Using Cost, Mix Design, Construction, and Performance Data to Inform Hot Mix Asphalt Pavement Policy and Standards

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Abstract

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This dissertation integrates and assesses in-service hot mix asphalt pavement data from several typically available but disconnected data sources to inform pavement policy and specification development. This in-service pavement data approach captures connected pavement data from different stages of pavement projects (e.g. mix design, construction, performance after completion) to better understand the relationship between actual in-service performance and mix design, structural design, and construction variables. The dissertation addresses the following research question: what is the value of the in-service pavement data approach in developing hot mix asphalt pavement policy and specifications? To test this question, the dissertation applies this approach using data from 2007 to 2017 to investigate several current Washington State Department of Transportation (WSDOT) research questions.

Using the in-service pavement data approach, WSDOT pavement performance questions regarding (1) 3/8-inch versus 1/2-inch nominal maximum aggregate size (NMAS) mixtures, (2) the influence of elevated in-place density mixtures and other mixture characteristics, and (3) high-reclaimed asphalt pavement (RAP) (> 20%) versus up-to-20%-RAP mixtures are analyzed. High level findings include: (1) there is no statistical evidence to suggest a difference in performance between 3/8-inch and 1/2-inch NMAS mixtures; however, the cracking/rutting performance of 3/8-inch NMAS mixtures may be trending higher for older mixtures (ages 9-10); (2) there is no field evidence to suggest an apparent trend between elevated density and increased cracking/rutting performance; however, fine-graded mixture cracking performance may be trending higher than coarse-graded mixtures for older contracts (ages 8-10) and no contracts with a density of 94% or higher perform poorly (≤ 50 cracking/rutting condition value); and (3) there is no statistical evidence to suggest a difference in performance between high-RAP (> 20%) and up-to-20%-RAP mixtures.

Ultimately, the in-service pavement data approach is a repeatable framework that can be used to better understand the relationship between actual in-service performance and mix design, structural design, and construction variables. Additionally, it is generalizable to any field with large data sets on in-service pavements (e.g. airfields, highways, etc.). Towards this end, the in-service pavement data approach and high-level findings of the WSDOT case studies may be applicable to the U.S. Air Force pavement program.

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Chapter 1. Introduction

Experimentation, either in the laboratory or in the field, and theoretical models are the most common approaches that current asphalt pavement research uses to inform mix design and construction processes as well as policy and specification development. Alternatively, the use of in-service (i.e. field and performance) pavement data can also provide information upon which to base pavement construction, policy, and specifications decisions. This approach offers an alternative to the traditional approach whereby an initial data analysis informs a follow-up laboratory experiment and/or field evaluation to validate the findings from the data analysis. Traditionally, this approach has been difficult because of limited data, computation capability, and resource availability. Recent increases in computing power and in-service pavement data provides the asphalt industry with the capability to use the in-service pavement data approach more frequently with more influence on policy and specifications development than at any time in the past.

This in-service pavement data approach was first proposed about 20 years ago by White et al. (2002), but recent advances in data collection, storage, and linkage make it more likely to be successful today. Most state highway agencies operate databases with cost, mix design, construction, and performance data. The availability of large amounts of in-service pavement data combined with the processing capability to link, analyze, and filter it provide opportunities to create value in understanding pavement performance. This combination makes it possible to analyze large data sets of in-service pavements to better understand the relationship between actual in-service performance and mix design, structural design, and construction variables. This type of information can be a powerful aid in developing and modifying pavement policy and specifications as well as design and construction processes. The approach works best when analyzing a specification or parameter with accompanying historical data reaching back many years or even just a few years. The in-service pavement data approach does not work well supporting new ideas such as the analysis of a new binder rating system or a new mix design not historically used by a state highway agency.

1.1 Background

White et al.'s (2002) proposal of an online database, a hot-mix database, integrates design, construction, usage, and performance data to inform oversight and construction operations. From an oversight perspective, the hot-mix database informs highway agency personnel in support of budget decisions and pavement policy/specification updates (White et al. 2002). From a construction operations perspective, the hot-mix database provides access to field and contractor personnel to improve the oversight and execution of HMA pavement projects (White et al., 2002). Similarly, Hudson et al. (2003) proposed an in-service pavement data approach to establish an "operational performance analysis" framework linking mix design, construction, and performance data by location and date.

About 20 years after White et al.'s analysis of the hot-mix database "highway agencies have made few advancements to formally link a construction phase with performance" (Rao et al. 2018). Further, Rao et al.'s (2018) survey of highway state agencies found that none were able to "automate or directly correlate QA [quality assurance] to PMS [pavement management system]" data. Additionally, Zimmerman's (2017) PMS survey found that only 11 of 48 (23%) agencies house "material or construction information" in their pavement management systems. Rao et al. (2018) found that most state highway agencies operate standalone PMSs that are separated from and not standardized with construction data systems. Despite the slow data integration progress, Zimmerman's (2017) PMS survey found that some highway agencies are interested in more robust data systems, 38% of agency respondents (6 of 16) would like to add "pavement layer and material data" to the PMS (Zimmerman 2017). The data disconnect may explain why the analysis in section 1.4 found that only a limited number of research publications explore in-service pavement data and even fewer explore the potential of an integrated set of mix design, construction (i.e. QA), and performance databases. As more organizations begin to link and mine their data, the in-service pavement data approach provides a rational framework for doing so that accounts for cost, mix design, field construction, pavement performance.

1.2 Scope

This dissertation uses an in-service pavement data approach to leverage large amounts of linked cost, mix design, construction, and performance data to inform mix design and construction processes as well as pavement policy and specification development. The approach uses shared fields (e.g. contract, mix design, and lot number) to link the pavement data. This approach captures pavement data from different stages of pavement projects (e.g. mix design, construction, performance after completion) to better understand the relationship between actual in-service performance and mix design, structural design, and construction variables. This dissertation addresses the following research question: *what is the value of the in-service pavement data approach in developing hot mix asphalt pavement policy and specifications*? To test this research question, the dissertation applies the in-service pavement data approach to investigate several current WSDOT research questions:

1. **Chapter 3 (Nominal Maximum Aggregate Size, NMAS):** (1) Are there measured field construction data differences between 3/8-inch and 1/2-inch NMAS mixtures that may, based on existing research, be indicative of performance differences?, and (2) are there measured performance differences between 3/8-inch and 1/2-inch NMAS mixtures?
2. **Chapter 4 (Density and mixtures characteristics):** (1) What is the financial incentive for contractors to change practices in response to WSDOT's raising of the lower specification limit from 91% of theoretical maximum density (TMD) to 92% of TMD?, (2) how does measured field density and field performance data compare with published literature on field performance related to density?, and (3) are there any related mix design parameters (e.g. fine-graded versus coarse-graded) that show an identifiable relationship to field performance?
3. **Chapter 5 (High-RAP):** (1) How does the measured field performance data compare with published literature on the relationship between high-RAP and long-term performance?, and (2) are there any measured mixture or field parameters [e.g. density, asphalt, voids in mineral aggregate (VMA), etc.] that show an identifiable relationship to field performance between high-RAP and up-to-20%-RAP mixtures?

The literature-based hypotheses for these research questions are:

- WSDOT 3/8-inch NMAS mixtures are more expensive, but have a longer service life based on higher in-place density at construction and more asphalt in the mix, which results in reduced cracking.
- There will be significant financial incentive for contractors to change current construction practices to meet the 92% density lower specification limit. Additionally, mixtures with higher density exhibit reduced cracking and rutting, and fine-graded mixtures exhibit reduced cracking and similar rutting.
- WSDOT high-RAP mixtures are less expensive and have a similar service life in comparison to up-to-20%-RAP mixtures based on lower virgin asphalt in the mix and similar cracking/rutting resistance.

The WSDOT HMA pavement data analyzed to answer these questions are (Chapters 2-5 provide more information about the data sources):

(1) **Unit Bid Analysis.** Online database of contractor bid prices for standard WSDOT pay items (i.e. HMA pavements) organized by contract.

(2) **Statistical Analysis of Materials (SAM).** SAM includes pavement mix design, field quality assurance (QA), and statistical evaluation data organized by lot, mix design, and contract.

(3) **Washington State PMS (WSPMS).** WSPMS includes HMA field performance data (e.g. cracking, rutting) organized by contract and lane mile section.

Once linked together, these data sources provide a unique opportunity to investigate how a large amount of historical cost, mix design, field, and performance data (10+ years) can be used to provide insight on mix design, construction, policy, and specification development. Since this type of pavement data is subject to numerous unmeasured variables, information and perceptions from WSDOT and industry are used to provide expert interpretation, feedback, and common industry perspectives. The perspectives from the WSDOT staff and Washington Asphalt Pavement Association (WAPA) members are captured through the use of a survey and interviews.

A limitation of this approach includes the availability of resources or personnel to create and maintain an integrated database. Rao et al. (2018) found that "data integration that allows mapping performance to QA data requires significant effort." For a homegrown database, the initial investment of time and resources preclude agencies from making progress. Additionally, the in-service pavement data approach relies on access to and possession of reliable data (Rao et al. 2018). Some state highway agencies only keep electronic records for a limited period of time (e.g. ten years); however, WSDOT's assemblage of pavement data uniquely began in 1965 (Rao et al. 2018; Uhlmeyer et al. 2016).

1.3 Overall Contribution: An In-Service Pavement Data Approach

The contribution of this dissertation defines and tests the in-service pavement data (cost, mix design, construction, and performance) approach to inform pavement mix design and construction processes as well as policy and specification development. Additionally, the dissertation uses findings in the literature and industry perspectives to compare and provide interpretation of the data. The dissertation also identifies the approach's capabilities and limitations. The WSDOT case studies offer the specific contributions below.

