JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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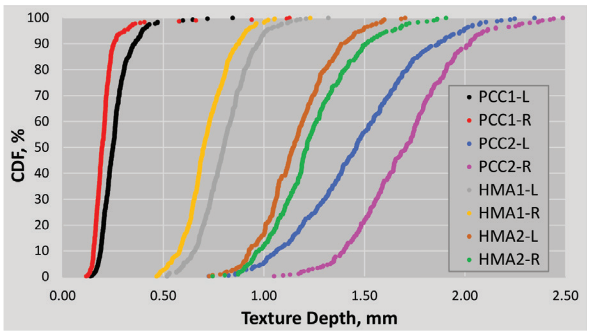
Quality Assurance Procedures for Chip Seal Operations Using Macrotexture Metrics



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16. Abstract

It is anticipated that in FYs 2017-21, the Indiana Department of Transportation (INDOT) will perform 1500 lane miles of chip seal work each year. To ensure successful chip seals, INDOT has implemented visual inspection quality assurance (QA) procedures. However, concerns, such as reliability and validity of visual inspection, time and labor, and safety, have been raised on the current QA procedures. In response, this study aimed at developing novel concepts and providing innovative solutions to enhance the current QA practices over chip seal jobs.

The mean profile depth (MPD) was selected as the macrotexture metric to measure the quality of chip seal by considering the performance measures for pavement construction. Extensive testing was conducted to validate the use of this macrotexture metric to provide a cost-effective solution to assuring the quality of chip seal construction. The setup of texture testing system was evaluated and verified on both test tracks and actual chip seal projects. A field test protocol was developed to implement QA for chip seal.

It was found that use of at least two point lasers, one for each wheel path, is needed and anticipated to acquire the necessary information for evaluating the characteristics of texture profiles and capturing the spots of bleeding or tracking in both wheel paths. Texture measurements in one direction can provide sufficient information for the quality assurance of chip seal. Chip seal in the driving lane may experience higher variability than that in the passing lane. Therefore, the texture depths in the driving lane may yield more strict standards for quality assurance of chip seal. The current two QA inspections performed after one month and 12 months of service, respectively, can be combined into a single, one-time QA inspection that should be conducted after the first snow season and can ensure both road safety and chip seal quality.

17. Key Words
chip seal, seal coat, quality assurance, quality rating, surface friction, surface texture, macro-texture metrics, mean profile depth (MPD), point texture laser

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EXECUTIVE SUMMARY

QUALITY ASSURANCE PROCEDURES FOR CHIP SEAL OPERATIONS USING MACROTEXTURE METRICS

Introduction

The Indiana Department of Transportation (INDOT) has implemented a comprehensive and proactive pavement preservation program to formalize preventive maintenance activities such as thin surface treatments, crack seal, and chip seal (seal coat) and to determine the optimum balance between preventive maintenance expenditures and capital expenditures. It is anticipated that in FYs 2017–21, INDOT's six districts will altogether perform approximately 1,500 lane miles of chip seal work each year. It has been recognized that the quality of chip seal relies to a great extent on the qualities of binder and aggregate, proper application rate, construction, and existing pavement condition. To ensure successful chip seals, INDOT has implemented special quality assurance (QA) procedures, i.e., Activity 2050 Mainline Seal Coat Quality Assurance Evaluation (MSQA) that allows INDOT maintenance engineers to assess the quality of a new chip seal based on visual inspection of two 1,000-foot sections selected from a chip seal project (INDOT, 2014).

However, concerns associated with the MSQA procedures have been identified by INDOT maintenance engineers. First, the quality of visual inspection by human eye relies on the vision, experience, and level of training of the inspector. Issues may arise over the reliability and validity of visual inspection. Two randomly selected 1,000-foot-long sections may not fully represent the overall quality of the chip seal project. Second, each district usually performs approximately 250 lane miles of chip seal work every year, which may encompass ten to twenty different roads. INDOT is currently able to inspect three to five roads per district per year. Third, visual inspection may become labor intensive, inefficient, and prone to errors as the current MSQA requires two visual inspections performed, respectively, one month and twelve months after construction. In addition, traveling vehicles may pose a threat to the inspector's safety during visual inspection.

In response to the growing concerns about chip seal quality and consequence and the need to enhance the efficiency of QA inspection, this study aimed to develop novel concepts and provide innovative solutions to enhance the current QA practices over chip seal jobs. Extensive testing was conducted to validate the concept of using macrotexture measurements to provide a cost-effective solution to assuring the quality of chip seal construction. The setup of a texture testing system was evaluated and verified on both test tracks and actual chip seal projects. Macrotexture metrics were determined by taking into account the performance measures for pavement construction. A field test protocol was developed to implement the QA for chip seal. There is no doubt that this study will not only ensure alignment between specifications, performance, and quality of end product, but also improve customer satisfaction, reduce life-cycle cost, and enhance operational efficiency.

Findings

Ride quality and safety are two critical performance measures that have been widely used to evaluate the quality of new pavement. The former is defined in light of pavement smoothness; the latter is defined in light of pavement friction. Pavement smoothness does not change much before and after placing chip seal, in particular single chip seal. However, chip seal premature or early failure is commonly accompanied by excessive aggregate loss or bleeding, or both, which will undoubtedly affect the surface frictional characteristics of chip seal. The surface of a failed chip seal tends to become slippery, leading to very low surface friction. Therefore, surface friction can be utilized as a performance-focused measure for assessing the quality of new chip seal.

INDOT conducts pavement friction testing in accordance with ASTM E274 (2015). This test requires intermittent acceleration or braking to adjust the speed of the test vehicle, which may impose significant impacts on traffic flow conditions and safety. In addition, this test cannot provide a seamless coverage of the road. Nevertheless, pavement friction varies with surface texture, test tire, presence of water, and test speed. When conducting friction testing at standard test conditions, surface texture becomes the dominant factor affecting pavement friction. Technologies are currently available to provide continuous texture measurements. It is advisable to use surface texture instead of friction for quality assessment or assurance.

Texture depth, spacing, and shape may be used to fully characterize the geometrical properties of a texture profile. To predict wet pavement friction, however, the mean profile depth (MPD) of macrotexture was found to be the best depth parameter. Field test results indicate a strong exponential relationship between MPD and friction exists, and MPD and friction variations follow a similar trend. It is evident that MPD is the best macrotexture metric to assess the surface friction, and therefore the quality of chip seal.

Field visual inspection revealed that bleeding and tracking are commonly found in the wheel paths, either in one wheel path or two wheel paths. Nevertheless, there are evident differences between the texture characteristics in the right and left wheel paths, due to the spatial variability of texture or the nature of pavement surface. Cumulative frequency distribution (CFD) provides an easy way to visualize large texture data sets and detect the small differences in the distribution of texture measurements.

Implementation

The following recommendations are made for future implementation:

- Use of two point lasers, one for each wheel path, is needed and anticipated to acquire the necessary information for evaluating the characteristics of texture profiles and capturing the spots of bleeding or tracking in both wheel paths.
- It is rational to perform texture testing in both directions for the quality assurance of chip seal. However, texture measurements made in one direction can provide sufficient information for the quality assurance of chip seal, which may be justified if resources are limited.
- Chip seal in the driving lane may experience higher variability than that in the passing lane. Therefore, the texture depths in the driving lane may yield more strict standards for the quality assurance of chip seal.
- The current two QA inspections performed after one month and twelve months of service can be combined into a single, one-time QA inspection that should be conducted after the first snow season and can ensure both safety and quality.

However, visual inspection is still necessary to identify problems earlier when corrective actions can still be taken and to avoid the consequence due to immediate and dramatic loss of surface friction. It is recommended that visual inspection should be conducted before applying fog seal.

- Chip seal QA can be measured in terms of the macrotexture metrics such as MPD and attribute percentile values. Although three equations have been developed to accomplish this, the equation below may yield the best estimation. $MSQA = 78.023 + 13.602 \times MPD - 0.011 \times Truck - 0.1716 \times Length$

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1. INTRODUCTION

1.1 Background

1.1.1 Problem Statement

The Indiana Department of Transportation (INDOT) has implemented a comprehensive and proactive pavement preservation program to formalize preventive maintenance activities such as thin surface treatments, crack seal, and chip seal (also known as seal coat), and determine the optimum balance between preventive maintenance expenditures and capital expenditures. To date, most INDOT pavement preventive work has been performed by INDOT maintenance crews. In fiscal year (FY) 2016, the pavement preservation projects by contractors, typically involving heavier treatments on higher traffic volume roadways, totaled approximately 262 lane miles. By contrast, INDOT maintenance crews completed more than 1,400 lane miles of chip seal. In particular, INDOT maintenance crews chip sealed more than 7,400 lane miles of pavement in the past five fiscal years (FYs 2012–16), more than 80% of the total lane miles of preservation work (excluding crack seal).

Successful chip seal relies to a great extent on the qualities of binder and aggregate, proper application rate, construction, and existing pavement condition. Special attention has also been directed toward identifying laboratory and field tests that can be correlated with successful chip sealing practice (Gransberg & James, 2005). To ensure a successful chip seal job, INDOT Maintenance Management and District Support has also developed special procedures, i.e., Activity 2050 Mainline Seal Coat Quality Assurance Evaluation (INDOT, 2014), to assist districts' maintenance crews in assessing the quality of chip seal. Poor quality control tends to affect chip seal performance due mainly to aggregate loss or bleeding, or both. Excessive aggregate loss or bleeding may cause a catastrophic failure of chip seal, which requires prompt repairs or remedial actions. It is anticipated that in FYs 2017–21, INDOT's six districts will altogether perform approximately 1500 lane miles of chip seal work each year. A rapid and practical field test will facilitate INDOT maintenance crews to ensure the success of chip sealing more efficiently.

In response to the growing concern about chip seal quality and consequence, this study aimed at developing novel concepts and innovative solutions that could allow INDOT to enhance the current QA practices over chip seal jobs. In addition, there is no doubt that this study will not only ensure alignment between specifications, performance and quality of end product, but also improve customer satisfaction, reduce life-cycle cost, and enhance operational efficiency.

1.1.2 Research Objectives

The primary objective of this study is to validate the concept of using macrotexture measurements to provide a cost-effective solution to assuring the quality of chip seal construction. The secondary objectives are: (1) to develop performance-driven metrics and criteria for accomplishing the primary objective; and (2) to identify the best practices to assist INDOT maintenance crews in further improving the current chip seal operations and quality control (QC) procedures.

1.2 Research Approach and Scope

To fulfill the objectives of this study, the research approach used in this study was a combination of physical measurements (data-driven) and subjective assessment (customer-focused). In addition to final report, the research scope included six main tasks as follows:

1. **Review of the state of the practice.** This task presented a synthesis of the state of the practice regarding QA or assessment of chip seal, in particular state DOTs' current practices such as procedures, field testing, and parameters used to assure chip seal quality and performance.
2. **Characterization of surface properties.** This task examined the effects of many factors on the quality and performance of chip seal and explored the potential relations between chip seal quality and surface properties. Focus was on the attributes of surface friction as friction number (or friction coefficient) and texture mean profile depth (MPD).
3. **Selection of testing system.** The test system was selected by taking into consideration the historical records and capabilities of the test system, verification test results, and initial cost. Preference was given to systems capable of providing both texture and roughness measurements at multiple positions such as right wheel path and left wheel path simultaneously. Verification testing was conducted on both the INDOT friction test track and actual chip seals.
4. **Field testing and inspection.** Extensive field testing was carried out to provide macrotexture and friction measurements in the selected chip seal sections. Visual inspection was also performed to provide assessment of chip seal quality. The selection of chip seal sections was carefully made in consultation with SAC members and districts maintenance managers. The factors considered when selecting the test sections include, but were not limited to aggregate type and size, application rate, traffic level, service time, and perceived quality.
5. **Data processing and analysis.** This task included three subtasks. The first subtask was data processing, in particular macrotexture test data processing. Default, proven procedures were employed to remove extreme values such as spikes in the measurements due to inherent system errors. The second subtask focused on the establishment of texture profiles that may represent the true surface texture profiles. The third subtask was to perform statistical analysis to examine the variability of chip seal surface texture and determine the statistical summaries of surface texture, such as mean, standard deviation and boundaries, from chip seal projects statewide. Cumulative frequency analysis and hypothesis test were also performed to detect the possible differences between texture attributes and validate system setup and test protocol.
6. **Macrotexture metrics and test protocol for chip seal QA.** This task was to establish and verify macrotexture metrics for implementing QA over chip seal. The macrotexture metrics were determined according to the test and analysis

results obtained in the previous tasks and can be readily verified. The field test protocol should be compatible or consistent with the test device proposed for checking the smoothness of a new pavement and be readily implemented.

2. CHIP SEAL QUALITY ASSURANCE AND TEXTURE METRICS

2.1 Current Practice for Chip Seal Quality Assurance

2.1.1 Potential Chip Seal Failure and Indicators

Many factors, such as asphalt binder, aggregate, existing pavement condition, weather, and construction operation, have been considered in the design and construction of chip seal. While INDOT has developed guidelines to implement quality control over the selection of materials, determination of application rate, equipment calibration, and construction operation (Lee & Shields, 2010), chip seal design, in particular application rate, may vary from road to road and project to project due to the variations associated with the factors that affect the success of a chip seal job. In addition, personnel experience and judgment has to some extent played an important role in achieving chip seal success. Therefore, the risk of chip seal failure may still exist as demonstrated by the chip seal project on SR-10 shown in Figure 2.1.

