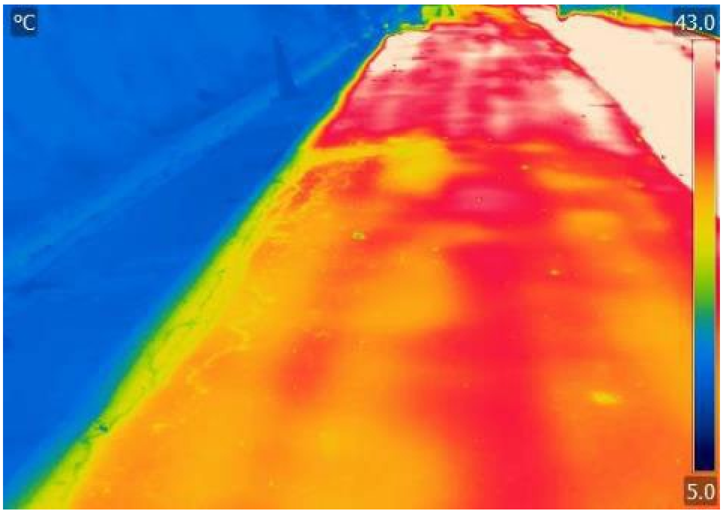


Figure 32 Thermal Image of the Asphalt Pavement before Traffic Opening

Temperature Segregation Observation

For infrared camera, one of the most frequent applications in pavement QC is to identify and assess the temperature segregation. Several typical segregation images captured by the infrared camera during pavement construction are shown in Figure 33.

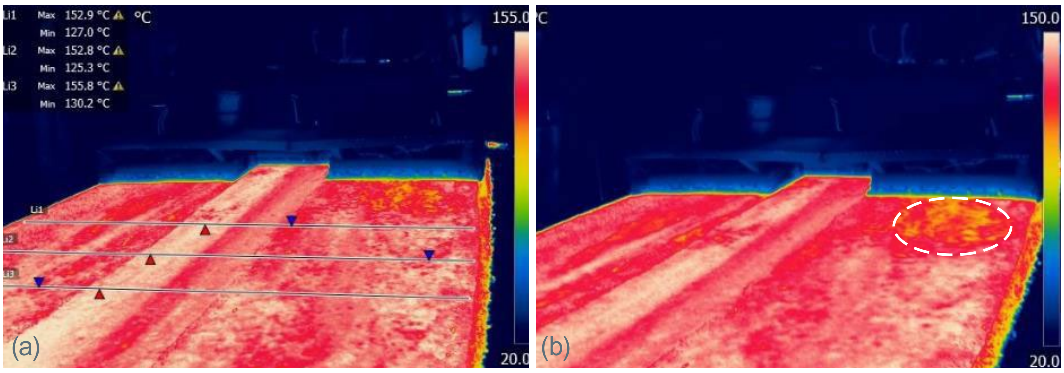


Figure 33(a) & (b) Thermal Image of the Asphalt Pavement during Paving

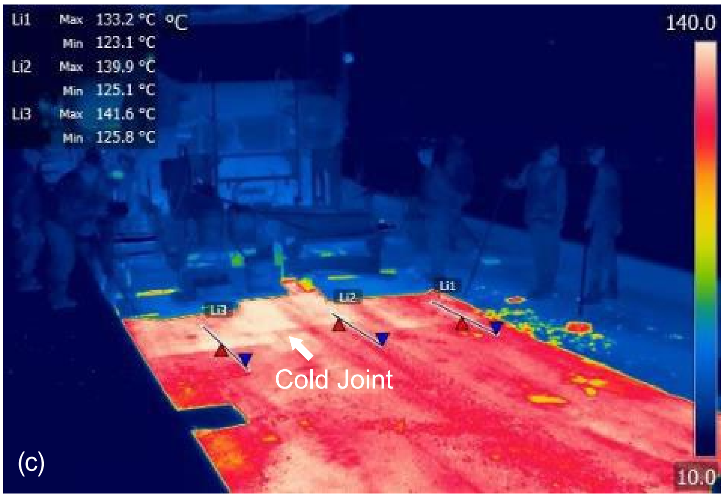


Figure 33(c) Thermal Image of the Asphalt Pavement during Paving

Because of the problem with screed, several streaks occurred during paving, as shown in Figure 33(a). These streaks may cause nonuniform mixture density distribution, leading to early pavement failures.

Figure 33(b) shows a typical truck end segregation (also known as cyclic segregation or end-of-load segregation). As aforementioned, asphalt mixture with lower temperature are placed at the top of the paver hopper after dumping (see Figure 29). If there is a delay between the haul trucks, the cooler asphalt mixture will be paved, therefore leading to the temperature segregation. Similarly, folding hopper wings may also cause cooler areas. However, since the hopper wings folding always happened at the time of truck end, throughout this study, it became clear that determining the differences in temperature segregation caused by truck end and by folding hopper wings would be almost impossible.