1. **Field performance analysis of 3/8-inch NMAS (versus 1/2-inch NMAS) asphalt pavement mixtures in Washington State using data from 2007 to 2017.** Within the last decade, WSDOT has increased the number of 3/8-inch NMAS contracts with the hypothesis that it may improve pavement service life. This increased commitment to smaller NMAS mixtures relies on published benefits in the literature such as reduced vulnerability to "raveling and surface cracking" and decreased permeability (Christensen and Bonaquist 2006). This chapter examines measured field construction and condition data differences between 3/8-inch and 1/2-inch NMAS mixtures to identify indications of performance differences. To support these objectives, the study analyzes construction cost, field asphalt content, in-place density, and cracking/rutting performance of 3/8-inch and 1/2-inch NMAS mixtures placed on the WSDOT road network from 2007 to 2017.
2. **Field performance analysis of asphalt pavement mixtures with elevated in-place density in Washington State using data from 2007 to 2017.** WSDOT uses HMA density data as a primary indicator for pavement performance and to determine contract financial incentives (i.e. pay factors and bonuses). Most of the literature indicates that an increased in-place field density results in higher performance with all other factors held constant (Aschenbrener et al. 2017; Tran et al. 2016). This chapter examines measured field density and field performance of mixtures placed on the WSDOT road network from 2007 to 2017 to determine if the data compares with published literatures on density and performance. Additionally, the chapter examines the financial incentive for contractors to change practices in response to WSDOT's raising of the lower specification limit from 91% to 92% of TMD. To support these objectives, the study analyzes in-place density, pay factor and price adjustments, field asphalt content, and cracking and rutting performance versus density.
3. **Performance analysis of high-RAP (> 20%) in comparison to up-to-20%-RAP asphalt pavement mixtures in Washington State using data from 2013 to 2017.** Mixtures containing more than 20% RAP by weight are termed "high-RAP" mixtures because 20% is the WSDOT threshold for adding testing and specification for RAP-containing mixtures. Because high-RAP mixtures are relatively new and long-term performance is unknown, the field performance of high-RAP pavements is of particular interest to WSDOT. The literature indicates that high-RAP mixtures are potentially cheaper and performance is similar to lower RAP mixtures with an increased rutting resistance; however, some of the high-RAP mixture

analyses exhibited reduced cracking performance (Stroup-Gardiner 2016; Timm et al. 2016). This chapter examines measured field construction and condition data differences between high-RAP and up-to-20%-RAP mixtures to determine how the data compare with published literature on the relationship between high-RAP and long-term performance. To support these objectives, the study analyzes construction cost, field asphalt content, in-place density, voids in mineral aggregate (VMA), and cracking/rutting performance of high-RAP and up-to-20%-RAP mixtures placed on the WSDOT road network from 2013 to 2017.

1.4 How Research on Pavements is Typically Done

This section quantifies typical pavement research methods by reviewing published literature to determine the frequency with which pavement research methods are used. These publications may contribute to pavement mix design and construction processes as well as policy and specifications development; however, not all decisions require published research.

1.4.1 *Methods*

The analysis counts the number of publications using two keyword searches and then categorizes, by topic, a recent subset of these publications. This analysis includes an initial counting of the number of U.S., English (language) Compendex publications in Engineering Village ("Engineering Village" 2018) from 2007 to 2017 using the two keyword searches: (1) "asphalt AND mix design AND performance" and (2) "asphalt AND pavement AND performance." The keyword searches use the 2007 to 2017 time frame because it represents recent publications and aligns with the time frames in the subsequent WSDOT studies in this dissertation. This analysis provides a sense of the number of publications on the topics.

Next, the analysis conducts a Transportation Research Board (TRB) database search with just publications and papers as well as a Compendex database publications search. The analysis comprises U.S. and English (language) using the same two keywords searches. For each keyword search, the analysis reviews a subset of the 2007 to 2017 publications, 300 total publications (150 TRB and 150 Compendex) publications in descending chronological order. The analysis uses an initial keyword search of 300 because it reaches back several years in both the TRB (2014) and Compendex (2016) databases for the first search. The first search yields 298 unique publication (two duplicates) and the second search yields 273 unique publications (27 duplicates) between the two databases. However, combined together, the two searches reveal an additional 73 duplicates yielding a final total of 498 unique publications.

The analysis classifies the HMA pavement research into seven major categories:

- **Laboratory Experiments.** This category analyzes lab produced or field produced mixtures using various tests (e.g. Hamburg Wheel Test).
    - Example. “Correlating Laboratory and Full-Scale Reflective Cracking Tests for Airfield Pavements” (Mandal et al. 2018).
- **Field Evaluation.** This category analyzes existing field pavements to explore the performance indicators of the pavement.
    - Example. “Impact of High Recycled Mixed on HMA Overlay Crack Development Rate” (Al-Qadi et al. 2017).
- **Accelerated Pavement Testing.** This category investigates pavement performance under accelerated loading conditions in the field (e.g. test tracks).
    - Example. “Prediction of Pavement Fatigue Cracking at an Accelerated Testing Section Using Asphalt Mixture Performance Tests” (Ozer et al. 2018).
- **Instrumented Field Section.** This category evaluates asphalt performance by constructing pavements with built-in data collection systems that also function as in-service pavements.
    - Example. “Effect of Pavement Structure on the Mechanical Response and Performance of Perpetual Pavements at the National Airport Pavement Test Facility” (Cary et al. 2018).
- **In-Service Pavement Data.** This category represents the approach of the dissertation. It analyzes historical mix design, QA, and/or PMS data to explore pavement behavior such as service life, rutting, cracking, and roughness. The intent is to identify trends that could inform pavement policy and specifications development.
    - Example. “Warm-Mix Asphalt Moisture Susceptibility Evaluation for Mix Design and Quality Assurance” (Yin et al. 2016).
- **Theoretical.** This category uses computer aided simulations or other types of models developed to predict pavement behavior and performance.
    - Example. “Multiscale Modeling of Asphaltic Pavements: Comparison with Field Performance and Parametric Analysis of Design Variables” (You et al. 2018).
- **State-of-the-Practice.** This category synthesizes the current state of the practice through efforts such as a literature review of current publications, surveys and interviews.
    - Example. “State of the Art: Asphalt for Airport Pavement Surfacing” (White 2017).

The analysis assigns a primary research category and a secondary research category (if applicable) to each publication by reviewing the abstract and if necessary, the article. The primary category is the publication's principal category used and is typically the first category mentioned. The secondary category is the category supporting or supplementing the primary category (e.g. a laboratory experiment with field evaluations of a test section).

1.4.2 *Results*

1.4.2.1 **Count of publications, 2007 to 2017**

An initial overview analysis on Engineering Village (2018) for English (language) Compendex publications in the U.S. from 2007 to 2017 reveals about 600 publications using the search terms "asphalt AND mix design AND performance" (Figure 1) as well as about 2,200 publications using the search terms "asphalt AND pavement AND performance" (Figure 2).

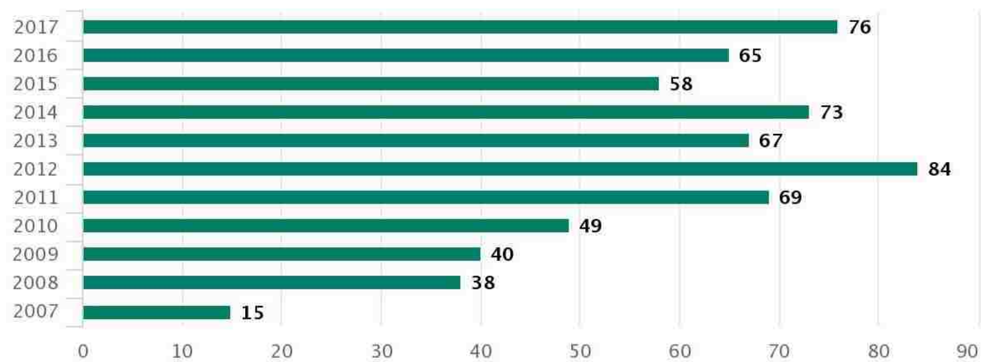


Figure 1. Number of Asphalt and Performance Publications, 2007 to 2017 ("Engineering Village" 2018).

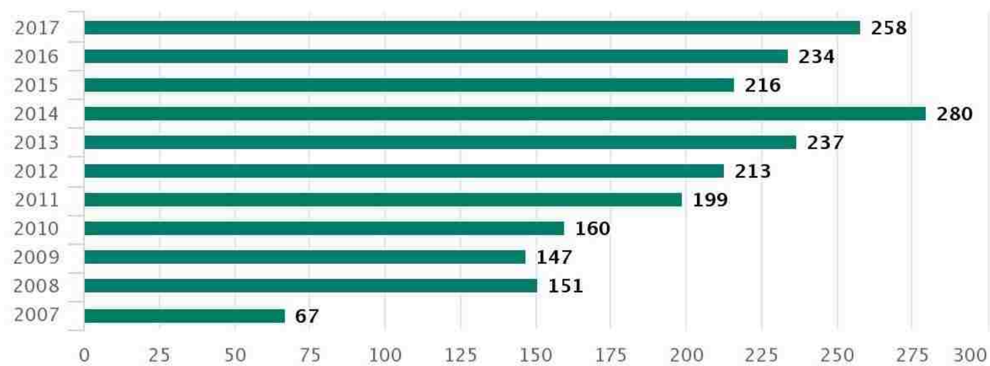


Figure 2. Number of Asphalt and Performance Publications, 2007 to 2017 ("Engineering Village" 2018).

The analyses by database and primary category show that the top two results include Lab Experiments and Theoretical research categories (Figure 3-Figure 7).

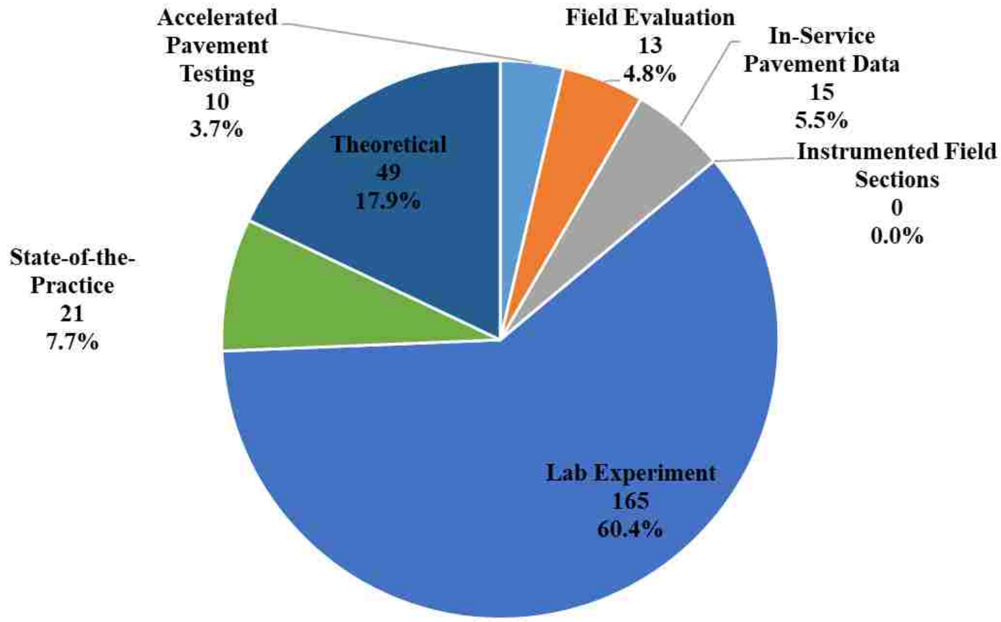


Figure 3. Literature Review Analysis by Primary Category (Top), Number of Publications (Middle), and Percentage (Bottom) of the "asphalt AND mix design AND performance" Keyword Search