The failure, in particular premature failure of chip seal, is usually accompanied by excessive aggregate loss or bleeding, or both that tend to result in dramatic reduction in surface friction and vehicle damage (Li, Shields, Noureldin, & Jiang, 2012). To enhance the retention of aggregate, INDOT Maintenance Management and District Support has accepted a standard practice to apply a fog seal on a new chip seal after the final sweeping, commonly a couple of days after the road seal is opened to traffic. However, it was demonstrated that in Figure 2.2, there is nothing to guarantee that the application a fog seal on a new chip seal can always improve aggregate retention, in particular over the long term.

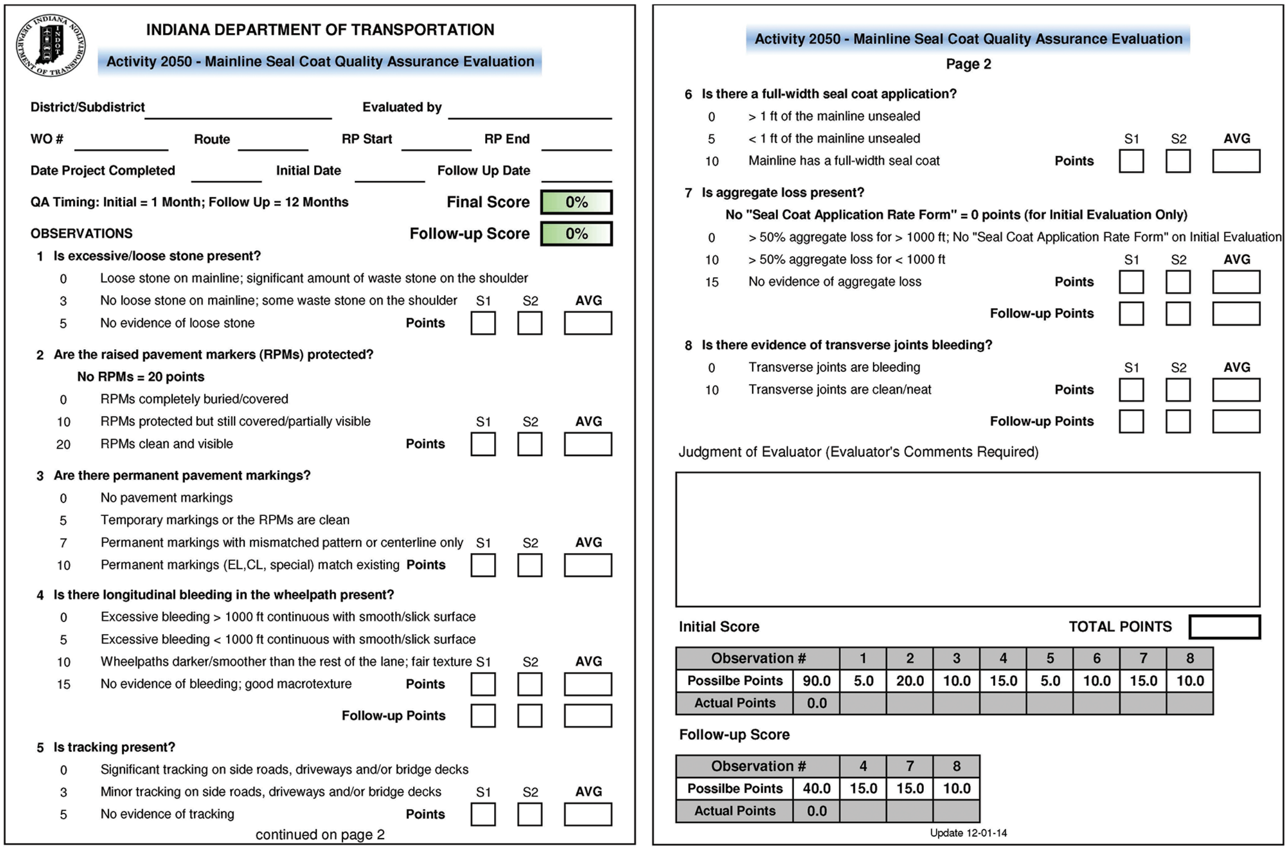
2.1.2 Current INDOT Practice

Mainline Seal Coat Quality Assurance Evaluation, hereafter referred to as MSQA, is currently utilized by INDOT maintenance crews to assess the quality of a new chip seal. MSQA consists of eight elements, of which four, including Observations 1, 4, 5 and 7, are related to either aggregate loss or bleeding as shown in Figure 2.3. MSQA allows INDOT to assess the quality of a new chips seal based on visual inspection of the chip seal surface. When performing visual inspection, two 1000-foot-long sections, designated as S1 and S2 (see Figure 2.3), are randomly selected from a chip seal project, and inspected independently. The inspection scores for each observation on the two sections are averaged and rounded to one decimal place. The sum of the average scores for all eight observations is used to rate the quality of the chip seal project. The perfect score for each observation item varies from 5 to 20 points and the total score ranges from 0 to 90 for the chip seal project. So far, MSQA has played a critical role in improving the qualities of material and workmanship incorporated in chip seal work and assuring that the performance of a new chip seal is in close conformity with the requirement.

However, there are three concerns associated with the above procedures. Firstly, the quality of visual inspection by human eye relies on the vision, experience (or knowledge), and level of training of the inspector. Issues may arise over the reliability and validity of visual inspection, particularly on a small scale. Travelling vehicles may pose a threat to the inspector's safety during visual inspection. Secondly, two randomly selected 1000-foot-long sections may not fully represent the overall quality of the chip seal project, particularly when it is several miles in length. Lastly, each district usually performs approximately 250 lane miles of chip seal work every year, which can encompass ten to twenty different roads. Currently we are only able to MSQA three to five roads per district per year. Visual inspection may become labor intensive, inefficient, and prone to errors as the current MSQA requires two visual inspections performed, respectively, one month and twelve months after construction.

Figure 2.1 Photo of chip seal experiencing aggregate loss.

Figure 2.2 Close-up of chip seal with fog seal.



INDIANA DEPARTMENT OF TRANSPORTATION

Activity 2050 - Mainline Seal Coat Quality Assurance Evaluation

District/Subdistrict ______ Evaluated by ______

WO # ______ Route ______ RP Start ______ RP End ______

Date Project Completed ______ Initial Date ______ Follow Up Date ______

QA Timing: Initial = 1 Month; Follow Up = 12 Months — Final Score 0%

OBSERVATIONS — Follow-up Score 0%

1 Is excessive/loose stone present?
- 0 Loose stone on mainline; significant amount of waste stone on the shoulder
- 3 No loose stone on mainline; some waste stone on the shoulder
- 5 No evidence of loose stone

Points: S1 S2 AVG

2 Are the raised pavement markers (RPMs) protected?

No RPMs = 20 points
- 0 RPMs completely buried/covered
- 10 RPMs protected but still covered/partially visible
- 20 RPMs clean and visible

Points: S1 S2 AVG

3 Are there permanent pavement markings?
- 0 No pavement markings
- 5 Temporary markings or the RPMs are clean
- 7 Permanent markings with mismatched pattern or centerline only
- 10 Permanent markings (EL,CL, special) match existing

Points: S1 S2 AVG

4 Is there longitudinal bleeding in the wheelpath present?
- 0 Excessive bleeding > 1000 ft continuous with smooth/slick surface
- 5 Excessive bleeding < 1000 ft continuous with smooth/slick surface
- 10 Wheelpaths darker/smoother than the rest of the lane; fair texture
- 15 No evidence of bleeding; good macrotexture

Points: S1 S2 AVG

Follow-up Points

5 Is tracking present?
- 0 Significant tracking on side roads, driveways and/or bridge decks
- 3 Minor tracking on side roads, driveways and/or bridge decks
- 5 No evidence of tracking

Points: S1 S2 AVG

continued on page 2

Activity 2050 - Mainline Seal Coat Quality Assurance Evaluation

Page 2

6 Is there a full-width seal coat application?
- 0 > 1 ft of the mainline unsealed
- 5 < 1 ft of the mainline unsealed
- 10 Mainline has a full-width seal coat

Points: S1 S2 AVG

7 Is aggregate loss present?

No "Seal Coat Application Rate Form" = 0 points (for Initial Evaluation Only)
- 0 > 50% aggregate loss for > 1000 ft; No "Seal Coat Application Rate Form" on Initial Evaluation
- 10 > 50% aggregate loss for < 1000 ft
- 15 No evidence of aggregate loss

Points: S1 S2 AVG

Follow-up Points

8 Is there evidence of transverse joints bleeding?
- 0 Transverse joints are bleeding
- 10 Transverse joints are clean/neat

Points: S1 S2 AVG

Follow-up Points

Judgment of Evaluator (Evaluator's Comments Required)

Initial Score — TOTAL POINTS

Observation #		1	2	3	4	5	6	7	8
Possilbe Points	90.0	5.0	20.0	10.0	15.0	5.0	10.0	15.0	10.0
Actual Points	0.0								

Follow-up Score

Observation #		4	7	8
Possilbe Points	40.0	15.0	15.0	10.0
Actual Points	0.0			

Update 12-01-14

Figure 2.3 Activity 2050 excel worksheets (INDOT, 2014).

2.2 Selection of Texture Metrics

2.2.1 Measures of Chip Seal Quality

Ride quality and safety are two critical pavement performance measures that have been widely used to evaluate the quality of new pavement. The former is commonly defined in light of pavement smoothness; the latter is often defined in light of pavement friction. Currently, INDOT quantifies pavement smoothness as International Roughness Index (IRI) and pavement friction as friction number (FN). It was found elsewhere that pavement smoothness does not change much before and after chip seal due to that chip seal, in particular single chip seal, is not thick enough to affect the profile of road surface (Lee, Ahn, Shields, Harris, & Li, 2013). This may imply that pavement smoothness may not be related to the quality of new chip seal. As pointed out earlier, chip seal premature or early failure is accompanied by excessive aggregate loss or bleeding, or both, which will undoubtedly affect the surface frictional characteristics of chip seal treatment. On the one hand, the surface of a failed chip seal tends to become slippery, leading to very low surface friction. On the other hand, chip seal is also a pavement preservation treatment commonly used to restore surface friction that is one of the critical pavement performance measures. *Therefore, surface friction can be utilized as one of the measures for assessing the quality of new chip seal.*

INDOT conducts pavement friction testing in accordance with ASTM E274 (ASTM, 2015). However, safety concerns may arise during field testing on highway facilities (Li, Noureldin, & Zhu, 2010). This is because when conducting friction testing on roadways, it requires intermittent acceleration or braking to adjust the speed of test vehicle, which may impose significant impact on the traffic flow conditions. In addition, the ASTM E274 test method cannot provide a seamless coverage of the road. Each friction test yields a friction number that is the average of friction resistance over a segment of approximately 60~90 feet long. Pavement friction varies with pavement texture, test tire, presence of water, and test speed. When conducting friction testing at standard test conditions, pavement texture becomes the dominant factor affecting pavement friction. Pavement texture is a physical aspect of the visual appearance of pavement surface and is independent of test conditions, such as tire and speed. Moreover, technologies are commercially available right now to provide continuous texture measurements. *It is advisable to use pavement texture measurements, instead of surface friction measurements, for quality assessment or assurance.*

2.2.2 Characterization of Pavement Texture

Pavement surface texture is generally divided into three groups in the Permanent International

Association of Road Congress (PIARC, 1987) international experiment below:

1. Microtexture: Wavelength < 0.5 mm (peak to peak amplitudes: 0.001~0.5mm)
2. Macrotexture: Wavelength = 0.5~50 mm (peak to peak amplitudes: 0.01~20mm)
3. Megatexture: Wavelength = 50~500 mm (peak to peak amplitudes: 0.1~50mm)
4. Unevenness: Wavelength > 500 mm

It has been recognized that microtexture and macrotexture are the two texture components that ultimately determine wet-pavement friction. Macrotexture varies with the mix properties, in particularly voids, aggregate (size, shape and gradation), and surface finishing, and can be readily measured at highway speeds. Microtexture, however, relies mainly on the surface feature of aggregate particle, and is measured using a surrogate. It was reported in the PIARC experiment that microtexture mainly affects wet pavement friction at low speeds and macrotexture becomes the dominant factor above 60 km/h. The above can be extended to conclude that it is reasonable to use macrotexture measurements to assess pavement friction. Currently, the macrotexture of pavement surface is characterized by a single parameter, i.e., the so-called mean profile depth (MPD) as follows (ASTM E1845-15, 2015):

$$MPD = \frac{1}{N}\sum_{i=1}^{N} MSD_i \quad (2.1)$$

in which, N is the total number of 100-mm long segments in the test section, and MSD is the mean segment depth of a 100-mm texture profile as illustrated in Figure 2.4, and is computed as the mean depth of the two peaks.