Figure 33(c) presents a cold joint resulted from paver stopping. Specifically, when the paver stopped to wait for the haul truck, the temperature of the paved asphalt mixture dropped dramatically. As a consequence, temperature segregation occurred. As shown in this figure, the temperature differential between the two sides was approximately 15°C. Although it is a low-level segregation, it may still increase the risk of transverse crack.

Data Analysis

Figure 34 plots the temperatures recorded by the infrared camera against the GPR predicted density of asphalt mixture. From this figure, no clear trend between them can be observed. It is worth noting that although temperature affects the workability and compactibility of asphalt mixture, it is not the single factor determining the final density of the compacted asphalt pavement. For example, the roller compacter operator may change the compaction number in different locations depending on temperature measurement or his/her experience.

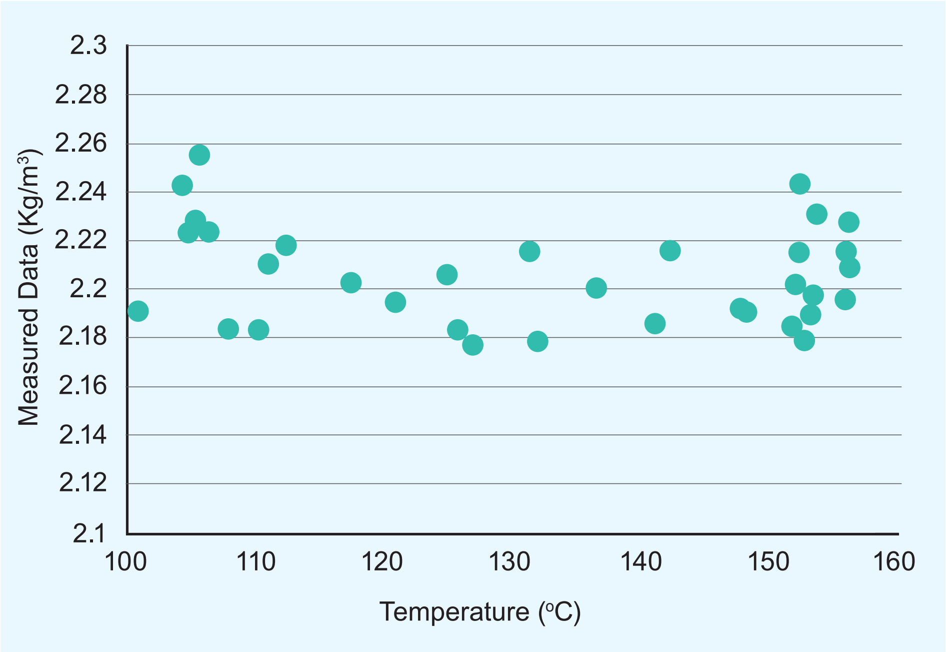


Figure 34 Relationship between Temperature and Density

Figure 35 presents the changes in density (ΔG_{mb}) and changes in temperature (ΔT). There's a weak trend that as the consequence of temperature differential increase, the density difference increases.

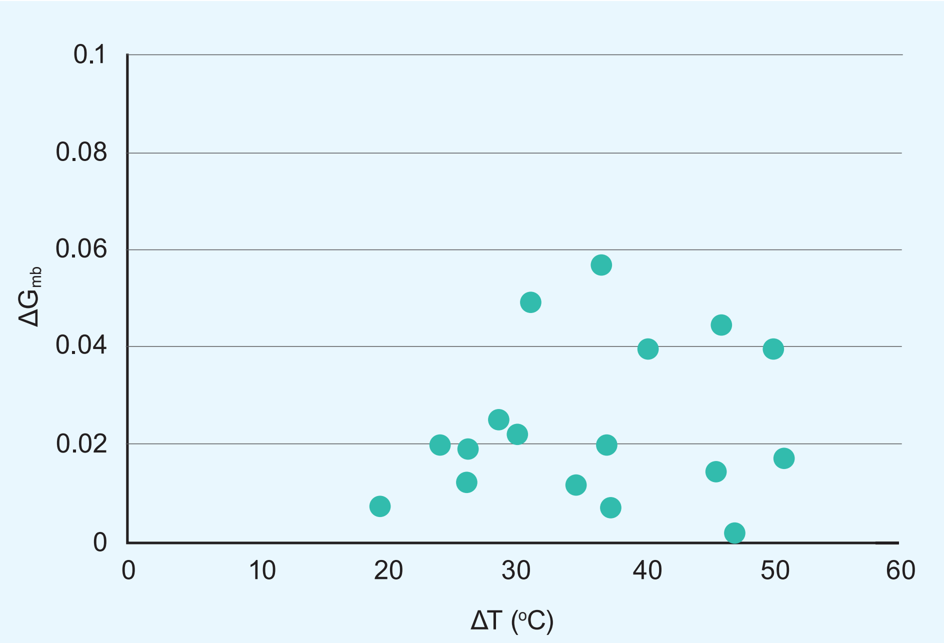


Figure 35 Relationship between Changes in Temperature and Changes in Density

Summary of Findings

During the field construction, temperature data of the paving mixture were collected to assess whether infrared camera could be utilized as an effective QC tool for asphalt pavement construction. It was found that:

- Infrared camera can provide real-time data on whether the paving temperatures are within user-defined limits.
- It is feasible to use infrared camera to detect compaction uniformity.
- Temperature segregation of the asphalt mixture during paving can be detected by infrared camera.
- No strong correlation was found between the paving temperature and final density of asphalt pavement, because temperature is only one of the factors affecting asphalt pavement density.
- The increase of temperature differentials may increase the density difference.

4 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

- QC testing using PQI and GPR is recommended, and the EM density gauge should be well calibrated before testing.
- Agency independent QA testing using EM density gauges is not recommended.
- GPR system is recommended as a non-destructive tool to provide the surface layer thickness profile of asphalt pavement.
- Real-time monitoring of asphalt pavement density of the entire pavement is feasible based on the GPR measurement.
- Infrared camera can be utilized as an effective tool detect temperature segregation during asphalt pavement construction.

Specifically, the following guidelines are proposed for the local pavement contractors to use the three nondestructive tools (EM density gauges, GPR, and infrared camera) for the purpose of asphalt pavement construction QC and improve the asphalt pavement construction quality:

1. Before using the EM density gauges, it should be calibrated. For each kind of asphalt mixture, at least 5 samples are required for calibration purpose.
2. For improving the measurement accuracy, Mix Calibration is recommended as the calibration method of PaveTracker. PQI should be calibrated following the manual.
3. During asphalt mixture paving, infrared camera can be used to provide the temperature distribution colour map of the laid loose mixture. If the overall mixture temperature is below the lower boundary of the desired paving temperature range, the construction should not be continued. For area with relatively lower temperature, more numbers of compaction should be applied during the compaction process to make sure its final density is similar to those of other areas and can meet the specification requirement.
4. During the compaction process, GPR measurement should be collected after each compaction pass. When the GPR signal reflection amplitudes become relatively constant, the compaction process can be stopped, and the density of the compacted mixture should be verified by the EM density gauge.
5. After the final compaction of the asphalt pavement, the full-coverage 2-D GPR data should be collected. The locations corresponding to the maximum GPR signal reflection amplitude and minimum GPR signal reflection amplitude should be identified, and EM density gauge data should be collected at these two locations as the controlling density values. Then the density values at other locations can be predicted correspondingly to produce a GPR density colour map similar to Figure 27(a). This colour map can be used as the final data showing the full-coverage density distribution of the paved asphalt mat.

This study has demonstrated that EM density gauges, GPR, and infrared camera are effective nondestructive tools for asphalt pavement construction quality control. After reviewing the outcome of this study, the Highways Department of HKSAR government provided a positive attitude on implementing these nondestructive tools in practice to effectively enhance the construction quality of asphalt pavement and ensure it durability, although more local practice is desired to further gain experience and build confidence on these tools.

As a continuation of this research, the following recommendations are proposed:

1. The moisture sensitivity of the EM density gauge and GPR should be evaluated within a wider moisture range.
2. Pavement roughness and the presence of paint may affect the accuracy of GPR. Effort can be spent on determining the effect of surface roughness and paint on the accuracy of the density prediction using GPR system.
3. User-friendly GPR operation guideline and signal procession software for the purpose of asphalt pavement density prediction should be developed.
4. To obtain the real-time monitoring of the in-situ asphalt mixture density during construction, it is recommended to examine the feasibility of integrating the GPR system into the roller compactor. Effort may be focused on the appropriate way to install the GPR system to avoid antenna vibration during compaction and on the development of software to visually illustrate the real-time pavement density in a screen graphic. It is also recommended to integrate the thermal camera into the paving machine to achieve real-time monitoring of the paving temperature.
5. In this study, a single high-resolution infrared camera was used to collect thermal image of asphalt mixture from road side during construction. In the further study, a bar with infrared camera lens array is recommended to be installed to the paving machine to collect thermal image of asphalt mixture in a better controlled way.
6. More field data should be collected using various nondestructive tools to accumulate more field experience on these tools and allow local pavement engineers and contractors to have more confidence on these tools.
7. Feasibility of using these nondestrutive tools as QA tools should be further explored.

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