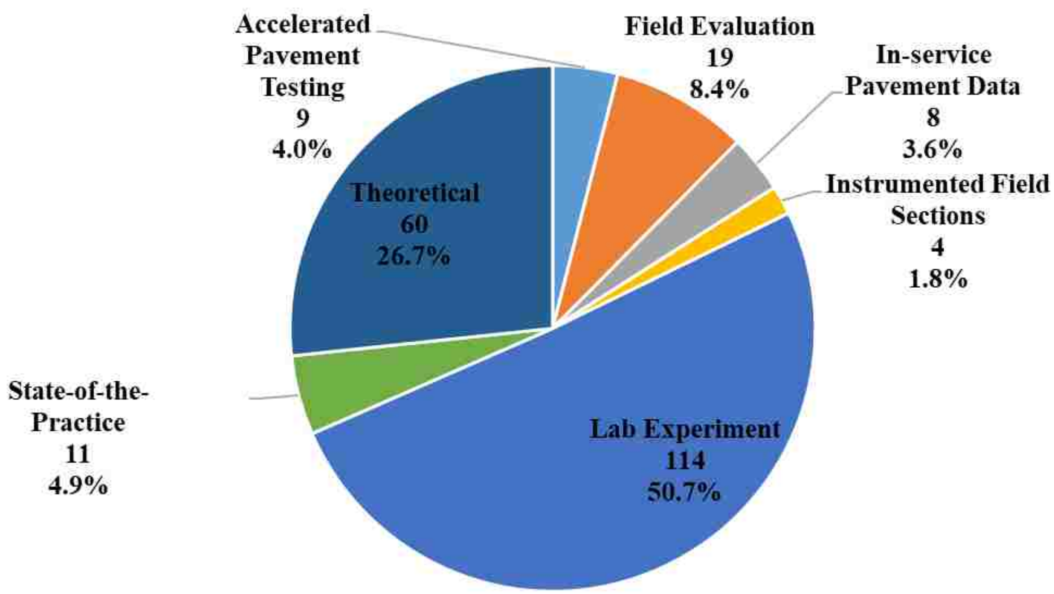


Figure 4. Literature Review Analysis by Primary Category (Top), Number of Publications (Middle), and Percentage (Bottom) of the "asphalt AND pavement AND performance" Keyword Search

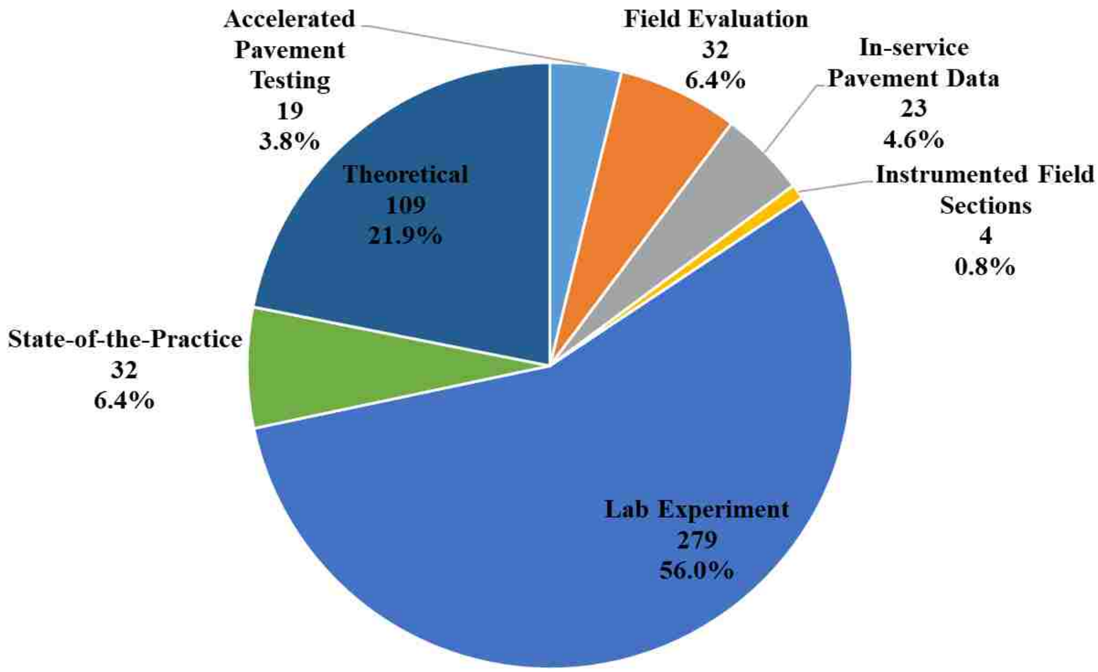


Figure 5. Combined Literature Review Analysis by Primary Category (Top), Number of Publications (Middle), and Percentage (Bottom) of Asphalt Pavement Research

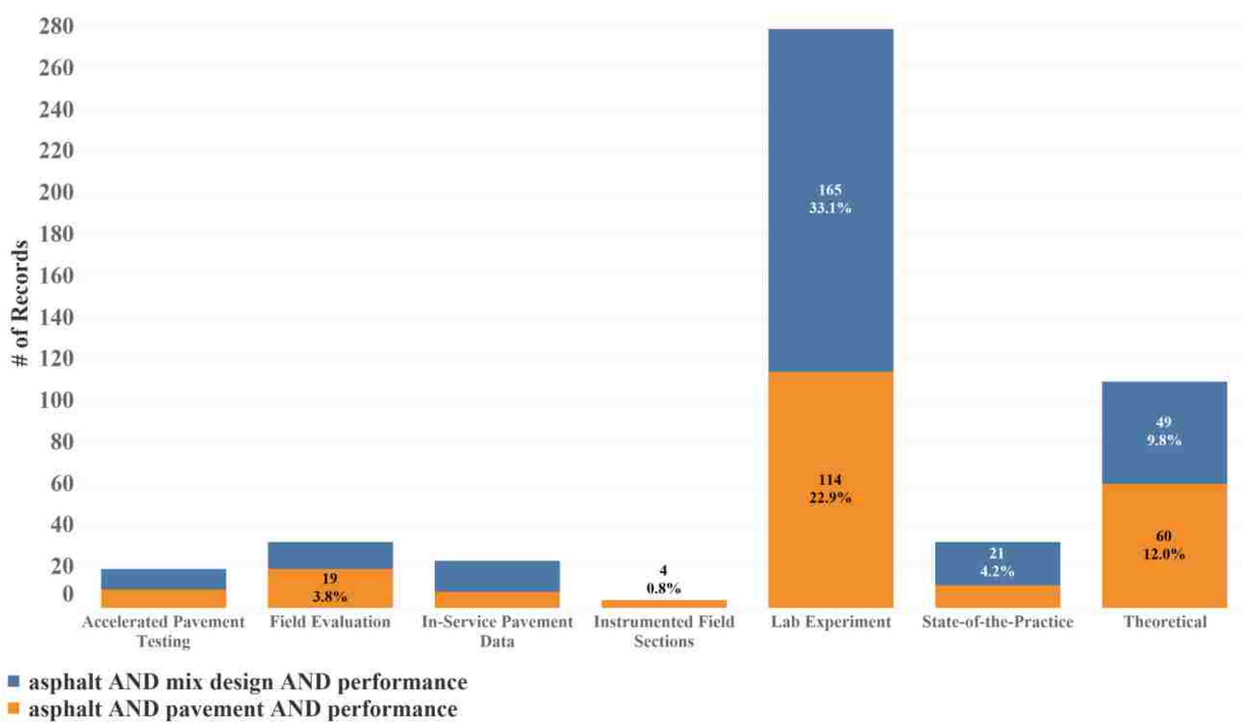


Figure 6. Number of Records Versus Primary Category by Keyword Search for the Combined Literature Review Analysis

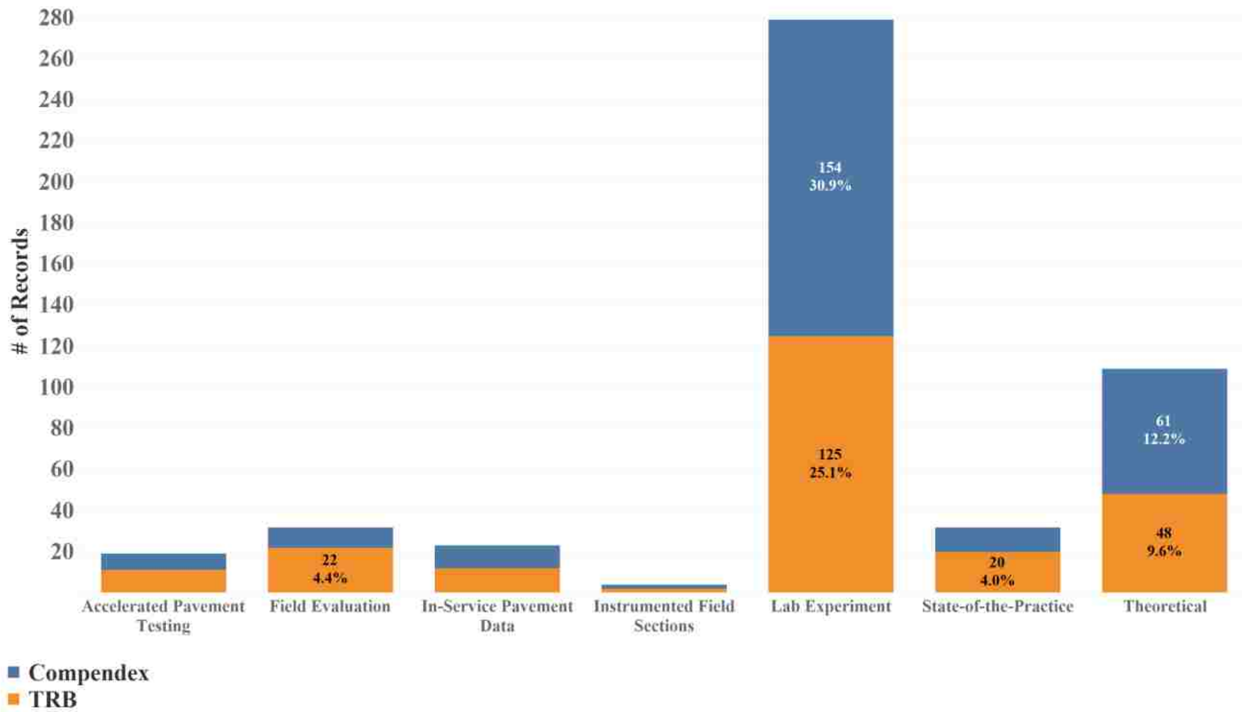


Figure 7. Number of Records Versus Primary Category by Database (Compendex and TRB) for the Combined Literature Review Analysis

1.4.3 *Discussion*

1.4.3.1 **Few research publications use the in-service pavement data approach**

Only 4.6% (23 of 498) use the in-service pavement data approach (Figure 5). The analysis produces similar result percentages for both keywords searches and both databases (Compendex versus TRB) (Figure 6-Figure 7). Of this subset, 10 use primarily PMS data, 7 use primarily mix design data, 4 use primarily Long Term Pavement Performance (LTPP) data, 1 uses primarily quality assurance (QA) data, and 1 uses mix design, QA, and performance data. Further, only 1 of the 498 unique publications aligns with the in-service pavement data approach in this dissertation. The primary reasons likely preventing more in-service pavement data publications include availability of resources and reliable data. Additionally, authors almost equally prefer using in-service pavement data as a secondary approach (21 publications) versus a primary approach (23 publications).