Fundamentally, surface texture is the composite of certain deviations that are typical of the real surface

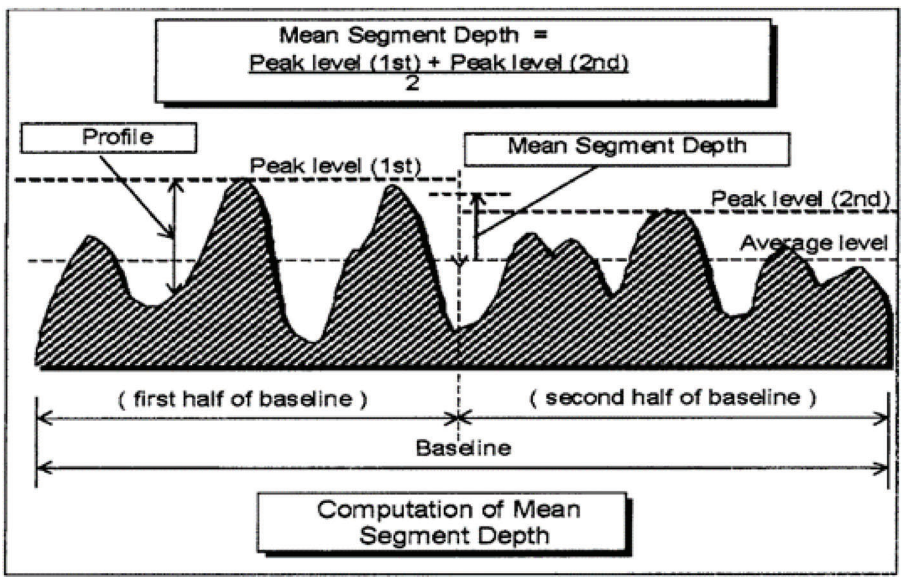


Figure 2.4 Illustration of procedures for computing mean segment depth (ASTM E1845-15, 2015).

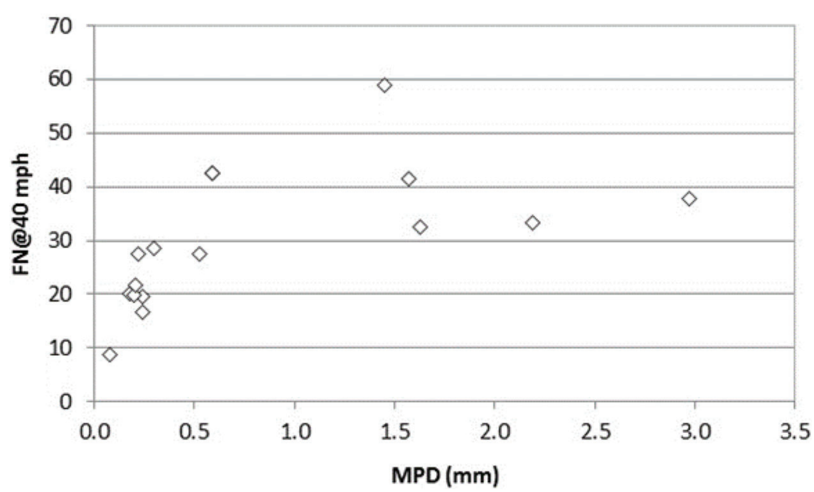


Figure 2.5 Correlation between FN and MPD made on different pavements.

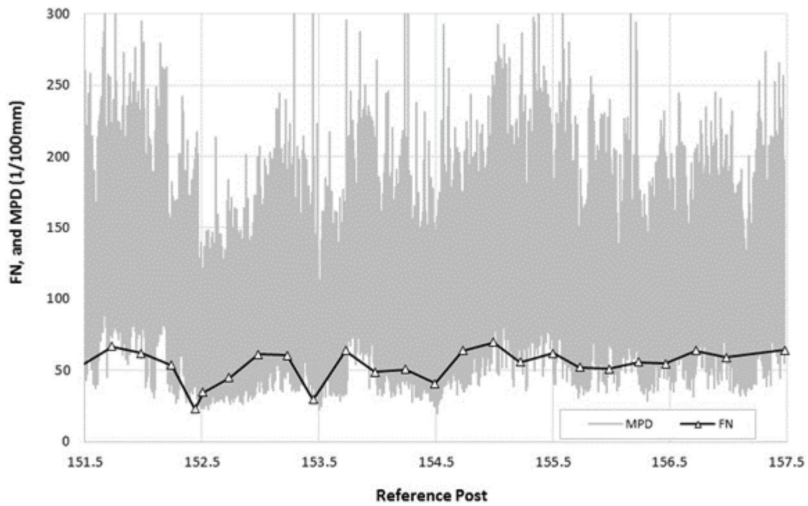


Figure 2.6 Variations of FN and MPD on new chip seal.

consisting of both peaks and valleys (ASME B46. 1-2009, 2009). To fully measure the characteristics of a texture profile for surface friction, three geometrical parameters, including texture depth, spacing, and shape, are commonly used to characterize the geometrical properties of texture profile. To predict wet pavement friction, however, the mean profile depth (MPD) of macrotexture was found to be the best depth parameter (Henry, 2000; PIARC, 1987). In reality, the authors have made both friction and texture measurements on various types of pavements as shown in Figure 2.5. It is shown that there exists a strong exponential relationship between MPD and FN at 40 mph using a smooth tire. The authors also measured both friction and MPD on a new chip seal (see Figure 2.6). Overall, MPD and FN variations followed a similar trend. *Evidently, MPD is the best macrotexture metric to assess the surface friction, and therefore the quality of chip seal.*

3. TESTING SYSTEM SETUP AND VERIFICATION

3.1 Setup of Testing System

3.1.1 Texture Measuring Instrument

Many noncontact profiling technologies, such as optical focus sensing and laser triangulation, are readily available for measuring surface texture profiles. To develop and validate the concept of using the MPD of macrotexture profile in assessing surface friction, and therefore assuring the quality of chip seal construction, the selection of texture measuring instrument was made by taking into consideration the many factors such as test speed, continuous measurement, accuracy, cost, and proven track record. Eventually, a laser-based instrument, as shown in Figure 3.1, was selected for field experimental studies. This instrument consists of a high-speed texture 100 kHz point laser that utilizes the triangulation methods and is capable of measuring macrotexture profiles at highway speeds. The detailed information about the specifications for the laser sensor can be found elsewhere (Ames Engineering, n.d.).

Figure 3.1 Point laser texture measuring instrument.

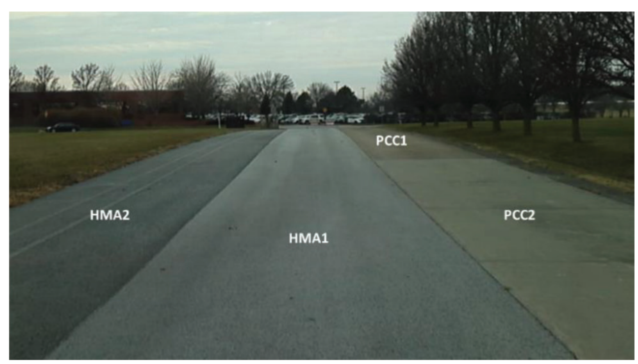


Figure 3.2 Close-ups of three different surfaces.

To verify the accuracy of the selected high-speed texture point laser, texture measurements were made using both the point laser and a portable 1 kHz laser texture scanner on three different pavements in the INDOT friction test track that is not open to traffic as shown in Figure 3.2. The three pavements, i.e., PCC1, HMA1, and HMA2, are transversely tined concrete pavement, 9.5-mm HMA pavement constructed in 2013, and 9.5-mm HMA pavement constructed in 2002, respectively. Notice that during testing, the 100 kHz point laser yields a single continuous texture profile that defined the MPD for each pavement surface. The 1 kHz laser texture laser that has been validated elsewhere (Li et al., 2010), however, scans a surface area of approximately 4.25″ × 2.835″ that is used to calculate the MPD. Presented in Table 3.1 are the average MPD values for these four different surfaces. It is shown that the MPD values measured using the two laser instruments, although there are some differences, are very close to each other.

3.1.2 System Setup

It has been recognized that the point laser can only produce a single texture profile that may not fully represent the true texture characteristics of a surface. Because of this, a number of point lasers may be required to yield more representative results. However, determination of the number of point lasers is not a pure science. In addition, the high-speed texture laser is currently expensive. As practical field trials, two point lasers were considered to simultaneously acquire texture profile data in the left and right wheel paths, respectively. The setup for the test system consisting of two point lasers is illustrated in Figure 3.3. In reality, it can be seen that in Chapter 2, the current chip seal field QA procedures, i.e., MSQA, include inspection of both longitudinal bleeding and tracking in the wheel paths. Field visual inspection also revealed that bleeding and tracking are commonly found in the wheel paths, in either one wheel path or two wheel paths as shown in Figure 3.4. Therefore, the use of two point lasers, one for each wheel path, is anticipated to acquire the necessary information for evaluating the characteristics of texture profiles and capturing the spots of bleeding or tracking in both wheel paths.

TABLE 3.1
MPD Values Measured Using Different Laser Sensors

Texture Instrument	PCC2	HMA1	HMA2
100 kHz Point Laser	1.583	0.761	1.199
1 kHz Laser Scanner	1.522	0.694	1.322

Figure 3.3 Photo of laser setup for acquiring texture data.

3.2 Track and Field Verifications

3.2.1 Verifications on INDOT Friction Test Track

Test trials were made to validate the system setup for acquiring texture profiles in the four pavement sections in the INDOT friction test track (see Figure 3.2). PCC2 is a concrete pavement with very smooth surface. Cumulative frequency distribution (CFD) was utilized to provide insight into the differences between the MPD measurements in the right and left wheel paths due to two main reasons. CFD provides an easy way to visualize large data sets and detect the small differences in the distribution of texture measurements. Second, peculiarities in the distribution can be easily perceived from the shape of cumulative frequency curve. Generally, a steep curve corresponds to close texture measurements, which may indicate a uniform surface. A flat curve, however, corresponds to texture values with high variability, which may suggest a non-uniform surface. As a result, the texture attribute values corresponding to a specific percentile such as the 25th,

(a) Bleeding occurred in left wheel path (b) Bleeding occurred in both wheel paths

Figure 3.4 Possible positions of bleeding and tracking in chip seal.

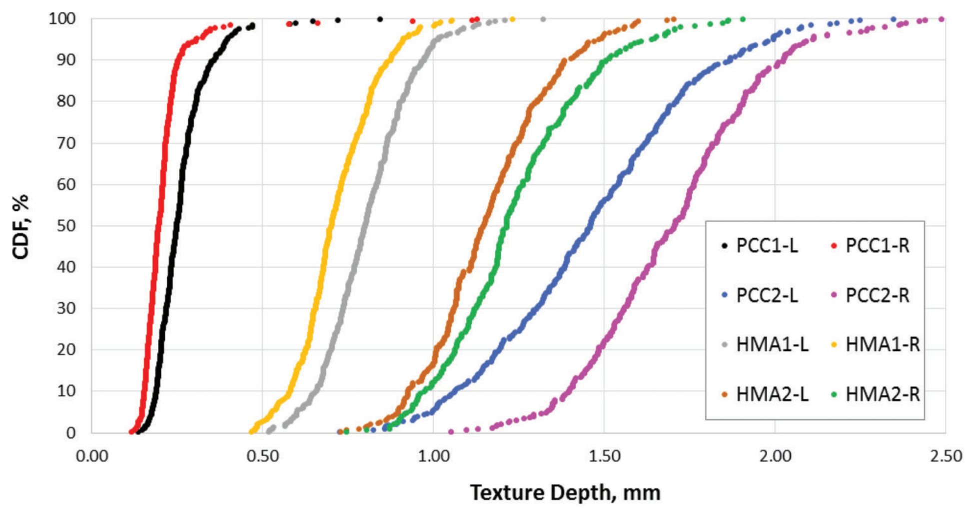


Figure 3.5 CFDs for texture measurements on INDOT friction test track.

50th, or 75th percentile can be identified and examined to possibly yield meaningful insights into the quality of a chip seal.

Figure 3.5 presents the CFD curves of the texture values measured over a 100-foot-long segment in the four pavement sections, respectively. In viewing the CFD curves, attention should be given to the shift and shape. A shift to the right indicates increase in texture depth. The CFDs for PCC1 show the steepest slope and much steeper than the CFDs for PCC2. The CFD curves for HMA1 are also steeper than the CFD curves for HMA2. One possible explanation is that HMA1 was constructed in 2013 and HMA2 was constructed in 2002. The former has not experienced raveling and the latter has experienced medium to severe raveling that has resulted in greater variability in surface texture. This implies that the CFD attributes may be utilized to evaluate the variability of surface texture. Second, there are evident differences between the CFD curves for the right and left wheel paths, regardless of the type of pavement. Again, this confirms that two point lasers, one for each wheel path, is needed to acquire the necessary information for determining the characteristics of surface texture.

3.2.2 Verifications on Actual Chip Seals

An original thought was that the differences between the texture measurements in the two wheel paths could be due to the spatial variability of texture or the nature of pavement surface, rather than the inherent errors of the testing system. To validate this thought, field testing was conducted to make texture measurements in the two wheel paths, over actual chip seals on SR-47, US-41, and US-136, respectively, by switching the two lasers. Figure 3.6 shows the CFDs for the texture measurements before and after switching the two lasers. Table 3.2 presents the statistical summaries of the texture measurements, including mean (MPD), standard deviation (Std Dev), and relative error, made before and after switching the two lasers. In all cases except for the left wheel path, US-136 eastbound and the right wheel path, US-41 southbound between RP 171 and 174, the before and after CFDs not only exhibit the same shape, but also are located approximately at the same position. The relative errors are 2.0% or less.

Statistical hypothesis tests were conducted to further verify whether there is any significant difference between the MPD values before and after switching lasers. The two assumptions first checked are whether the two samples are independent and whether the two samples follow the normal distribution. Since two lasers were always testing the same wheel path, the two samples should be inherently dependent. The Q-Q plot, which compares observed quantiles of MPD with quantiles of the normal distribution, is an intuitive graphical technique to detect the normality of a sample dataset. As shown in Figure 3.7, the x-axis of both Q-Q plots represents the normal quantile and the y-axis stands for quantiles of the sample data. The data points fall approximately along the straight reference line. It is likely that the sample follows the normal distribution.