1.4.3.2 **Most research publications use laboratory experiments**

Fifty six percent (279 of 498) of the research publication use laboratory experiments (Figure 5). The first keyword search produces more laboratory experiments than the second keyword search (~33% versus ~23%) and Compendex produces slightly more laboratory experiment publications than TRB (~31% versus ~25%) (Figure 6-Figure 7). About 22% of the laboratory experiments contain an identifiable secondary category. Of the laboratory experiments with secondary categories, they typically use theoretical (~47%) and field evaluations (~40%) to support the research. Until the last approximately 20 years, most state highway agencies likely did not have large collections of field data or the capability to analyze this data and as a result, laboratory experiments represented the primary approach to simulate and test field conditions.

1.4.3.3 **Theoretical research is the second most popular**

The second most popular publication approach uses theoretical research (Figure 5). The second keyword search produces slightly more theoretical experiments than the second keyword search (~12% versus ~10%) and Compendex produces slightly more theoretical experiment publications than TRB (~12% versus ~10%) (Figure 6-Figure 7). About 40% of the theoretical experiments contain an identifiable secondary category. Of this subset, they typically use in-service pavement data (~35%) and laboratory experiments (~33%). Theoretical research represents another effective method to simulate field conditions in addition to laboratory experiments.

1.4.3.4 **Instrumented field section research is the least popular**

Less than one percent (4 of 498) of publications use the instrumented field section approach (Figure 5). All four of these publications came from the second keyword search. Instrumented sections rarely occur because of high costs and the coordination required for construction of an in-service pavement in a non-laboratory setting.

1.4.3.5 **Pavement research is driven largely by laboratory research and theory**

Laboratory experiments and theoretical research publications represent nearly four out of every five publications (77.9%) (Figure 5). Again, laboratory experiments and theoretical models represent the primary approach to simulate and test field conditions without access to or the capability to analyze large amounts of field data.

1.4.3.6 **Limitations**

This analysis reviews recent publications as far back as 2014 but it is not an exhaustive analysis reviewing decades of publications. The analysis uses just two representative keyword searches to review the publications but it does not capture the breadth and depth of pavement research and its methods. The category titles and assigned categories for each publication use engineering judgement and as a result, the process includes subjectivity. Only publications in the

U.S. comprise the contents of this analysis and it does not include federal or state highway agency reports. Additionally, the analysis does not include informal, unpublished findings from experienced laboratory or field observations that could influence policy or specifications through leadership channels. This analysis treats each publication as an equal contributor to the asphalt pavement industry and does not account for the relative influence of each publication.

1.5 Dissertation Format

The dissertation is organized as follows:

- **Chapter 1 (Introduction).** Presents the in-service pavement data research approach, the research scope, and the contributions of the dissertation.
- **Chapter 2 (Method).** Describes the method of the in-service pavement data approach to include data sources, acquisition, cleansing, etc.
- **Chapter 3 (NMAS).** Investigates the measured cost, mix design, field construction, and field performance differences between 3/8-inch and 1/2-inch NMAS HMA mixtures.
- **Chapter 4 (Density and mixture characteristics).** Investigates measured field density and other mixture characteristics in comparison to published literature on field performance related to density using mix design, field construction, and field performance data.
- **Chapter 5 (High-RAP).** Investigates the performance of high-RAP (> 20%) and up-to-20%-RAP HMA mixtures in comparison to published literature on the relationship between high-RAP and long-term performance using cost, mix design, field construction, and field performance data.
- **Chapter 6 (Conclusion).** Summarizes the contributions/findings of the dissertation, discusses the use of the in-service pavement data approach in the U.S. Air Force, and offers recommendations.
- **Chapter 7 (Bibliography).** References.

Chapter 2. Method

This chapter discusses the dissertation method (an iterative process) and its eight components listed below. The same general method applies for each pavement case study and it provides a repeatable research framework to better understand the relationship between actual in-service performance and mix design, structural design, and construction variables.

1. Definitions
2. Preconditions
3. Data sources
4. Data acquisition
5. Data cleansing
6. Data assembling
7. Final data set
8. Observations

2.1 Definitions

2.1.1 *Data*

According to Rowley (2007), "data are discrete, objective facts or observations, which are unorganized and unprocessed, and do not convey any specific meaning." For example, the dissertation identifies the nominal maximum aggregate size (NMAS) for each pavement mixture.

2.1.2 *Information*

Rowley (2007) describes the definition of information with three components which include (1) "data that have been processed so that they are meaningful", (2) "data that have been processed for a purpose", and (3) "data that have been interpreted and understood by the recipient." Predicted service life represents an example of information in this context since the Washington State Department of Transportation (WSDOT) uses a predictive model to determine the time from completion to the rehabilitation timeline. Information also includes the pavement management system (PMS) indices (e.g. structural condition, rutting). For instance, WSDOT uses data gathered from its pavement survey van to calculate a PMS index for each section of pavement (Uhlmeyer et al. 2016).

2.1.3 *Knowledge*

An appropriate definition of knowledge offered by Rowley (2007) includes “data and/or information that have been organized and processed to convey understanding, experience, accumulated learning, and expertise as they apply to a current problem or activity.” An example of knowledge in this context includes reviewing hot mix asphalt (HMA) lot density over enough time to make conclusions about performance.

2.2 Preconditions

The in-service pavement data approach works best with available and reliable HMA pavement cost, mix design, construction, and performance data over a long period. The approach does not work well on new initiatives without recorded field data (e.g. new mix design) nor does it work well in small time frames because pavement performance typically does not change much in the first few years particularly with an average pavement service life of about 15 years. Given these conditions, the analysis identifies the data sources, preselects the data source parameters (e.g. NMAS), and length of time. The next section addresses the data sources and parameters. The length of time must be long enough to observe noticeable trends in pavement performance. This dissertation uses the 2007 to 2017 time frame because it captures nearly all of the 3/8-inch NMAS mixtures and the most current Washington State PMS (WSPMS) data available (2017).

2.3 Data Sources

This section describes the HMA pavement data sources and availability within WSDOT. The data is limited to state highway agencies and does not include city, county or other organizations.

2.3.1 *Unit Bid Analysis*

WSDOT uses a searchable online database called the Unit Bid Analysis (Figure 8) which contains contractor bid prices for standard WSDOT pay items (e.g. HMA pavements). For example, the Unit Bid Analysis includes contract number, standard item number, location by WSDOT region, low bid price per ton, and planned quantity (tons). Each chapter addresses the relevant pieces of Unit Bid Analysis used for the dissertation.

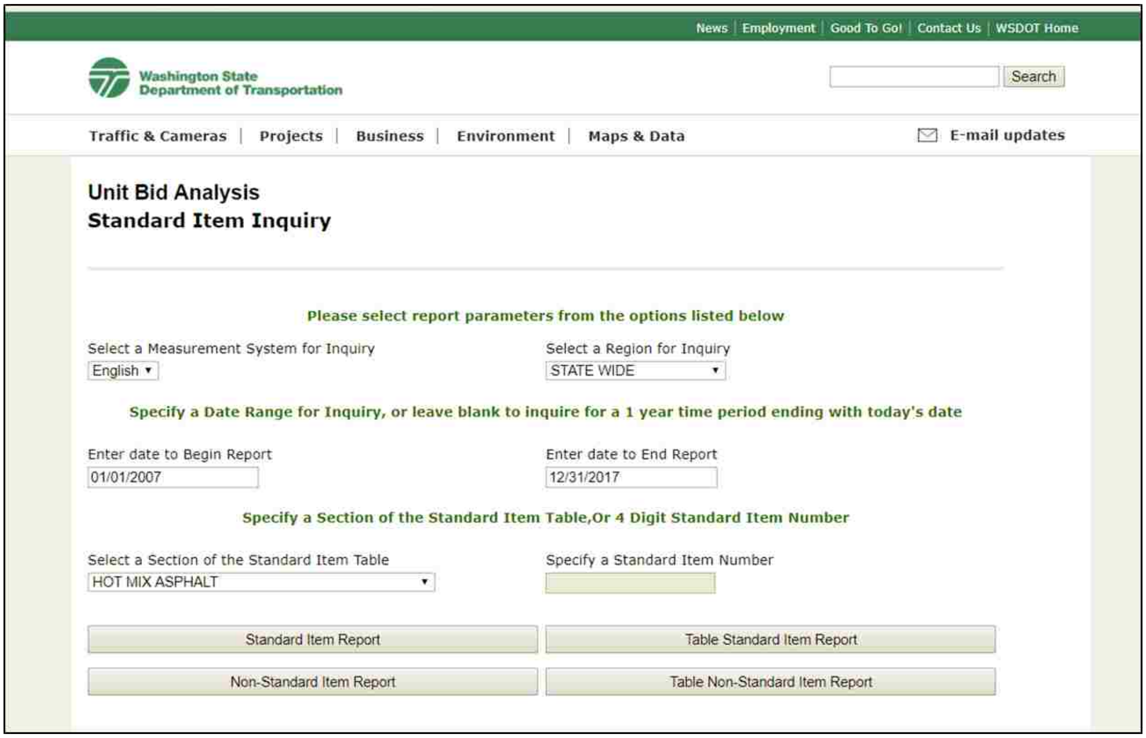


Figure 8. WSDOT Unit Bid Analysis Snapshot (WSDOT 2018a)

2.3.2 *Statistical Analysis of Materials (SAM)*

WSDOT uses a database called SAM (Statistical Analysis of Materials) to house its construction (QA) and mix design data. WSDOT offers an online SAM database that includes the QA data for individual contracts but it is not ideal for large data extractions. SAM includes contract number, NMAS, completion year, mix design number, lot number, sublot number, tons of mix, field measurements (e.g. asphalt content, density, gradation, and volumetrics), and statistical evaluation data (Figure 9). Each chapter addresses the relevant pieces of SAM used for the dissertation.