Table 3.3 shows the results two normality tests, including Shapiro-Wilk and Kolmogorov-Smirnov tests. The null hypothesis of a normality test is that the sample does not significantly vary from the normal distribution. If the p-value is less than 0.05, the null hypothesis is rejected and the sample is not normally distributed. If the p-value is larger than 0.05, it fails to reject the null hypothesis and the assumption is valid. The Kolmogorov-Smirnov test is more accurate when the sample size is large, while the Shapiro-Wilk test is commonly used when the sample size is small. Based on the Shapiro-Wilk test, the sample before switching lasers follows a normal distribution because the p-value is 0.0765. After switching the lasers, the p-value is 0.0492 that is slightly less than 0.05, the sample barely follows a normal distribution.

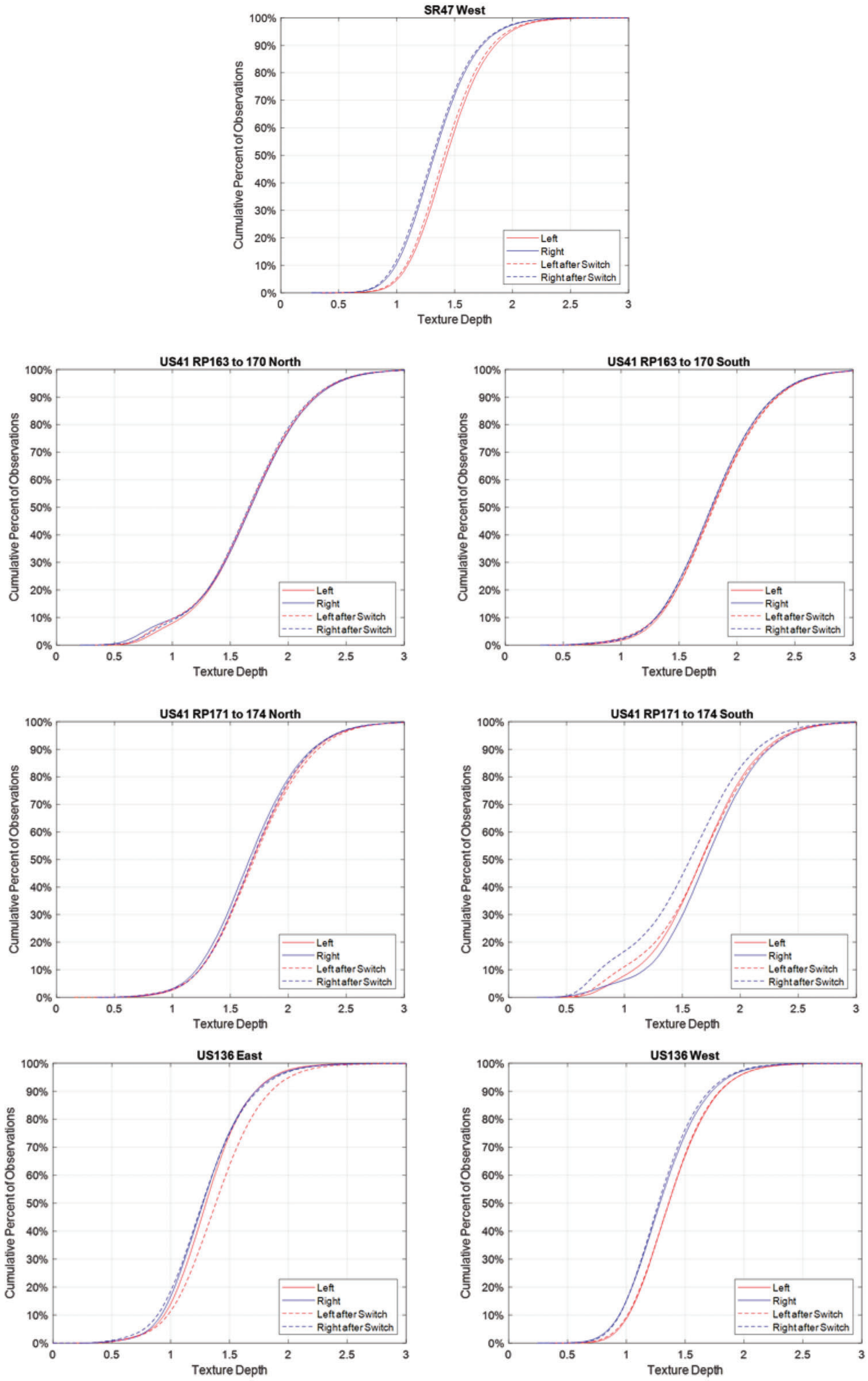


Figure 3.6 CFDs for texture measurements before and after switching lasers.

There are four methods, such as two sample t-test, Wilcoxon-Mann-Whitney test, paired t-test, and Wilcoxon Signed Rank test, available to test two sample means. Because the two samples are dependent and the samples follow a normal distribution before switching lasers and barely follow a normal distribution after switching lasers, both the paired t-test and Wilcoxon signed rank test can be used to test the differences

TABLE 3.2
Summaries of Texture Measurements before and after Switching Lasers

Road	Direction	Wheel Path	Laser Position	MPD (mm)	Std Dev (mm)	Relative Error (%)
SR-47	West	Left	Before Switching	1.465	0.301	1.86
			After Switching	1.434	0.298	
		Right	Before Switching	1.349	0.298	2.09
			After Switching	1.334	0.298	
US-41a (RP 163-RP 170)	North	Left	Before Switching	1.674	0.449	1.02
			After Switching	1.657	0.459	
		Right	Before Switching	1.662	0.472	0.42
			After Switching	1.655	0.454	
	South	Left	Before Switching	1.814	0.415	0.06
			After Switching	1.813	0.404	
		Right	Before Switching	1.796	0.410	-0.28
			After Switching	1.801	0.409	
US-41b (RP 171-RP 174)	North	Left	Before Switching	1.720	0.396	-0.64
			After Switching	1.731	0.406	
		Right	Before Switching	1.693	0.400	-0.95
			After Switching	1.709	0.391	
	South	Left	Before Switching	1.662	0.437	0.72
			After Switching	1.650	0.472	
		Right	Before Switching	1.705	0.437	9.85
			After Switching	1.537	0.493	
US-136	East	Left	Before Switching	1.317	0.320	-6.45
			After Switching	1.402	0.376	
		Right	Before Switching	1.302	0.34	0.61
			After Switching	1.294	0.352	
	West	Left	Before Switching	1.390	0.312	0.36
			After Switching	1.385	0.315	
		Right	Before Switching	1.314	0.317	0.76
			After Switching	1.304	0.304	

between MPD samples before and after switching lasers. The null hypothesis H_0 states that there is no significant difference of MPD by two lasers, while the alternative hypothesis H_a states that the difference of MPD is significant. Table 3.4 shows the basic and test statistics for the difference of MPD. The p-value is 0.2684 from paired t-test and 0.7520 from Wilcoxon signed rank test. Since the p-values for both tests are greater than 0.05, it fails to reject the null hypothesis, the difference of two sample means is insignificant. *Therefore, there is no significant difference about test results if two lasers are switched.*

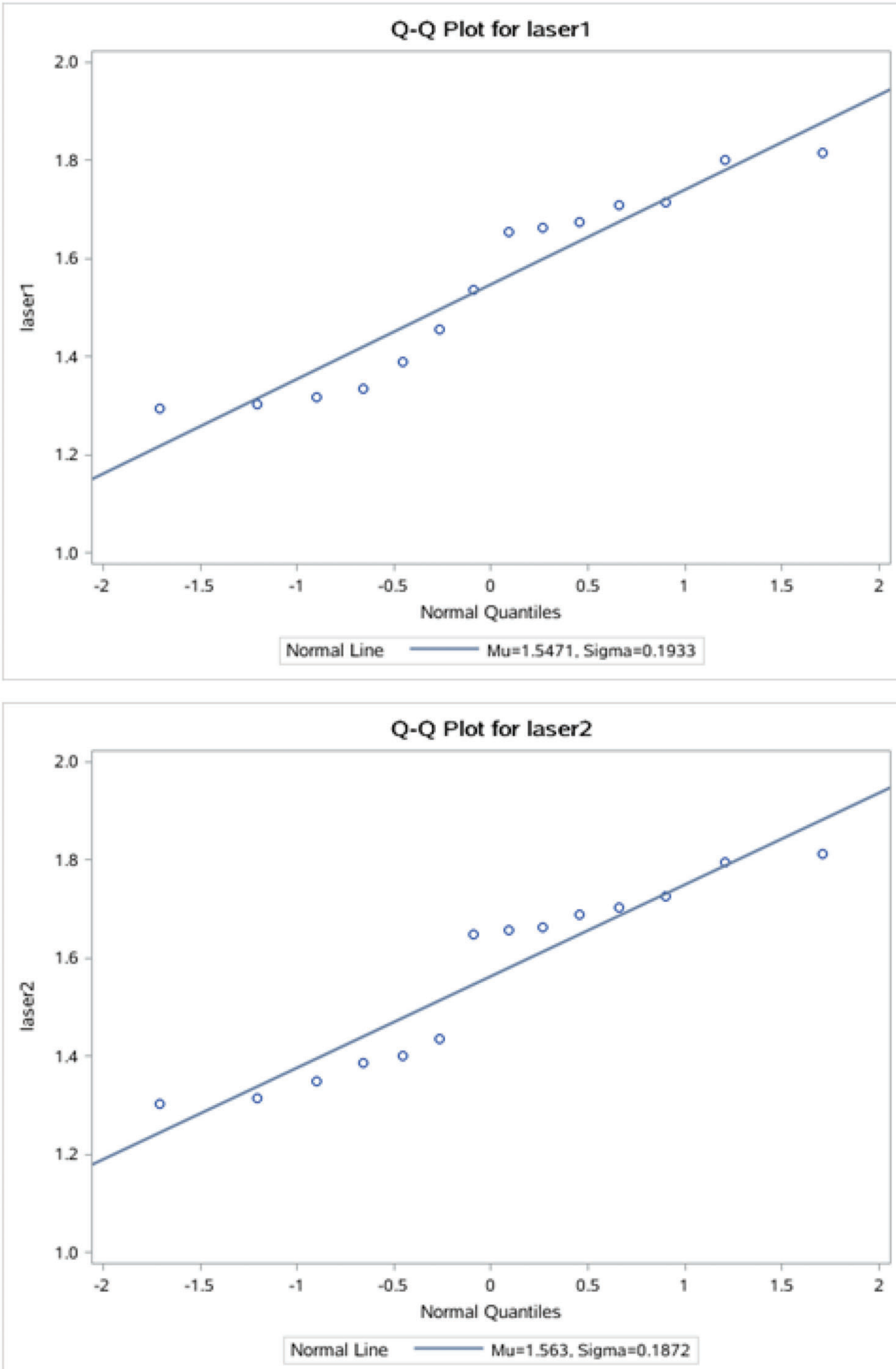


Figure 3.7 Q-Q plots for texture measurements before and after switching lasers.

TABLE 3.3
Normality Test for Two Laser Test Samples

Laser Position	Test Method	Statistic	p-Value
Before Switching	Shapiro-Wilk	W 0.888334	Pr < W 0.0765
	Kolmogorov-Smirnov	D 0.209782	Pr > D 0.0924
After Switching	Shapiro-Wilk	W 0.874885	Pr < W 0.0492
	Kolmogorov-Smirnov	D 0.248446	Pr > D 0.0196

TABLE 3.4
Test Statistics for the Laser Difference

Number of Observations	14
Mean	-0.0159
Standard Deviation	0.0513
Variance	0.0026
Skewness	-2.4806
Kurtosis	6.3752
Coefficient of Variation (%)	-323.64
Student's t Statistic, t	-1.1561
Student's t Test p Value	0.2684
Signed Rank Statistic, S	-5.5
Signed Rank p Value	0.7520

4. EXPERIMENTAL FIELD STUDIES

4.1 Spatial Variations of Chip Seal Surface Texture

4.1.1 Variations with Locality

INDOT is divided into six geographical districts for the purpose of organizing and managing highway planning, construction, maintenance, traffic, development and testing. In addition to differences in weather conditions, differences also exist between the construction practices for chip seal by the districts. Table 4.1 shows six chip seal projects that demonstrate different aggregates and asphalt emulsion binders used by the six districts. The detailed information on the aggregate and asphalt emulsion properties can be found elsewhere (INDOT, 2017). In addition, different roads may have different geometric features, undergo different traffic applications, and experience different pavement conditions. In the same section of a certain road, both pavement and traffic conditions may vary from direction to direction and lane to lane. Therefore, spatial variations associated with chip seal surface texture are natural and inevitable. The texture attributes of chip seal may vary from district to district, road to road, direction to direction, lane to lane, and location to location.

Field experimental tests were conducted on a total of 64 chip seal projects completed by five districts, including Crawfordsville, Fort Wayne, Greenfield, LaPorte, and Seymour, in 2017, and the results, including MPD and standard deviation (Std Dev), are presented in Figure 4.1. The MPD values for LaPorte District varied most significantly from road to road, and the MPD values for Seymour District varied least significantly from road to road. However, the standard deviations of texture measurements for Greenfield District varied most significantly from road to road, and the standard deviations of texture measurements for LaPorte District varied least significantly from road to road. Summarized in Table 4.2 are the average values of MPD, standard deviation, and coefficient of variation (COV) for all chip seal projects by district, as shown in Figure 4.2. Overall, the chip seals in LaPorte District demonstrate the largest texture depth but the lowest variability, and the chip seals in Seymour District demonstrate the medium texture depth but the highest variability.