2.3.3 *Washington State Pavement Management System (WSPMS)*

The Washington State PMS (WSPMS), a robust, homegrown software product initially launched in the 1980s (Uhlmeyer et al. 2016). It identifies the pavement condition, classifies pavement sections requiring rehabilitation, provides an indication of the type of rehabilitation required, and indicates the predicted service life of the pavement which informs the timing of future projects (Uhlmeyer et al. 2016; Baker and Mahoney 2000). The WSPMS also includes data fields such as contract number, NMAS, completion year, location, terrain, and equivalent single axle loads (ESALs). Figure 10 displays a snapshot of the WSPMS. Each chapter addresses the relevant pieces of WSPMS used for the dissertation.

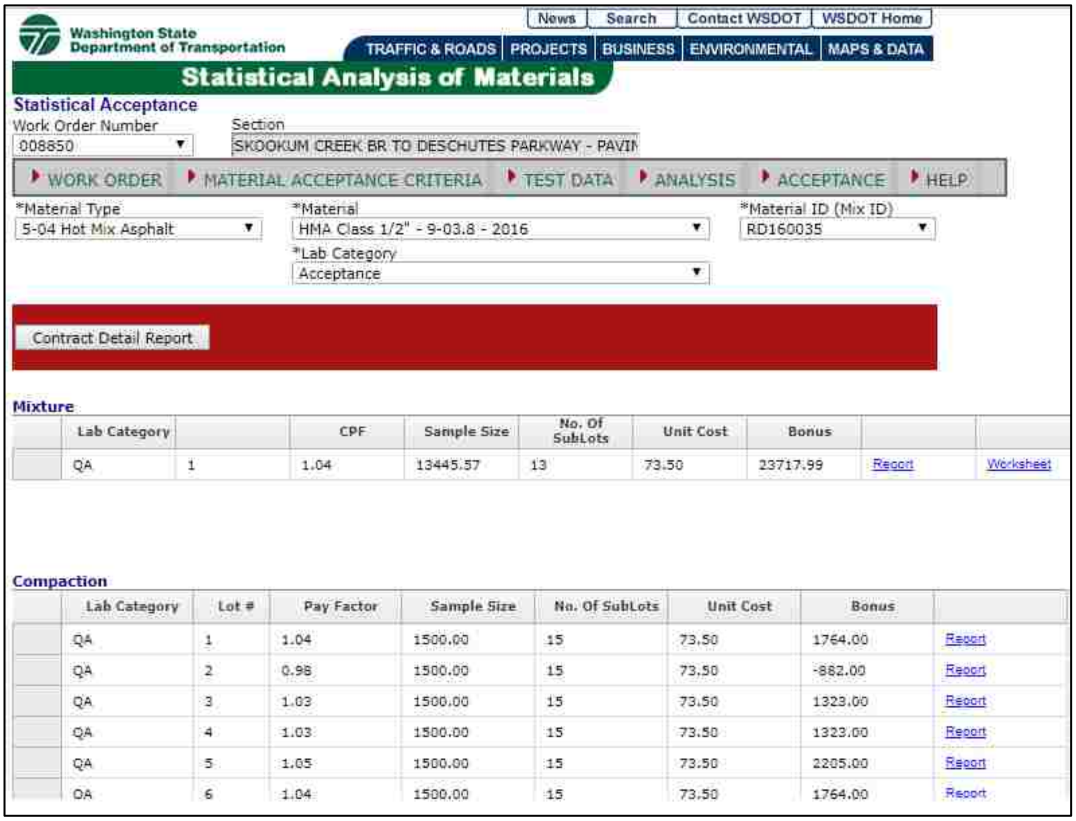


Figure 9. WSDOT SAM Snapshot (WSDOT 2018b)

Figure 10. WSPMS Snapshot (WSDOT 2019)

2.4 Data Acquisition

The dissertation uses its scope and data sources to identify the parameters for each case study (Table 1). Once selected, the dissertation acquires the necessary data.

2.4.1 *Unit Bid Analysis*

The Unit Bid Analysis online database offers WSDOT standard item data extraction in Excel between specified dates. For this dissertation, the analysis extracted HMA price data between 1 January 2007 and 31 December 2017.

2.4.2 *SAM*

The WSDOT staff extracted all HMA QA data from its internal SAM database to Excel for contracts completed between 2007 and 2017. Occasionally, the dissertation uses the online SAM database to confirm or fill in missing QA data. For example, the WSDOT extraction did not include the number of sublots for each lot but the online database offers this data.

2.4.3 *WSPMS*

The WSDOT staff extracted all HMA WSPMS data from its internal WSPMS database to Access for contracts completed between 2007 and 2017 with 2017 condition data, the most current available. Occasionally, the dissertation uses WSDOT's internal online WSPMS database to confirm or fill in missing WSPMS data. For example, the WSDOT extraction did not include the contract region or terrain but the online database offers this data.

Table 1. Preselected HMA Data Parameters Supporting the WSDOT Case Studies

	WSDOT Case Study		
Data Source	**NMAS**	**Density and Mixture Characteristics**	**High-RAP**
Unit Bid Analysis	Contract number Standard item Award year Low bid price Planned quantity (tons)	Contract number Standard item Award year Low bid price Planned quantity (tons)	Contract number High-RAP (Y/N) Standard item Award year Low bid price Planned quantity (tons)
Statistical Analysis of Materials (SAM)	Contract number Contract description Lot number Mix design number NMAS Completion year Tons of mix Field asphalt content Field density Gradation (No. 8 and No. 200 sieve)	Contract number Contract description Lot number Mix design number NMAS Completion year Tons of mix Field asphalt content Field density Gradation (No. 8 and No. 200 sieve) Voids in mineral aggregate (VMA)	Contract number High-RAP (Y/N) Contract description Lot number Mix design number NMAS Completion year Tons of mix Field asphalt content Field density Gradation (No. 8 and No. 200 sieve)
Washington State Pavement Management System (WSPMS)	Contract number Contract description NMAS Completion year Total pavement thickness (feet) Number of lane miles per section Cracking condition per lane mile section Rutting condition per lane mile section Number of equivalent single axle loads (ESALs)	Contract number Contract description NMAS Completion year Total pavement thickness (feet) Number of lane miles per section Cracking condition per lane mile section Rutting condition per lane mile section Number of equivalent single axle loads (ESALs)	Contract number High-RAP (Y/N) Contract description NMAS Completion year Total pavement thickness (feet) Number of lane miles per section Cracking condition per lane mile section Rutting condition per lane mile section Number of equivalent single axle loads (ESALs)

2.5 Data Cleansing

This section describes the process of identifying and eliminating unusable data after the initial extraction. Table 2 provides a high-level contract breakdown for each data source.

2.5.1 *Unit Bid Analysis*

The final version of the Unit Bid Analysis dataset includes 716 contracts (~50% of original HMA data) using only the HMA standard items for 3/8-inch and 1/2-inch NMAS mixtures. The initial HMA Unit Bid Analysis extraction provides construction bid prices data for about 1,419 contracts and 10 HMA related standard items. The analysis removes 659 contracts which captures 9 of 11 unusable HMA standard items (3/4-inch HMA, Class A HMA, HMA for preleveling, pavement repair, and approach for 3/8-inch and 1/2-inch NMAS mixtures). Additionally, the analysis removes 44 bridge deck and chip seal contracts.

2.5.2 *SAM*

2.5.2.1 Asphalt content

The final version of the asphalt content dataset from SAM includes 529 contracts (~90%). The initial data extraction includes 587 contracts but the analysis removes 14 contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). Of the remaining 573 contracts, the analysis removes 44 bridge deck and chip seal contracts.

2.5.2.2 Density

The final version of the density dataset from SAM includes 543 contracts (~90% of original data) using only the 3/8-inch and 1/2-inch NMAS mixtures. The initial density extraction includes 608 contracts but the analysis removes 15 contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). Of the remaining 593 contracts, the analysis removes 50 bridge deck and chip seal contracts.

2.5.2.3 Gradation (No. 8 Sieve)

The final version of the gradation (No. 8 sieve) dataset from SAM includes 527 contracts (~75% of original data) using only the 3/8-inch and 1/2-inch NMAS mixtures. The initial gradation extraction includes 702 contracts but the analysis removes 129 contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). Of the remaining 573 contracts, the analysis removes 46 bridge deck and chip seal contracts.

Table 2. Number of Contracts (Initial Extraction, Data Removed, and Final Data) by In-service Pavement Data Source, 2007 to 2017

Pavement Data Source	Number of Contracts	Percentage of Initial Data
Unit Bid Analysis		
Initial Data Extraction	1,419	
Data Removed	703	49.5%
Final Data	716	50.5%
SAM		
Asphalt Content		
Initial Data Extraction	587	
Data Removed	58	9.9%
Final Data	529	90.1%
Density		
Initial Data Extraction	608	
Data Removed	65	10.7%
Final Data	543	89.3%
Gradation (No. 8 Sieve)		
Initial Data Extraction	702	
Data Removed	175	24.9%
Final Data	527	75.1%
Gradation (No. 200 Sieve)		
Initial Data Extraction	571	
Data Removed	46	8.1%
Final Data	525	91.9%
VMA		
Initial Data Extraction	586	
Data Removed	74	12.6%
Final Data	512	87.4%
WSPMS		
Initial Data Extraction	451	
Data Removed	44	9.8%
Final Data	407	90.2%

2.5.2.4 Gradation (No. 200 Sieve)

The final version of the gradation (No. 200 sieve) dataset from SAM includes 525 contracts (~92% of original data) using only the 3/8-inch and 1/2-inch NMAS mixtures. The initial gradation extraction includes 571 contracts but the analysis removes 46 bridge deck and chip seal contracts.

2.5.2.5 **VMA**

The final version of the VMA dataset from SAM includes 512 contracts (~87% of original data) using only the 3/8-inch and 1/2-inch NMAS mixtures. The initial VMA extraction includes 586 contracts but the analysis removes 15 contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). Of the remaining 571 contracts, the analysis removes 24 contracts without VMA data and 35 bridge deck and chip seal contracts.

2.5.3 ***WSPMS***

The final version of the WSPMS dataset includes 407 contracts (~90% of original data) of 3/8-inch and 1/2-inch NMAS mixtures. The initial WSPMS extraction includes 451 contracts but the analysis removes three 2017 contracts and 13 contracts using other mixtures (3/4-inch NMAS, open-graded friction course, cold in-place recycling, hot in-place recycling, and class A). Of the remaining 435 contracts, the analysis removes 28 bridge deck and chip seal contracts yielding 407 contracts. Of these contracts, 305 (~75%) and 400 (~98%) contracts contain cracking and rutting condition data, respectively.