4.1.2 Variations with Longitudinal Position

To illustrate the variations of chip seal surface texture in longitudinal position, Figure 4.2 shows the texture measurements made in a 1-mile segment from an 8.0-mile long chip seal project on SR-14. As illustrated in Equation 2.1, the MSD is calculated in terms of 100-mm long segment. There are approximately 16130 MSD values in each wheel path over a 1-mile segment. Clearly, Figure 4.2 shows the variations and spikes of MSD values over the entire 1-mile segment. However, it does not provide detailed and accurate information to detect the trend of variation and compare the two MSD datasets from the right wheel path (RWP) and left wheel path (LWP), respectively. For a several-mile long chip seal project, in particular, the test dataset will be very large. It may become more difficult to use traditional charts to produce conclusive insights.

Instead, this study frequently utilized CFD analysis as shown in Chapter 3. CFD provides an easy way to visualize large data sets and detect the small differences in the distribution of texture measurements. Peculiarities in the distribution can be easily perceived from the shape of CFD curve. Generally, a steep curve corresponds to close texture measurements, which may indicate a uniform surface. A flat curve, however, corresponds to texture values with high variability, which may suggest a non-uniform surface. Plotted in Figure 4.3 are the CFDs for the same texture measurements as presented in Figure 4.2. It is demonstrated that the two texture datasets in the right and left wheel paths are evidently different. The texture depth ranges approximately between 0.1 mm and 2.2 mm in the left wheel path (LWP), and between 0.1 mm and 2.6 mm in the right wheel path (RWP). More than 95% of the texture depths are approximately 1.25 mm or less. Most importantly, the differences

TABLE 4.1
Typical Materials and Application Rates for Chip Seal by District

		Aggregate			Asphalt Emulsion	
District	**Road**	**Size**	**Type**	**Rate (lb/yd^2)**	**Type**	**Rate (gal/yd^2)**
Crawfordsville	SR-42	SC 16	Gravel	20.0~25.0	AE-90S	0.360
Fort Wayne	US-24	SC 16	Dolomite	19.0	CRS-2P	0.370
Greenfield	SR-38	SC 11	Limestone	21.3	AE-90S	0.368
LaPorte	US-231	SC 16	Gravel	22.3	AE-90S	0.325
Seymour	SR-45	SC 11	Dolomite	24.0	CRS-2P	0.378
Vincennes	SR-257	SC 11	Dolomite	24.0	AE-90S	0.320

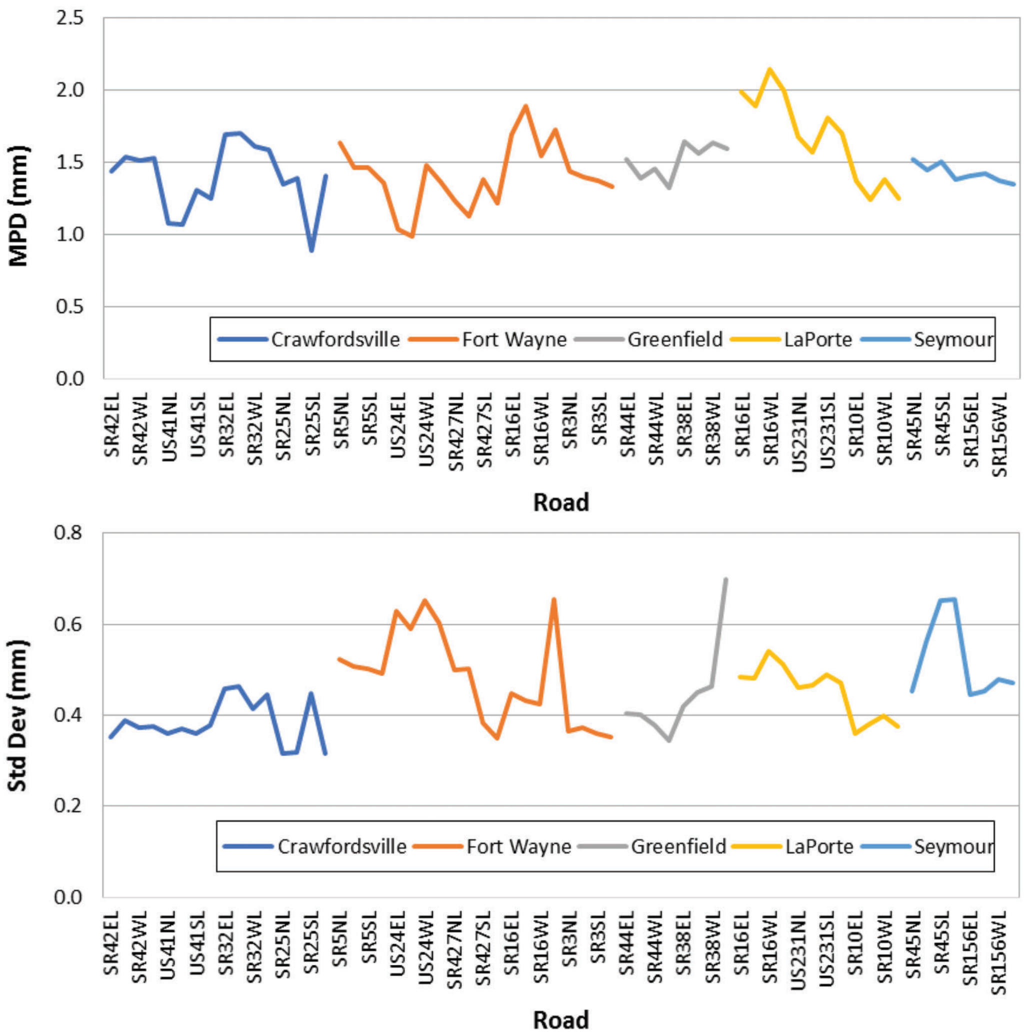


Figure 4.1 MPD and standard deviations by road.

TABLE 4.2
Statistical Summaries of Chip Seal Texture Measurements by District

Road	**Crawfordsville**	**Fort Wayne**	**Greenfield**	**LaPorte**	**Seymour**
MPD (mm)	1.394	1.406	1.512	1.667	1.425
Std Dev (mm)	0.384	0.482	0.445	0.452	0.521
COV (%)	27.5	34.3	29.4	27.1	36.6

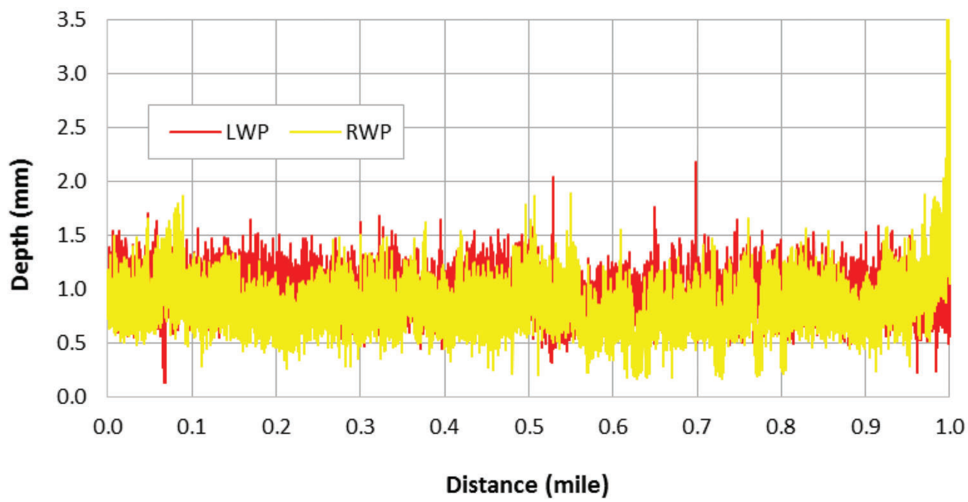


Figure 4.2 Texture depth variations on SR-14 eastbound.

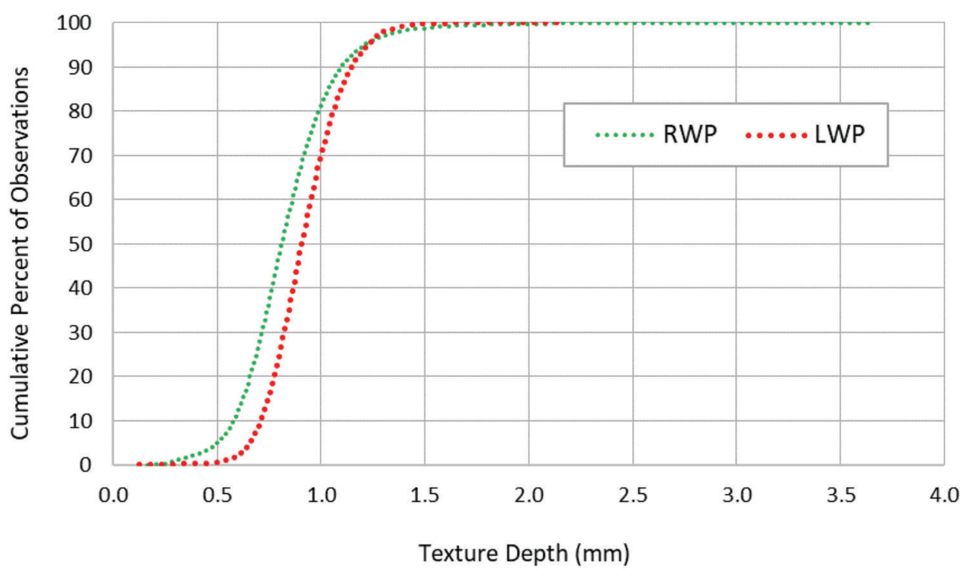


Figure 4.3 CFDs for texture measurements on SR-14 eastbound.

may be quantified with respect to the differences between the texture attribute values corresponding to a specific percentile such as the 25th, 50th, or 75th percentile.

4.1.3 Variations with Lateral Position

To examine the texture variations with lateral position from lane to lane and direction to direction, texture testing was conducted on six actual chip seals, including two constructed in 2015 on SR-75 and SR-10, one constructed in 2016 on US-12, and three constructed in 2017 on US-41 and SR-136. Plotted in Figure 4.4 are the CFDs for the texture measurements from these six chip seals. Again, it is demonstrated that there are evident differences between the texture measurements in the right and left wheel paths. Careful inspection of these CFD curves further reveals that for all chip seals except for the one on SR-136, the two texture datasets for the two right (or left) wheel paths in both directions exhibit approximately the same distribution, regardless of service time. Hypothesis test was also conducted on the texture measurements. At a confidence level of 95%, the texture dataset from the right (or left) wheel path in one direction is identical to the texture dataset from the right (or left) wheel path in the other direction. The above can be extended to conclude that the texture measurements in one direction can provide sufficient information for the quality assurance of chip seal.

Plotted in Figure 4.5 are the CFDs for the texture measurements made in all lanes over chip seal on a 4-lane, SR-9. In both directions, the CFDs for both the passing (left) and driving (right) lanes exhibit a similar trend and shape. However, the CDFs for the driving lanes shift to the right. This indicates that the texture depth in the driving lane is generally less than that in the passing lane, particularly in the right wheel path. One possible reason is the unequal traffic distribution

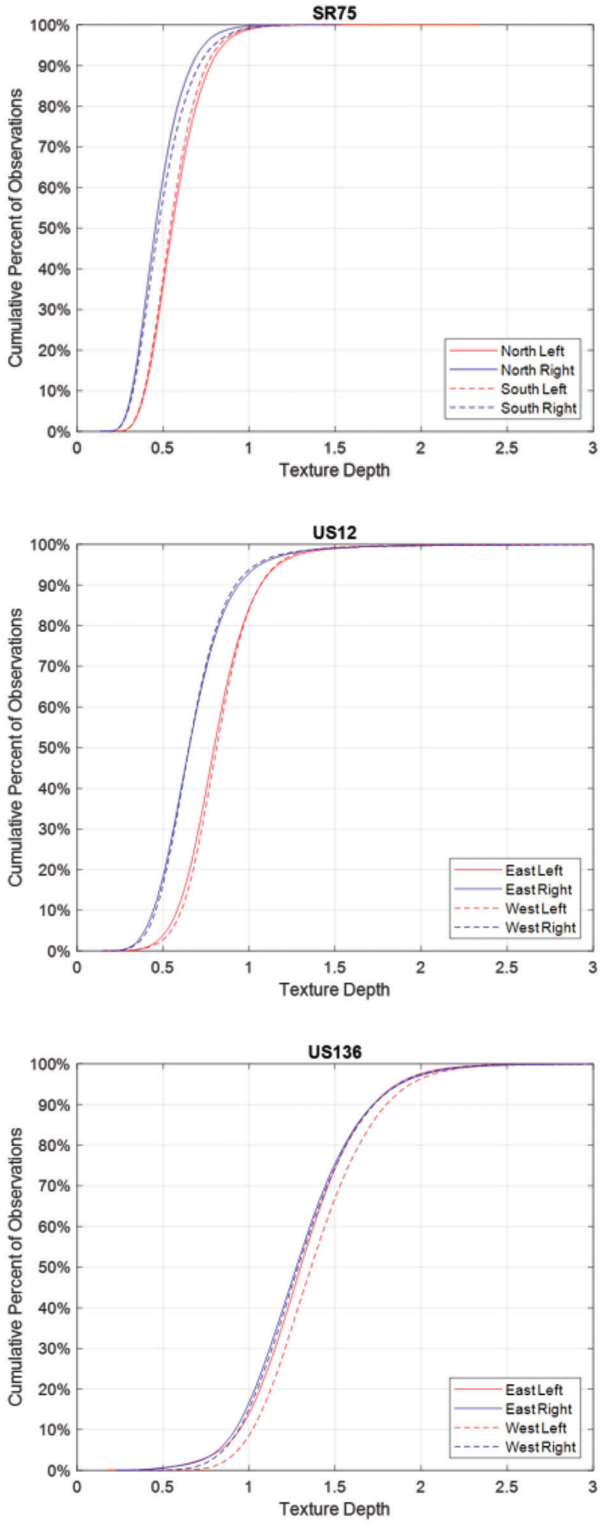


Figure 4.4 CFDs for texture measurements on six different roads.

between the driving and passing lanes. Traffic lane distribution varies with vehicle type and the driving lane may carry up to 94% of total five-axle semi-trucks on a four-lane road (Jiang, Li, Nantung, & Chen, 2008). Table 4.3 presents the statistical summaries of the texture measurements for each lane. On average, the MPD in the driving lane is 9.0% less than that in the passing lane. This implies that chip seal in the driving lane may

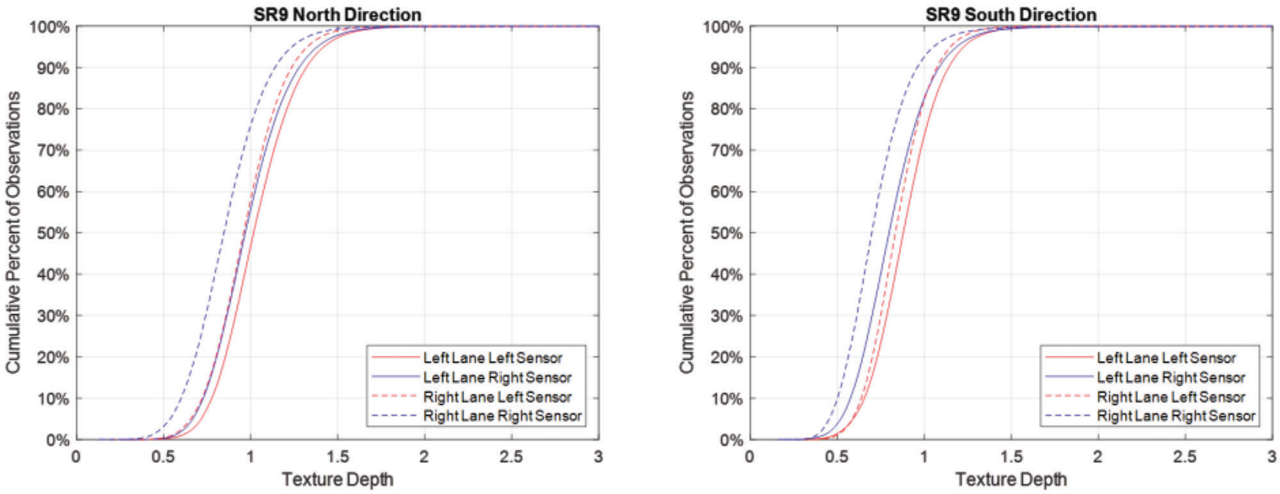


Figure 4.5 CFDs for texture measurements in different lanes.

TABLE 4.3
Statistical Summaries of Texture Measurements by Lane

			Texture Depth (mm)				
Direction	**Lane**	**Wheel Path**	**Min.**	**Max.**	**MPD**	**Std Dev**	**COV (%)**
North	Left	Left	0.261	3.640	1.037	0.219	21.1
		Right	0.252	3.816	0.991	0.222	22.4
	Right	Left	0.190	2.938	0.972	0.204	21.0
		Right	0.129	3.800	0.862	0.217	25.2
South	Left	Left	0.252	4.957	0.892	0.199	22.3
		Right	0.161	5.824	0.819	0.210	25.6
	Right	Left	0.306	9.423	0.847	0.176	20.8
		Right	0.196	4.243	0.721	0.196	27.2

experience higher variability than that in the passing lane. Texture depths in the driving lane may yield more strict standards for quality assurance of chip seal.

4.2 Temporal Variations of Chip Seal Surface Texture

4.2.1 Year-to-Year Texture Variations

It is hard to overstate the importance of the timing for quality assurance inspection for chip seal construction. The current QA procedures by INDOT consists of two inspections, including an initial inspection performed one month after construction and a follow-up inspection performed 12 months after construction. To verify the current practice, this study examined the texture variations of chip seal projects over time. Due to lack of historical texture test data, texture measurements were simultaneously made on chip seals constructed by different districts in 2015, 2016, and 2017, which allows the authors to evaluate the year-to-year texture variations approximately. In reality, year-to-year texture variations may eliminate seasonal effects and provide an effective way to perceive the trends of long-term texture variations for chip seals. Plotted in Figure 4.6 are the MPD values for chip seals over time by district.

Because texture tests were simultaneously conducted in 2017, the MPD measurements on chip seals constructed in 2015 were used as surrogate MPDs for chip seals after two years of service, and the MPDs measured on chip seals constructed in 2016 were used as surrogate MPDs for chip seals after one year of service. It is shown that in Figure 4.6, the MPD values are 0.813 mm, 1.015 mm, and 1.481 mm in 2015, 2016, and 2017, respectively, over these five districts. On average, the MPD decreased approximately by 31% from 2017 to 2016, i.e., in the first year, and 20% from 2016 to 2015, i.e., in the second year. In addition, the MPD in 2016 and 2017 varied more significantly than in 2015. This indicates that the MPD for a chip seal tends to decrease over time and the decreasing rate decreases over time. *Therefore, it can be concluded that if surface texture metrics are utilized for QA of chip seal construction, the inspection should be performed no later than 12 months after construction.*

4.2.2 Monthly Friction Variations

To provide more precise information on the variation of chip seal surface texture over time, this study re-examined the friction test results reported elsewhere

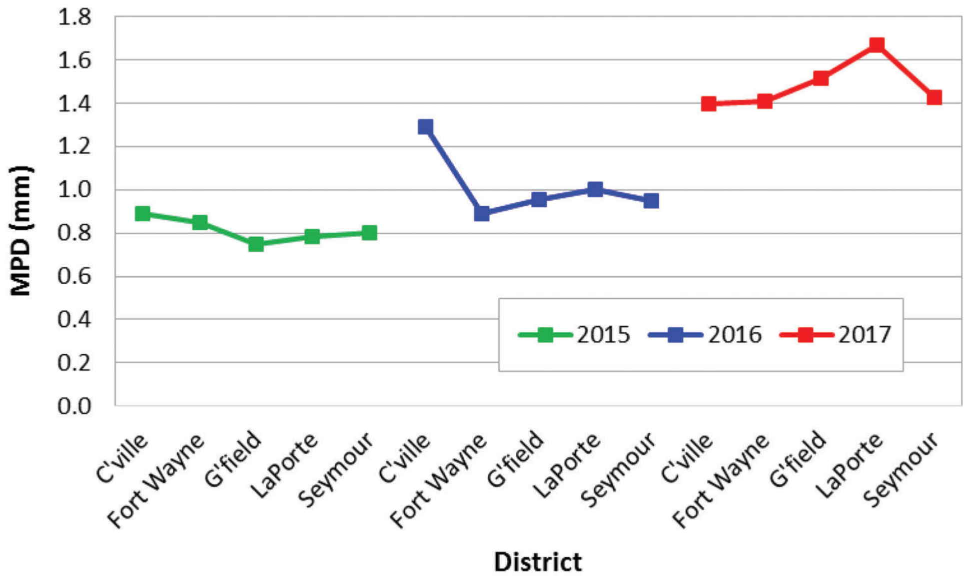


Figure 4.6 Variations of MPD and COV over time by district.

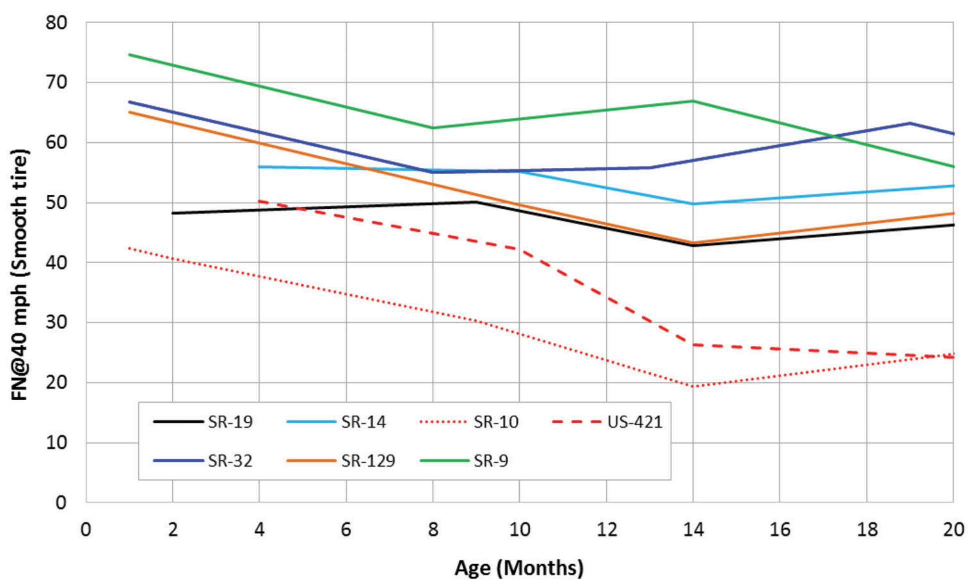


Figure 4.7 Friction variations of single chip seal over time.

(Li, Noureldin, Jiang, & Sun, 2012; Li et al., 2017). Presented in Figure 4.7 and Figure 4.8 are the surface friction numbers on two types of chip seals such as single chip seal and single chip seal with fog seal. The single chip seal with fog seal is a variation of the single chip seal and involves applying fog seal to the single chip seal approximately two days later. Field visual inspections revealed that three chip seals, including two single chip seals on SR-10 and US-421, and one single chip seal with fog seal on US-36, had experienced either excessive aggregate loss, bleeding, or both. Accordingly, dramatic decreases in friction occurred in these three chip seals during the first year of service. After around 12 months of service, the friction numbers on these three chip seals fluctuated around 20 over time.

The friction of chip seal surface experienced greater variability during the first 12 months. Particularly during the period of first six to eight months, the trend of friction variation varied over time and from project to project. Notice that chip seals are commonly placed from June to September in Indiana. There are two advantages associated with the current QA practice by INDOT. First, the initial QA inspection conducted after one month of service can detect any pre-mature failure timely and result in immediate actions. Second, the follow-up QA inspection conducted after 12 months of service can detect the potential effect of snow plow and ensure long-term performance. As shown in Figures 4.7 and 4.8, catastrophic failure that may cause significant reduction in friction typically occurs after 12 months of

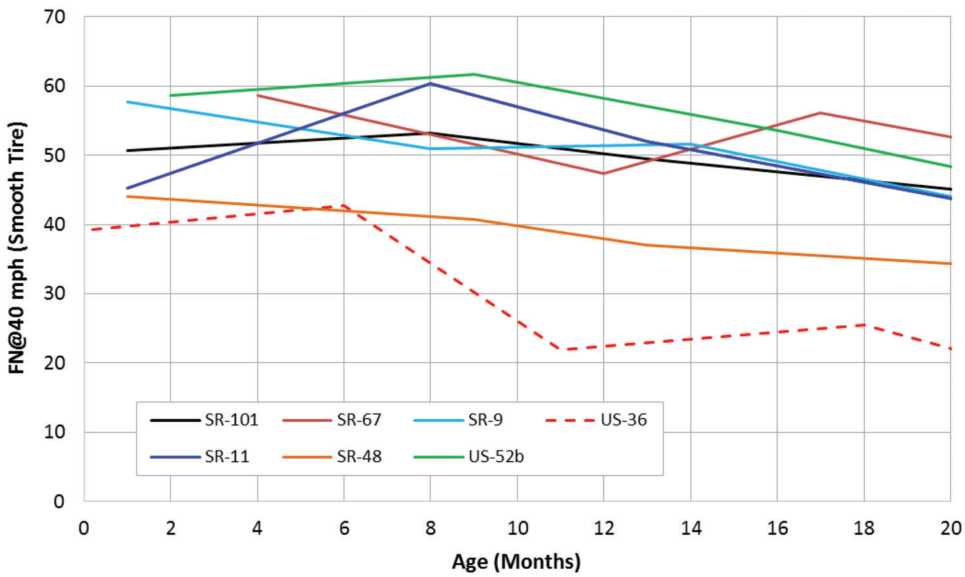


Figure 4.8 Friction variations of single chip seal with fog seal over time.

service. In addition, new chip seals will have been in service for about six to eight months when the first snow season ends. *Consequently, the current two QA inspections performed after one month and 12 months of service can be combined into a single, one-time QA inspection that should be conducted after the first snow season and can ensure both road safety and chip seal quality.*

4.3 Establishment of Macrotexture Metrics

4.3.1 2017 Chip Seal Projects

To explore and develop the relationships between objective texture measurements and subjective MSQA scores, a total of 30 new chip seal projects completed in 2017 were selected, of which 6 projects were from Crawfordsville District, 7 projects from Fort Wayne District, 4 projects from Greenfield District, 3 projects from LaPorte District, 9 projects from Seymour District, and one project from Vincennes District. Tabulated in Table 4.4 are the descriptive statistics of texture measurements, including sample size, mean (MPD), standard deviation (Std), minimum value (Min), maximum value (Max), and various percentiles denoted by letter “P”. For example, P75 stands for the 75th percentile, that is, 75% of texture data falls below the value of P75. Because the percentiles may provide insight into chip seal quality, they were included in the analysis in addition to MPD and standard deviation. It should be pointed out that because 15 out of 30 chip seal projects were rated 100% in terms of MSQA, bias and complexity could arise associated when correlating texture measurements to MSQA rating.