2.6 Data Merging/Linking

Oftentimes, the dissertation requires linking different data sources or linking data sources with itself. The three fields used to link the data include: (1) contract number, (2) mix design number, and (3) lot number.

- **Contract number.** The most common linkage data field, links all of the data sources because all of the data sources contain a uniquely identifiable contract number.
- **Mix Design number.** The second most common linkage data field links data within SAM data (e.g. asphalt content with density). More commonly, the mix design number links data internally. Because of the data format provided, the SAM data uses multiple tabs to house the data (e.g. contract description, field results, and mix design data). As a result, the analysis uses the mix design number to link the tabs in the SAM data extraction.
- **Lot number.** The analysis only uses the lot number to link with the SAM density data. Similar to the mix design number, the lot number links density data internally. For example, the density analysis uses the lot number linkages to identify the number of sublots in support of the density pay factor and bonus analysis.

2.7 Final Data Set

Some or all data generated or used during the dissertation are available from the author by request. The data includes Unit Bid Analysis, SAM, and WSPMS.

2.8 Observations

- **The data framework offers a method to examine asphalt pavement performance at high- and low-levels.** Because the data includes the complete population, the analysis can easily shift from high-level findings (e.g. completion year) to more detailed, low-level findings (e.g. lot, sublot). As a result of this flexibility, the data analysis can investigate apparent high-level trends at a deeper level or determine if trends at the lot or contract level are manifested at a higher level.
- **The resource commitment to perform the in-service pavement data approach is significant.** Until the process is automated or a homegrown data architecture is built, the resource commitment (e.g. time, personnel hours, system education, etc.) required to assemble the data is quite high. For example, the estimated database build time for this dissertation is conservatively about 1,500 person-hours (includes data collection, processing, and synthesis for all three WSDOT case studies).
- **The pavement data disconnect across different systems (WSPMS, SAM, Unit Bid Analysis) limits the usefulness of the data.** The WSDOT pavement data architectures were built as standalone, disconnected systems. Because of this, sublot and lot SAM data is not traceable to an identifiable lane mile section in WSPMS nor is condition data of a lane mile section in WSPMS traceable to sublot and lot data in SAM. For example, given a selected 0.2 lane mile section in WSPMS, it may be possible in rare instances to determine the field density; however, it is not possible to determine field asphalt content, VMA, etc. of that section using just the available data. Consequently, a connected WSPMS and SAM data analysis at the lane mile section and/or lot level is not achievable as currently constructed. Further, SAM sublot and lot identification numbers are not aligned across parameters. For example, the lot identification numbers for VMA do not align with the lot identification numbers for asphalt content, density, gradation, etc. Similarly, a connected SAM analysis across lot and sublots is not achievable; however, such a traceable system is possible, but it will likely require the creation of a new system.

Chapter 3. Performance of 3/8-inch Nominal Maximum Aggregate Size Asphalt Pavement Mixtures in Washington State

3.1 Preface

The in-service pavement data approach introduced in Chapter 1 describes using cost, mix design, construction, and performance data to examine existing pavement specifications and policy. This chapter uses the approach with preselected analysis parameters to analyze the performance of the Washington State Department of Transportation's (WSDOT) 3/8-inch nominal maximum aggregate size (NMAS) pavements in comparison to its 1/2-inch NMAS pavements. Performance of 3/8-inch NMAS is of particular interest to WSDOT since it awarded 61 contracts between 2018-2019 (about 53% of tonnage during this time), a significant increase from the 66 contracts between 2007-2017 (about 9% of tonnage). The upward trajectory in contract and tonnage for the 3/8-inch NMAS mixture shows WSDOT's commitment to this mix design. Findings from the research indicate that pavement mixtures with smaller NMASs exhibit decreased cracking, decreased permeability, and decreased compactive effort (Christensen and Bonaquist 2006; Brown et al. 2004; Cooley et al. 2002).

This study is from a manuscript submitted for publication in the American Society of Civil Engineers (ASCE) Journal of Transportation Engineering, Part B: Pavements (submitted January 2019 and submitted revision in June 2019).

3.2 Abstract

This paper compares Washington State Department of Transportation (WSDOT) 3/8-inch and 1/2-inch nominal maximum aggregate size (NMAS) mixtures using cost, mix design, field quality assurance, and field pavement management system data for contracts completed between 2007 and 2017. During this time, WSDOT's use of 3/8-inch NMAS mixtures increased to about 21% of contracts and 26% of tonnage to address asphalt pavement durability concerns.

The construction bid price and average weighted asphalt content of 3/8-inch NMAS mixtures exceed 1/2-inch NMAS mixtures by about $8 per ton and 0.7%, respectively. The overall average weighted field density for both 3/8-inch and 1/2-inch NMAS mixtures is about 93%. Although there is not sufficient statistical evidence to conclude that 3/8-inch NMAS mixtures produce a different overall average weighted structural and rutting condition over time than 1/2-inch NMAS mixtures, 3/8-inch NMAS mixtures produce slightly higher condition averages at ages 9 and 10.

Author keywords: Asphalt; Pavement; Nominal Maximum Aggregate Size; Performance; Mix Design; Construction; Pavement Management System; Quality Assurance.

3.3 Introduction

Since the implementation of Superpave in 2004, the Washington State Department of Transportation (WSDOT) has primarily used 1/2-inch nominal maximum aggregate size (NMAS) mixtures for surface courses. Within the last decade, WSDOT has increased the number of 3/8-inch NMAS contracts with the hypothesis that it may improve pavement service life by reducing fatigue cracking, raveling, oxidation/premature aging, and permeability. WSDOT's use of 3/8-inch NMAS mixtures in HMA pavements began around 2007 as a somewhat rare exception (generally about 9% of contracts and tonnage per year out of 66 contracts and about 711 thousand tons) to 1/2-inch NMAS mixtures in response to research studies on smaller NMASs. Durability concerns resulting from their initial Superpave mixtures (e.g. coarser aggregate structure and lower asphalt content) led to experimentation with smaller NMAS mixtures with increased asphalt content (FHWA 2010; Christensen and Bonaquist 2006). In 2016 and 2017, WSDOT awarded 32 contracts totaling about 404 thousand tons with the 3/8-inch NMAS mix design (about 21% of contracts and 26% of tonnage during those two years).

3.3.1 *Research scope and objectives*

This study tests the original WSDOT hypothesis that 3/8-inch NMAS mixtures may improve pavement service life using the last 10+ years of data on WSDOT's in-service pavements. Specifically, this study compares WSDOT 3/8-inch and 1/2-inch NMAS mixtures using cost, mix design, field quality assurance (QA), and pavement management system (PMS) data. To supplement this field data, this study gathers industry perspectives from the WSDOT staff and Washington Asphalt Pavement Association (WAPA) members through the use of a survey and interviews. The study addresses the following two NMAS research objectives:

1) Are there measured field construction data differences between 3/8-inch and 1/2-inch NMAS mixtures that may, based on existing research, be indicative of performance differences?
2) Are there measured performance differences between 3/8-inch and 1/2-inch NMAS mixtures?

The hypothesis is that 3/8-inch NMAS mixtures are more expensive, but have a longer service life based on higher in-place density at construction and more asphalt in the mix, which results in reduced cracking. This study analyzes the following cost, QA, and performance components of 3/8-inch and 1/2-inch NMAS mixtures placed on the WSDOT road network from 2007 to 2017:

- Construction cost per ton (adjusted for inflation) of 3/8-inch and 1/2-inch NMAS mixtures;
- Field asphalt content of 3/8-inch and 1/2-inch NMAS mixtures with pavement age;
- In-place density of 3/8-inch and 1/2-inch NMAS mixtures with pavement age;
- Cracking and rutting of 3/8-inch and 1/2-inch NMAS mixtures with pavement age.

3.3.1.1 **Potential use of large linked field and performance data sets**

The WSDOT pavement data sets used in the study are: (1) Unit Bid Analysis, (2) Statistical Analysis of Materials (SAM), and (3) Washington State PMS (WSPMS) for contracts completed between 2007 and 2017. A description of each data set is included in later sections. The availability of this field and performance data over a 10+ year period presents a unique opportunity to investigate how a large amount of historical measured field and performance data can be linked and used to provide insight on policy decisions. Since this type of data is subject to numerous unmeasured variables, interpretation and feedback from WSDOT and industry are used to provide further insight into observed trends.

3.3.2 ***Summary of reported benefits and issues of 3/8-inch NMAS from the literature***

The literature highlights benefits and issues of the smaller NMAS (e.g. 3/8-inch) mixtures but does not conclude that these mixtures are better. Benefits include reduced vulnerability to "raveling and surface cracking," decreased permeability, decreased compactive effort, and increased pavement performance in hard climates (Wen et al. 2016; Newcomb 2009; Christensen and Bonaquist 2006; Brown et al. 2004). Issues include higher costs, additional rutting, and increased production time (Kim et al. 2017; Aschenbrener et al. 2017; Newcomb 2009).

3.3.2.1 **Asphalt content**

A reduced NMAS results in increased asphalt binder content with other factors held constant (Christensen and Bonaquist 2006). A reduced NMAS increases the surface area of the aggregate in the mixture and additional asphalt content is required to "coat and bind the aggregate" sufficiently (Newcomb 2009). As a result, smaller NMAS mixtures may exhibit less susceptibility to "raveling and surface cracking" when the asphalt content is higher (Christensen and Bonaquist 2006). Timm et al. (2006) found that Superpave mixtures with higher asphalt content can be constructed with no rutting performance issues.

3.3.2.2 Permeability

At the same density, a smaller NMAS typically results in decreased permeability (Christensen and Bonaquist 2006; Cooley et al. 2002). Permeable pavements can generate "moisture-induced damage" and "premature cracking" (Cooley et al. 2002). Christensen and Bonaquist (2006) recommend regulating permeability through intentional selection of NMAS, finding that a smaller NMAS improves "fatigue resistance and durability" and that a decreased permeability is usually achieved using a 3/8-inch NMAS at 6-7% air voids. Cooley et al. (2002) found that "increasing the NMAS requires higher densities to ensure an impermeable pavement."

3.3.2.3 Density and lift thickness

For a given lift thickness, smaller NMAS mixtures allow the in-place density requirement to be achieved with less compactive effort (Brown et al. 2004). Cooley et al. (2002) found that at the same density, "as the lift thickness increases of a given pavement (and mixture), permeability decreases." Brown et al. (2004) state that at a minimum lift thickness to NMAS ratio (t/NMAS) of five, additional compactive effort is unnecessary to achieve sufficient density. WSDOT's minimum lift thickness for 1/2-inch NMAS mixtures is 45.7 mm (1.8 inches), a t/NMAS of 3.6 (WSDOT 2018c). Using the same minimum lift thickness, the t/NMAS for 3/8-inch NMAS mixtures is 4.8. Because 3/8-inch NMAS mixes have a higher t/NMAS at the same lift thickness, theses mixtures should achieve sufficient in-place density with less compactive effort.