Table 4.5 presents the calculated MPD, standard deviation (Std), confidence interval, and percentiles by MSQA rating that is divided into five levels at 5-point interval or three levels at 10-point interval. When the MSQA rating is divided into 3 levels, the MPDs are 1.412, 1.379, and 1.028 for 100%, 90%~100%, and 80%~90%, respectively. When the MSQA rating is divided into five levels, the MPD fluctuates within a small range, but overall decreases as MSQA score decreases. The confidence intervals are very narrow due to the large sampling size during texture testing, resulting in limited information on MSQA rating. It can be concluded that overall, there exists correlation between MSQA rating and summary statistics such as MPD and percentile texture attributes.

4.3.2 Analysis of Texture Depth Percentiles by Principal Component Analysis

The MPD, texture Standard Deviation, texture P10, P25, P50, P75, and P90 in Table 4.4 are all summary statistics from texture measurements and correlations may exist among these variables. Pearson correlation coefficients were calculated to measure the relationships between these variable as shown in Figure 4.9. All texture percentile variables (P10 to P90) in the correlation matrix are positively correlated. Strong correlations ($|\rho|>0.8$) and moderate correlations ($0.4<|\rho|<0.8$) are found for most pairs of variables. However, the standard deviation (Std) has weaker relationships with some percentiles ($\rho<0.4$) . Due to the collinearity among MPD, P10, P25, P50, P75, and P90, interpretation can be difficult if all of them are included in the regression model, but more predictor variables usually contain more information.

Principal component analysis (PCA) was used to deal with the above dilemma. PCA is a widely used dimensionality reduction technique to reduce a larger set of correlated variables to a smaller set that contains most of the information in the larger set (Jolliffe, 2002). In short, PCA is performed on the correlation matrix or covariance matrix of the existing p variables (i.e., P10 to

TABLE 4.4
Statistical Summary of 2017 Chip Seal Projects

District*	Road	QA	IRI	N	MPD	Std	Min.	Max.	P10	P25	P50	P75	P90
CF	SR157a	95	115.41	318227	1.446	0.380	0.238	5.662	0.991	1.177	1.411	1.679	1.948
CF	SR157b	98	119.19	318899	1.317	0.364	0.001	9.100	0.884	1.096	1.310	1.540	1.772
CF	SR236	100	84.58	320000	1.496	0.305	0.308	8.573	1.130	1.282	1.471	1.682	1.895
CF	SR32	100	84.4	658593	1.645	0.445	0.176	9.856	1.108	1.354	1.625	1.919	2.209
CF	SR47	91	64.84	324780	1.364	0.300	0.263	4.120	1.003	1.155	1.340	1.548	1.758
CF	US136	95	98.66	323601	1.330	0.324	0.173	9.823	0.953	1.111	1.305	1.522	1.744
FW	SR124	100	71.3	194920	0.919	0.288	0.203	5.990	0.580	0.711	0.887	1.092	1.297
FW	SR14	100	89.62	368528	1.182	0.364	0.123	7.050	0.729	0.929	1.161	1.407	1.648
FW	SR16	100	119.08	573529	1.710	0.433	0.231	9.220	1.180	1.409	1.683	1.982	2.276
FW	SR18	100	94.19	146406	1.525	0.419	0.160	8.750	0.991	1.278	1.531	1.786	2.032
FW	SR427	100	102.25	393355	1.234	0.453	0.148	7.567	0.671	0.916	1.199	1.506	1.822
FW	SR5	100	93.65	802809	1.479	0.514	0.165	9.970	0.809	1.117	1.464	1.817	2.150
FW	SR9	83	93.99	640940	0.893	0.227	0.129	9.423	0.618	0.735	0.876	1.030	1.185
GF	SR13	95	82.56	127520	1.405	0.344	0.192	9.332	1.002	1.188	1.391	1.613	1.836
GF	SR213	100	99.24	125692	1.238	0.305	0.184	8.548	0.893	1.032	1.205	1.409	1.627
GF	SR234	85	77.92	192318	1.069	0.258	0.211	7.223	0.765	0.891	1.046	1.221	1.403
GF	SR28	83	91.04	180017	1.017	0.279	0.008	9.976	0.709	0.834	0.989	1.165	1.352
LP	SR331	100	79.19	256520	1.528	0.331	0.391	7.267	1.136	1.298	1.500	1.726	1.955
LP	SR39	100	93.61	150460	1.249	0.328	0.221	3.590	0.833	1.044	1.250	1.458	1.657
LP	US231	100	82.43	420218	1.685	0.479	0.205	6.685	1.090	1.370	1.670	1.986	2.296
SM	SR156	91	94.62	1087559	1.384	0.448	0.001	9.968	0.836	1.060	1.354	1.665	1.965
SM	SR160	100	141.41	335766	1.401	0.344	0.151	9.993	1.005	1.171	1.370	1.596	1.832
SM	SR250a	98	134.84	331096	1.265	0.314	0.001	9.252	0.904	1.053	1.234	1.440	1.659
SM	SR250b	95	159.26	69954	1.265	0.346	0.119	5.020	0.869	1.030	1.226	1.457	1.701
SM	SR252	95	134.87	177700	1.344	0.361	0.162	5.309	0.913	1.096	1.320	1.562	1.798
SM	SR45a	94	134.21	736556	1.464	0.463	0.001	9.673	0.915	1.147	1.426	1.737	2.053
SM	SR45b	100	76.45	328810	0.921	0.270	0.119	9.487	0.622	0.765	0.908	1.061	1.225
SM	SR46	100	59.61456	152586	0.733	0.260	0.139	8.115	0.495	0.571	0.675	0.821	1.035
SM	US421	88	75.89	256700	1.345	0.336	0.251	5.292	0.942	1.114	1.319	1.547	1.780
VC	SR257	95	102.4	286059	1.379	0.311	0.248	9.646	1.011	1.174	1.361	1.566	1.771

*CF, Crawfordsville; FW, Fort Wayne; GF, Greenfield; LP, LaPorte; SM, Seymour; VC, Vincennes.

TABLE 4.5
Statistical Summary of Texture Depth Grouped by MSQA Rating

MSQA Level	MSQA Range	N	MPD	Std	Lower Bound	Upper Bound	P10	P25	P50	P75	P90
5 Levels	100	5228192	1.412	0.488	1.412	1.413	0.786	1.067	1.392	1.723	2.045
	95≤MSQA<100	1953056	1.347	0.348	1.346	1.347	0.940	1.115	1.321	1.552	1.789
	90≤MSQA<95	2148895	1.408	0.436	1.408	1.409	0.884	1.108	1.375	1.669	1.967
	85≤MSQA<90	449018	1.226	0.334	1.225	1.227	0.833	0.989	1.191	1.426	1.667
	80≤MSQA<85	820957	0.920	0.245	0.919	0.921	0.633	0.754	0.899	1.061	1.227
3 Levels	100	5228192	1.412	0.488	1.412	1.413	0.786	1.067	1.392	1.723	2.045
	90≤MSQA<100	4101951	1.379	0.398	1.379	1.379	0.912	1.112	1.346	1.610	1.885
	80≤MSQA<90	1269975	1.028	0.316	1.028	1.029	0.673	0.809	0.983	1.199	1.444

P90 here), represented by. $X' = [X_1, X_2, \ldots, X_p]$ The calculated eigenvalue-eigenvector pairs from can be expressed as, $(\lambda_1,e_1),(\lambda_2,e_2),\ldots,(\lambda_p,e_p)$, where. $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_p \geq 0$. Thus, the ith principal component (PC) can be denoted as $Y_i = e'_i X = e_{i1}X_1 + e_{i2}X_2 + \cdots + e_{ip}X_p$ with properties, $Var(Y_i) = e'_i \sum e_i = \lambda_i$ and $Cov(Y_i, Y_k) = e'_i \sum e_k = 0$, where i=1,2,…,p and $i \neq k$. Therefore, PCs are uncorrelated linear combinations of existing p variables with variances equal to the eigenvalues of Σ. Larger eigenvalue means more information is explained by the PC, so it is reasonable to keep only a few PCs because most of information has been explained by them.

As shown in Tables 4.6, PCA was performed on scaled variables, P10, P25, P50, P75, and P90. The standard deviation is the square roots of the eigenvalues (λ_i) *and the Total Variance*$=\Sigma\lambda_i = 5$. The first PC explains 94.81% of the total variance and the second PC explains 4.96% of total variance. Since the first two PCs already account for 99.77% of total variance, the rest of PCs can be dropped in the later analysis. By carefully examining the coefficients of existing

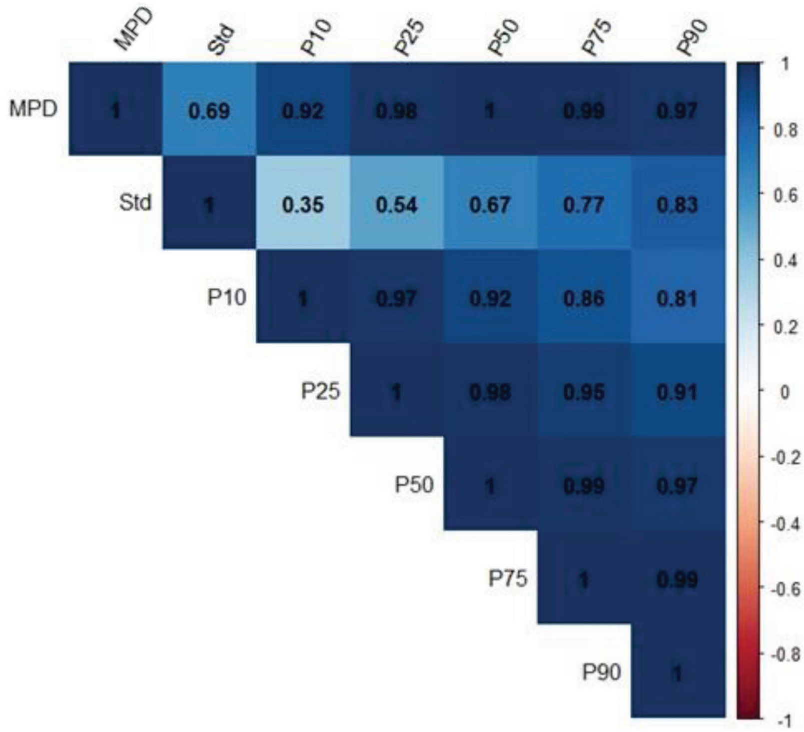


Figure 4.9 Correlation matrix for MPD, standard deviation, and percentiles.

TABLE 4.6
Results of Principal Component Analysis

Variable	PC1	PC2	PC3	PC4	PC5
Standard Deviation	2.1773	0.4978	0.1030	0.0329	0.0073
Proportion of Variance (%)	94.81	4.96	0.21	0.02	0.00
Cumulative Proportion (%)	94.81	99.77	99.98	100.00	100.00
P10 Coefficient	-0.4296	0.7019	0.5200	0.2167	0.0735
P25 Coefficient	-0.4540	0.2873	-0.4645	-0.5809	-0.3978
P50 Coefficient	-0.4584	-0.0744	-0.4598	0.1870	0.7334
P75 Coefficient	-0.4523	-0.3453	-0.0906	0.6199	-0.5326
P90 Coefficient	-0.4411	-0.5478	0.5423	-0.4432	0.1217

variables for each PC in Table 4.6, the first two principal components can be expressed as follows:

$$PC_1 = -0.4296 * P10 - 0.4540 * P25 - 0.4584 * P50 - 0.4523 * P75 - 0.4411 * P90$$

$$PC_2 = -0.7019 * P10 + 0.2873 * P25 - 0.0744 * P50 - 0.3453 * P75 - 0.5478 * P90$$

Since it is still difficult to interpret PC1 and PC2, other variables are considered to replace PC1 and PC2 into the final regression model. However, examining the coefficients in PC1 and PC2 calculations revealed that PC1 is essentially a sum of P10 to P90. The coefficients in PC1 are quite close, and in fact, none of variables contributes significantly more than the others. If the distribution of measured texture depth is symmetric and unimodal, PC1 can be expressed as a function of P50, which is the sample mean (MPD) in essence. PC2 is a weighted difference from P10 to P90, in which the weight of P50 is significantly smaller than the others. After carefully examining the form of PC2, the initial speculation is that Interquartile Range (IQR) may be used to represent PC2. IQR, used as a measure of sample variability, is the difference between P75 and P25 representing the range of middle 50% of sample. To further demonstrate relationship between PC1 and MPD and between PC2 and IQR, scatter plots are made as shown in Figure 4.10.

It is shown that in Figure 4.10, strong linear relationships exist between PC1 and MPD and between PC2 and IQR. The coefficient of determination, R^2 is 0.9998 for PC1 and MPD, and 0.9887 for PC2 and IQR.

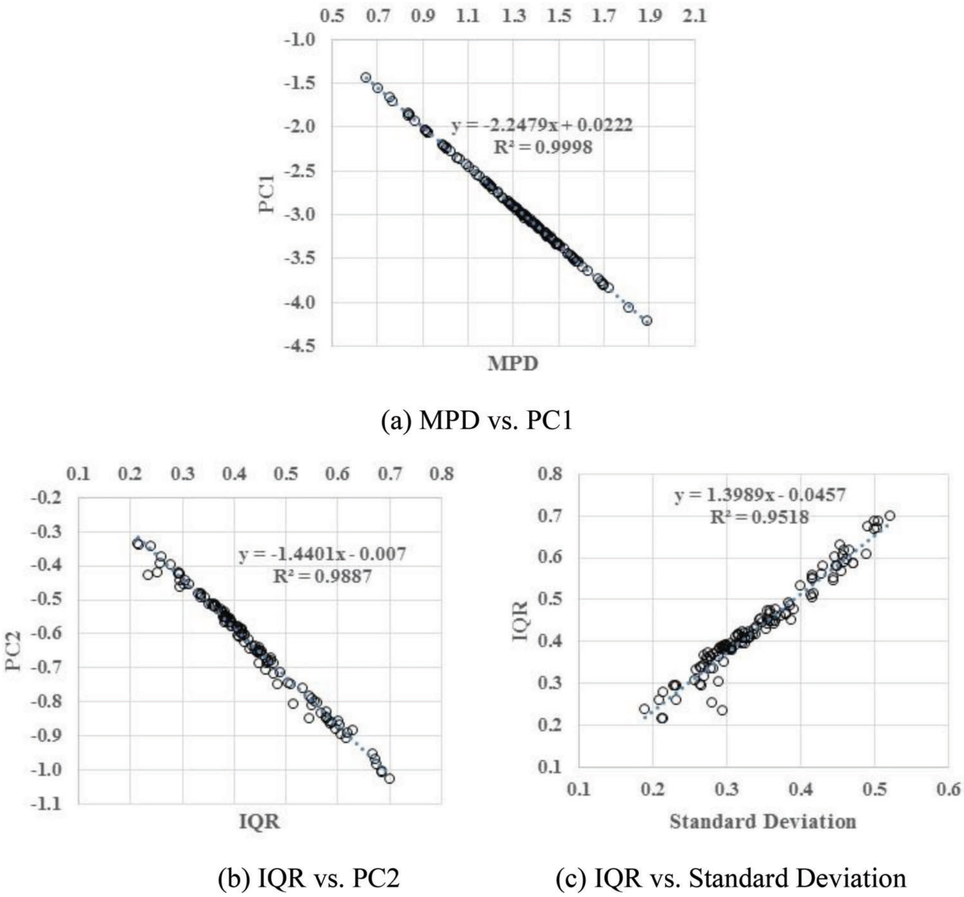


Figure 4.10 Scatter plots among PC1, PC2, MPD, IQR, and standard deviation.

Therefore, it is reasonable to replace PC1 and PC2 by MPD and IQR for modeling without losing key information. Further relationship check was conducted for IQR and texture depth Standard Deviation. As shown in Figure 4.10 (c), strong linear relationship was detected as well between IQR and Standard Deviation. The R^2 for these two variables is as high as 0.9518, indicating that either one of them can be used for modeling. The texture depth Standard Deviation is used for later analysis for simplicity. It should be noted that the findings in this chapter are purely based on the dataset used in this study, and IQR and Standard Deviation are not always used interchangeably.

4.3.3 Regression Model Development

In Table 4.4, the dataset contains information of 30 chip seal projects. However, 15 out of 30 projects have MSQA equal to 100. The measured MPDs among these 15 projects vary greatly ranging from 0.73 to 1.71. The dispersion of MPD for projects with MSQA equal to 100 is understandable because visual inspection is a subjective evaluation method. When the pavement surface is free of obvious distresses, it is hard for the inspection crew to accurately estimate the characteristics of surface texture. Due to the uncertainty of MPD in projects with MSQA of 100, projects with MSQA equal to 100 are not included in the regression model. Because texture measurements were conducted for both wheel paths on both directions, there are a total of 15*4 = 60 data entries in the final dataset. Each data entry has 10 variables, among which there are 7 continuous variables and 3 categorical variables as shown in Table 4.7. The continuous variables are mainly related to texture measurements, traffic, and MSQA rating. The categorical variables include the type of chip, traffic direction, and laser sensor position.

Moreover, the MSQA rating is used as dependent/response variable predicted by other independent/explanatory variables in the dataset. The multiple linear regression by the method of Ordinary Least Squares (OLS) was conducted to estimate the model and the estimated model parameters are shown in Table 4.8. To test the significance of explanatory variables and the overall goodness of fit, a commonly used significance level (α) of 5% was utilized. The initial model which includes all the variables has a F-statistic of 14.73 with P-value less than 0.0001 indicating that comparing to the null model (all regression parameters are zero), a significant linear relationship exists between MSQA and other variables. The measures of how well the model fits the data (goodness of fit) include R^2 and adjusted R^2,

TABLE 4.7
Summary of Variables for Modeling

Variable Name	Variable Description
MPD	Mean profile depth (mm), continuous variable
Std Dev	Texture depth standard deviation (mm), continuous variable
AADT	Average annual daily traffic, continuous variable
Truck	The number of truck in AADT, continuous variable
MSQA	Seal coat quality assurance evaluation (total of 100 points adjusted for surface distress related only), continuous variable
Speed	Measured 85th percentile speed (mph), continuous variable
Length	Length of measured road segment (mile), continuous variable
Aggregate	Type of chip: SC11 and SC16, categorical variable
Direction	Direction of road: increasing "A" and decreasing "B", categorical variable
Sensor Position	The position of testing laser sensor: left wheel path "L" and right wheel path "R", categorical variable

TABLE 4.8
Model Parameter Estimation

Variable	Estimate	Std. Error	t-value	p-value
	Initial Model (R^2 = 0.726)			
Intercept	72.705	5.750	12.644	$<2*10^{-16}$
MPD	9.665	3.808	2.538	0.014
Std Dev	22.231	12.587	1.766	0.084
AADT	-0.001	0.001	-0.912	0.366
Truck	-0.010	0.003	-3.792	0.0004
Speed	0.087	0.070	1.248	0.218
Length	-0.389	0.162	-2.394	0.021
Aggregate-SC16	0.427	0.820	0.520	0.605
Direction-Decreasing	0.474	0.741	0.639	0.526
Sensor Position-Right Wheel Path	-1.061	0.826	-1.284	0.205
	Final Model 1 (R^2 = 0.696)			
Intercept	78.023	3.245	24.042	$<2*10^{-16}$
MPD	13.602	2.429	5.600	$6.73*10^{-7}$
Truck	-0.011	0.002	-5.928	$1.99*10^{-7}$
Length	-0.172	0.108	-1.587	0.118
	Final Model 2 (R^2 =0.505)			
Intercept	67.063	3.372	19.886	$<2*10^{-16}$
MPD	20.536	2.692	7.630	$2.84*10^{-10}$
Length	-0.270	0.135	-2.002	0.050
	Final Model 3 (R^2 = 0.471)			
Intercept	67.523	3.451	19.568	$<2*10^{-16}$
MPD	19.098	2.660	7.179	$1.47*10^{-9}$

which are 0.7261 and 0.6768 respectively. The interpretation of R^2 which is equal to 0.7261 is that the model can explain 72.61% of the variability in the response variable MSQA.

In addition, by looking at the p-value for each variable in the initial model, one can identify that MPD, Truck, and Road Length are the significant variables with p value less than 5%. It is also found that AADT is insignificant, but Truck is significant. This can be explained because the effect of passes by truck on the embedment of aggregate in the chip seal is greater than that by passenger cars. The manipulation of trucks is one of reasons response for chip seal failures. In addition, all categorical explanatory variables including the type of aggregate, testing road direction, and laser sensor position are insignificant. To interpret the model parameters, the initial model was refined by conducting the regression with only the significant variables: MPD, Truck, and Road Length. This final model is presented in the lower part of Table 4.8. The F-statistic of the final model is 42.74 with p-value less than 0.0001, so the linear relationship between response and explanatory variables are still significant. R^2 in the final model dropped slightly to 0.696 as well as adjusted R^2 to

0.6797 because some variables in the initial model were removed. The final model can be expressed as follows:

$$MSQA = 78.023 + 13.602 \times MPD - 0.011 \times Truck - 0.1716 \times Length \quad (4.1)$$

in which, MPD stands for Mean Profile Depth, Truck is the number of truck in AADT, and Length is the length of sealed road.

The coefficient of MPD is 13.6, meaning that with other variables remaining the same, one-millimeter increase in MPD will produce an increase of 13.6 in MSQA. Regarding Truck variable, one unit increase in the number of truck will decrease MSQA by 0.011 when other variables are kept constant. The last variable is Road Length, the coefficient of which indicates that with other variables staying the same, if Road Length is increased by one mile, the MSQA will decrease by 0.172. In sum, higher MPD tends to produce better MSQA, while more truck and longer sealed road seems having lower MSQA.

Another situation may arise that traffic data is not available to predict MSQA, so model without using Truck variable as one explanatory variable was developed as well. As shown at the bottom of Table 4.8, this model has a R^2 equal to 0.505 and MPD and Road Length are found significant explaining MSQA. Therefore, MSQA can be predicted by MPD and Road Length with the following equation:

$$MSQA = 67.063 + 20.536 \times MPD - 0.270 \times Length \quad (4.2)$$

where, MPD stands for Mean Profile Depth and Length is the length of sealed road.

When MPD is only included to predict MSQA, the model equation becomes:

$$MSQA = 67.523 + 19.098 \times MPD \quad (4.3)$$

where, MPD stands for Mean Profile Depth. This model has a R^2 equal to 0.4705.

Finally, it should be mentioned that MSQA ranges from 0 to 100, so any prediction by the developed models outside this range is meaningless. As mentioned earlier, great variability of MPD was found in those chip seal projects with MSQA equal to 100 was. Therefore, the model developed in this study can only be served as a reference to identify the potential relationships among different variables.

5. FINDINGS AND RECOMMENDATIONS

5.1 Main Findings

Ride quality and safety are two critical pavement performance measures that have been widely used to evaluate the quality of new pavement. The former is defined in light of pavement smoothness; the latter is defined in light of pavement friction. Pavement smoothness does not change much before and after chip seal, in particular single chip seal. However, chip seal premature or early failure is commonly accompanied by excessive aggregate loss or bleeding, or both, which will undoubtedly affect the surface frictional characteristics of chip seal. The surface of a failed chip seal tends to become slippery, leading to very low surface friction. Therefore, surface friction can be utilized as a performance-focused measure for assessing the quality of new chip seal.

INDOT conducts pavement friction testing in accordance with ASTM E274 (2015). This test requires intermittent acceleration or braking to adjust the speed of test vehicle, which may impose significant impact on the traffic flow conditions and safety. In addition, this test cannot provide a seamless coverage of the road. Nevertheless, pavement friction varies with surface texture, test tire, presence of water, and test speed. When conducting friction testing at standard test conditions, surface texture becomes the dominant factor affecting pavement friction. Technologies are currently available to provide continuous texture measurements. It is advisable to use surface texture, instead of friction for quality assessment or assurance.

Texture depth, spacing, and shape may be used to fully characterize the geometrical properties of texture profile. To predict wet pavement friction, however, the mean profile depth (MPD) of macrotexture was found to be the best depth parameter. Field test results indicate there exists a strong exponential relationship between MPD and friction, and MPD and friction variations follow a similar trend. It is evident that MPD is the best macrotexture metric to assess the surface friction, and therefore the quality of chip seal.

Field visual inspection revealed that bleeding and tracking are commonly found in the wheel paths, either in one wheel path or two wheel paths. Nevertheless, there are evident differences between the texture characteristics in the right and left wheel paths, due to the spatial variability of texture or the nature of pavement surface. Cumulative frequency distribution (CFD) provides an easy way to visualize large texture data sets and detect the small differences in the distribution of texture measurements.

5.2 Major Recommendations

To advance the concept of MPD-based chips seal QA towards implementation, the following recommendations may be used as guidance for test system setup and field testing:

- Use of two point lasers, one for each wheel path, is needed and anticipated to acquire the necessary information for evaluating the characteristics of texture profiles and capturing the spots of bleeding or tracking in both wheel paths.
- It is rational to perform texture testing in both directions for quality assurance of chip seal. However, texture measurements made in one direction can provide sufficient information for the quality assurance of chip seal, which may be justified if resources are limited.

- Chip seal in the driving lane may experience higher variability than that in the passing lane. Therefore, the texture depths in the driving lane may yield more strict standards for quality assurance of chip seal.
- The current two QA inspections performed after one month and 12 months of service can be combined into a single, one-time QA inspection that should be conducted after the first snow season and can ensure both safety and quality. However, visual inspection is still necessary to identify problems earlier when corrective actions can still be taken and avoid the consequence due to immediate and dramatic loss of surface friction. It is recommended that visual inspection should be conducted before applying fog seal.
- Chip seal QA can be measured in terms of the macrotexture metrics such as MPD and attribute percentile values. Although three equations have been developed to accomplish this, Equation 5.1 may yield the best estimation.

$$MSQA = 78.023 + 13.602 \times MPD - 0.011 \times Truck - 0.1716 \times Length \quad (5.1)$$

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The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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