3.3.2.4 Location and terrain

One paper speculates that smaller NMAS mixtures (e.g. 3/8-inch) may increase pavement cracking performance in areas of inclement weather (Wen et al. 2016). Variable climates in Washington State range from the moderate, wet conditions in the west to the cold, wet conditions in the Cascade Mountains to the arid conditions with excessive temperatures of the east (Wen et al. 2016). These conditions drive different pavement performance across Washington State.

3.3.3 *Relevant WSDOT Specifications*

3.3.3.1 NMAS and lift thickness specifications

The WSDOT specifications establish a minimum surface lift thickness for each NMAS to ensure sufficient compaction (WSDOT 2018d). The minimum thickness for 3/8-inch NMAS is 30.5 mm (1.2 inches), yielding a t/NMAS of 3.2 and 45.7 mm (1.8 inches) for 1/2-inch NMAS yielding a t/NMAS of 3.6 (WSDOT 2018c). Despite the allowable minimum surface lift thickness, WSDOT generally paves at the same surface thickness (45.7 mm) for both NMASs.

3.3.3.2 **Asphalt content and density specifications**

From 2007 to 2017, specifications required an asphalt content tolerance of ± 0.5% from the approved Job Mix Formula (JMF) and a lower specification limit of 91% of theoretical maximum density as measured by the core calibrated nuclear gauge (WSDOT 2018d).

3.4 Method

3.4.1 *Data collection and processing*

This study collects and processes data from the following WSDOT data sources: (1) Unit Bid Analysis, (2) SAM and (3) WSPMS for contracts completed between 2007 and 2017. The Unit Bid Analysis contains all of the construction bid price and tonnage data, SAM contains WSDOT QA data, and WSPMS contains WSDOT's pavement performance data. The 2007 to 2017 time period captures nearly all of the WSDOT 3/8-inch NMAS contracts. Once collected, the analysis processes the data from each source by linking the data using contract number. Also, during processing, the analysis excludes unusable data (e.g. contracts with an NMAS other than 3/8-inch or 1/2-inch). The data subsections describe the calculations for each component. All of the statistical tests (i.e. t-tests, linear regression, etc.) are parametric and assume that the distribution of the populations are normal. Table 3 provides a summary of the number of contracts, lane kilometers/miles, and sample size by NMAS and data source from 2007 to 2017. Each analysis excludes most bridge deck and all chip seal contracts; however, seven of the bridge deck contracts with field density and large tonnage data were retained.

The general calculation approach for cost, asphalt content, density, and pavement condition in this paper uses quantity/sample size per contract or lane kilometers per contract to weight each contract's data. This method reduces unwanted bias towards contracts with a small/large sample size or contracts with a small/large number of lane kilometers measured. Also, by aggregating the data by contract, this approach tracks the data by location.

Table 3. Number of Contracts, Lane Miles, and Tons of Mix by NMAS and Data Source [Cost, Asphalt Content, Density, Pavement Structural Condition (PSC), Pavement Rutting Condition (PRC)], 2007 to 2017

Parameter	Cost	Asphalt Content	Density	PSC	PRC
Total Contracts	716	529	543	305	400
Average Contracts Per Year	65	48	49	31	40
3/8-inch NMAS Contracts	66	32	27	21	34
Eastern Washington Location Contracts	N/A	N/A	N/A	17	27
Western Washington Location Contracts	N/A	N/A	N/A	4	7
Flat/Rolling Terrain Contracts	N/A	N/A	N/A	13	20
Mountainous Terrain Contracts	N/A	N/A	N/A	8	14
1/2-inch NMAS Contracts	650	497	516	284	366
Eastern Washington Location Contracts	N/A	N/A	N/A	94	113
Western Washington Location Contracts	N/A	N/A	N/A	190	253
Flat/Rolling Terrain Contracts	N/A	N/A	N/A	271	347
Mountainous Terrain Contracts	N/A	N/A	N/A	13	19
Total Lane Miles	N/A	N/A	N/A	3,143	4,322
Average Lane Miles Per Year	N/A	N/A	N/A	314	432
Total Tons of Mix	8.3M	11.5M	8.3M	N/A	N/A
Average Tons of Mix Per Year	754K	1.0M	757K	N/A	N/A

#N/A: data not available or not used in the analysis

3.4.1.1 **Construction cost**

The cost analysis uses historical cost data on WSDOT's Unit Bid Analysis web page to explore the construction bid price per ton for contracts between 2007 and 2017 (WSDOT 2018a). This data provides the bid history for WSDOT's standard bid items (WSDOT 2018a). To gather this data, the analysis completes a standard item search of HMA between 2007 and 2017. The analysis uses key fields which include contract number, WSDOT standard item number, low bid cost, planned quantity (tons), average weighted low bid (Eq. (1)), and inflation factor (Eq. (2)). All of the costs are adjusted to reflect 2017 U.S. dollars.

The statistical analysis performs a t-test for two independent samples on each contract's average weighted low bid by NMAS per year. The analysis only includes the primary HMA items, 3/8-inch and 1/2-inch NMAS (Table 1). It does not include the HMA standard items for preleveling, pavement repair, and approach categories.

$$\text{Average Weighted Low Bid} = \frac{1}{P}\sum_{i=1}^{N} b_i * p_i \qquad (1)$$

$$\text{Annual Inflation Factor} = \frac{\text{2017 Average Weighted Low Bid}}{\text{Annual Average Weighted Low Bid}} \tag{2}$$

where,

subscript $i \in \{1, \ldots, N\}$ denotes contract i out of N total contracts,

b_i = low bid for contract i (2017 U.S. dollars),

p_i = total planned HMA weight (tons) for contract i, and

P = sum of planned HMA weight (tons) across all N contracts.

3.4.1.2 **Asphalt content and density**

WSDOT uses an in-house system, SAM, to store QA data which includes contract statistical evaluation, pay factor, and mix design data for each HMA parameter. This QA analysis uses a SAM data extraction of field measured asphalt content and field density data to explore the HMA contracts completed between 2007 and 2017.

The asphalt content and density analyses integrates the data using contract numbers. The asphalt content analysis uses key fields which include contract number, completion year, NMAS, mix design number, number of years after completion (Eq.(3)), total contract sample size (Eq.(4)), average weighted asphalt content (Eq.(5)), average weighted JMF (Eq.(6)), and average JMF difference (Eq.(7)). The analysis uses the JMF difference to determine contracts not within WSDOT specifications.

$$\text{Number of Years After Completion (i.e. Contract Age)} = 2017 - Y_i \tag{3}$$

$$\text{Total Contract Sample Size (tons)} = \sum_{i=1}^{N} \sum_{j=1}^{M_i} s_{i,j} \tag{4}$$

$$(AWAC)_i = \frac{1}{S_i} \sum_{j=1}^{M_i} \left(s_{i,j}\right) * (AC)_{i,j} \tag{5}$$

$$(AWJMF)_i = \frac{1}{S_i} \sum_{j=1}^{M_i} \left(s_{i,j}\right) * (JMF)_{i,j} \tag{6}$$

$$(\Delta JMF)_i = (AWAC)_i - (JMF)_i \tag{7}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

M_i = total distinct number of mix designs included in contract *i*,

N = total number of contracts,

Y_i = completion year of contract *i*,

$AWAC_i$ = average weighted asphalt content of contract *i*,

$s_{i,j}$ = sample size of mix design *j* of contract *i*,

S_i = sample size of contract *i*, summed across all M_i contracts,

$AC_{i,j}$ = asphalt content of mix design *j* in contract *i*,

$JMF_{i,j}$ = Job Mix Formula (JMF) of mix design *j* in contract *i*,

$(AWJMF)_i$ = Average weighted JMF of contract *i*, and

$(\Delta JMF)_i$ = Job Mix Formula (JMF) difference for contract *i*.

The density analysis uses key fields which include contract number, completion year, NMAS, mix design number, contract age (Eq.(3)), total contract sample size (Eq.(4)), and average weighted density (Eq.(8)). The density analysis also tracks all contracts that do not meet WSDOT specifications.

$$\rho_i = \frac{1}{S_i} \sum_{j=1}^{M_i} (d_{i,j}) * \left(s_{i,j}\right) \tag{8}$$

where,

ρ_i = average weighted density of contract *i*,

M_i = total distinct number of mix designs included in contract *i*,

$d_{i,j}$ = field density of mix design *j* of contract *i*,

$s_{i,j}$ = sample size of mix design *j* of contract *i*, and

S_i = sample size of contract *i*, summed across all M_i contracts.

The statistical analysis performs a t-test for two independent samples on the average weighted asphalt content and the average weighted density by contract. Table 3 provides a summary of the QA data used.

3.4.1.3 **Contracts not within specifications**

About 99% of the asphalt content and density averages conformed to WSDOT specifications demonstrating that the pavements are mostly within specifications.

- **Asphalt Content.** All of the 3/8-inch NMAS contract averages were within the WSDOT asphalt content ±0.5% tolerance, while 5 of the 497 (1.0%) 1/2-inch NMAS contract averages were outside the ±0.5% tolerance. All of these contracts were small, about 5,152 tons (0.04% of total tonnage), exhibiting little influence overall. The contracts with out of specification asphalt content averages did not correspond to any noticeable decrease in pavement performance;

- **Density.** One of the 27 (3.4%) 3/8-inch NMAS and 4 of the 516 (0.8%) 1/2-inch NMAS contract averages were below the WSDOT 91.0% minimum density specification. All of these contracts were small, 2,541 tons (0.03% of total tonnage), exhibiting little influence overall. Additionally, the contracts out of specification did not correspond to any noticeable decrease in pavement performance.

3.4.1.4 **Pavement condition**

The WSDOT WSPMS database uses three indices to describe pavement condition which includes structural, rutting, and roughness condition data. This analysis focuses on structural and rutting condition index values, not roughness index values since roughness is typically a lagging indicator of cracking (Li et al. 2004). The index values of structural and rutting condition values do not account for raveling. Uhlmeyer et al. (2016) and Wen et al. (2016) describe these indices (see below) and the index scale ranges from 0 (very poor) to 100 (very good). An index value of 45 to 50 triggers a pavement rehabilitation requirement (Uhlmeyer et al. 2016).

- **Pavement Structural Condition (PSC).** PSC is a cracking index that accounts for longitudinal, transverse, and alligator cracking as well as patching (Uhlmeyer et al. 2016; Kay et al. 1993). Generally, "top-down cracking is a common distress mode" for HMA pavements in Washington State particularly for pavements thicker than about 6.3 inches (Uhlmeyer et al. 2000). Of the 305 contracts with cracking data, the average total pavement thickness is about 9.6 inches and about 90% have a total pavement thickness greater than about 6.3 inches. The rehabilitation trigger index value of 50 represents about "10% equivalency cracking (EC) in the wheel paths" (Wen et al. 2016; Uhlmeyer et al. 2016; Kay et al. 1993). "Equivalency cracking" represents the amount of "alligator, longitudinal, transverse cracking and patching", see Eq. (9) (Kay et al. 1993). WSPMS does not include a PSC index value for chip seals or for HMA between zero and three years old from 2011 to the present (Uhlmeyer et al. 2016). Because of this, the number of contracts with a PSC value is less than the number of PRC contracts (Table 3).

$$PSC = 100 - 15.8 * (\text{Equivalency Cracking})^{0.5} \quad (9)$$

- **Pavement Rutting Condition (PRC).** PRC is a rutting index (Uhlmeyer et al. 2016; Wen et al. 2016). Rutting index ratings of 75, 50, and 25 translate to a rutting depth of about 0.20 inches, 0.35 inches, and at least 0.55 inches (Pierce et al. 2001).

The WSPMS condition analysis uses a data extraction for contracts completed between 2007 and 2016 which only includes surface data. The condition analysis excludes 2017 data (pavement age of zero) since it is unknown when the 2017 data were taken in relation to the paving (Table 1). The cracking and rutting performance analyses use contract number, completion year, NMAS, WSDOT region, terrain (flat/rolling and mountainous), contract age (Eq.(3)), lane kilometers (Eq.(10)), and average weighted condition value (Eq.(11)). Both analyses focus on investigating 3/8-inch and 1/2-inch NMAS mixtures for only the published 2017 condition data in comparison to contract age.

$$L_i = \sum_{k=1}^{Q_i} \lambda_{i,k} \quad (10)$$

$$(CV)_i = \frac{1}{L_i} \sum_{k=1}^{Q_i} (\lambda_{i,k}) * (SCR)_{i,k} \quad (11)$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(CV)_i$ = average weighted condition value of contract i, and

$(SCR)_{i,k}$ = section condition rating of segment j in contract i.

A paired t-test by age is performed for 3/8-inch and 1/2-inch NMAS condition results to determine if the difference between the average PSC and PRC condition values per year from 2007 to 2016 is statistically significant. In the paired t-test, one expects the means to be very close in the early years as both pavements are performing well. As the pavements age, they might begin to separate. As a result, the paired t-test is not a very strong indicator of anything if the null is not rejected. A paired t-test measures the difference between paired sets of numbers and has no way of accounting for the growth in difference over time. Additionally, a linear regression is performed to determine the R^2 coefficient of NMAS, average weighted condition, and contract age.

Contract region and terrain were extracted manually from the online WSPMS since they were not included in the WSPMS extraction. The WSDOT regions determined the location of the contract (Eastern and Western Washington). Eastern Washington includes the Eastern, North Central, and South Central regions while Western Washington includes the Northwest, Olympic, and Southwest regions (Wen et al. 2016). The WSDOT Design Manual (WSDOT 2017) describes flat (i.e. level) as a terrain that "offers few or no obstacles to the construction of a highway", rolling as a terrain "with slopes that rise and fall gently" and mountainous as a terrain with "high, steep drainage divides; and mountain ranges." Mountain terrains are thought to reduce service life as a result of severe climates and more difficult construction environments than flat/rolling terrains (Wen et al. 2016). Figure 11 shows the location of the WSPMS extracted data covering all six WSDOT regions and Table 3 breaks down the number of contracts by condition, location, and terrain.

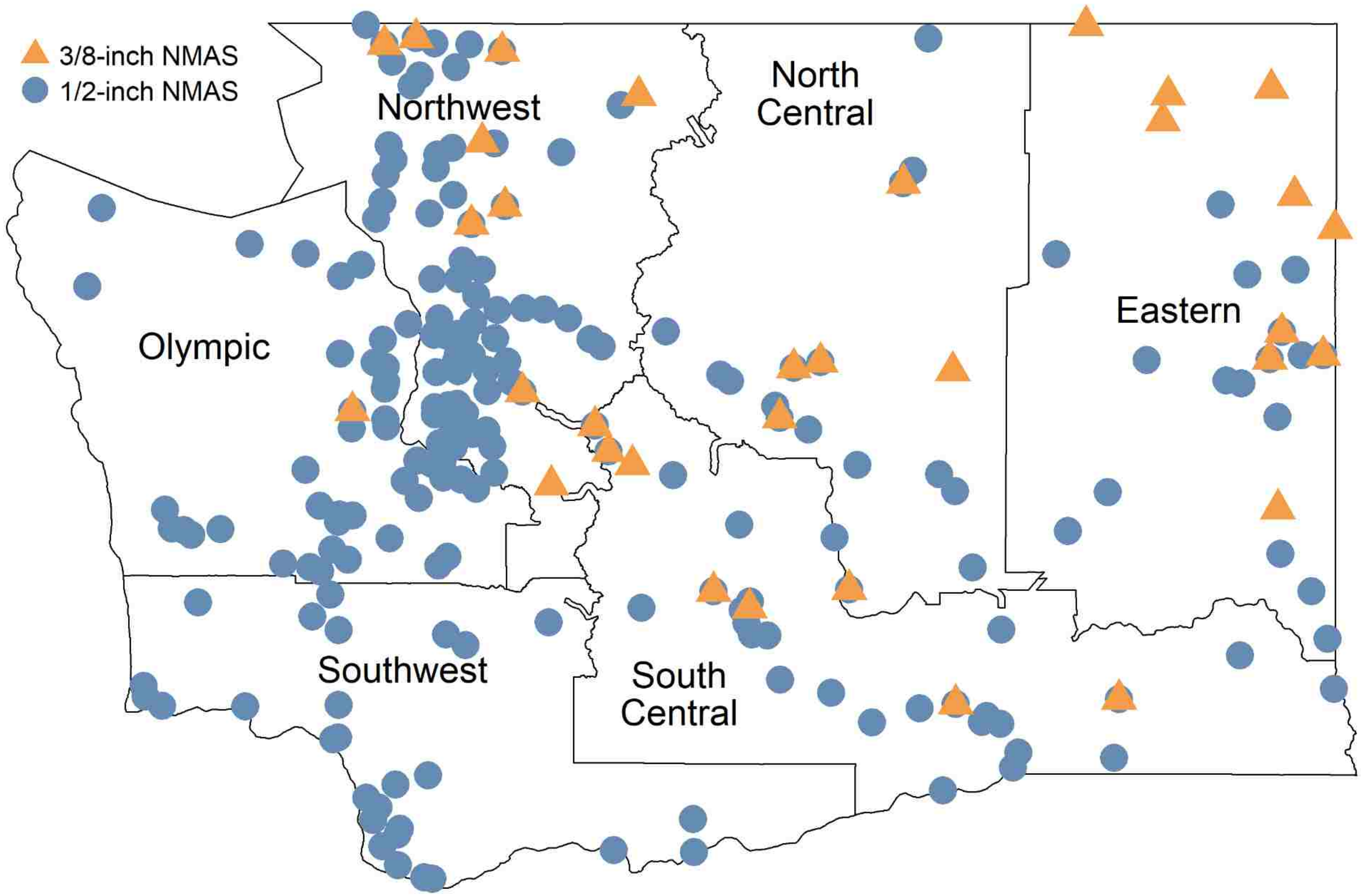


Figure 11. WSPMS Contracts by WSDOT Region for 3/8-inch and 1/2-inch NMAS Asphalt Pavement Mixtures Completed Between 2007 and 2016

3.4.2 *Survey and interviews*

3.4.2.1 **WAPA survey**

A general survey given to 37 WAPA members from 14 companies (11 asphalt producers, 2 subsidiaries, and 1 asphalt testing laboratory) in Washington State provides industry perspective. In partnership with WAPA and WSDOT, the survey asks selected local participants to offer interpretation, feedback, and common industry reasons explaining the pavement data results. The survey contains 24 questions on a variety of asphalt topics including three NMAS-focused questions (see below). The useful survey response rate, a measure of the total number of surveys taken, complete or not, included 18 of 37 individuals (49%).

1. In 2017, what portion in tons of your project mix designs use the [following] NMASs: (1) 3/8-inch, (2) 1/2-inch, (3) 3/4-inch and (4) 1-inch?;
2. Generally speaking, what is your preferred NMAS? Please explain why;
3. What have been your observations with the production and placement of 3/8-inch NMAS mix design pavements in comparison to 1/2-inch NMAS mix design pavements?

3.4.2.2 **WAPA/WSDOT interviews**

Interviews with 7 WAPA and 9 WSDOT people, averaging about one hour per interview, were used to follow up on the survey. These semi-structured interviews capture specific information on a variety of asphalt topics and were meant to uncover, in a conversational manner, industry and owner sentiment not easily expressed in a short survey (e.g. opinions on mix design, construction practices, performance, etc.). The interviewers generated a set of questions for the WAPA members as well as the WSDOT staff and asked all of the interviewees the same questions to maintain consistency. Using a conversational approach, the interviewers asked additional questions depending on the knowledge of the interviewee.

About 15 minutes of each interview focused on 3/8-inch and 1/2-inch NMAS mixtures. The interview topics included volumetrics, lift thickness, stockpiling, performance, permeability, cost, placement, 3/8-inch versus 1/2-inch NMAS, RAP, and bridge decks.

3.5 Results

3.5.1 *Construction cost*

The average weighted low bid price per ton of 3/8-inch NMAS contracts is $92.75 per ton and for 1/2-inch NMAS contracts is $84.46 per ton, a difference of $8.30 per ton. Figure 12 shows the average weighted low bid per ton for each year in 2017 dollars and planned quantity in tons by NMAS from 2007 to 2017. Contract prices in 2017 dollars for 3/8-inch and 1/2-inch NMAS contract were compared using a t-test for two independent samples (H_0 = no difference between contract price means). Cost results fail to reject the null hypothesis at 95% confidence (p-value = 0.081, 95% confidence interval of difference between the means is -2.869, 49.472).

3.5.2 *Asphalt content*

The overall average weighted asphalt content of 3/8-inch NMAS contracts is 6.05% and for 1/2-inch NMAS contracts is 5.39%, a difference of 0.66%. The box and whisker plots (Figure 13) show the average weighted field asphalt content percentage in comparison with contract age. Asphalt content for 3/8-inch and 1/2-inch NMAS mixtures were compared using a t-test for two independent samples (H_0 = no difference between asphalt content means). Asphalt content results reject the null hypothesis at 95% confidence (p-value < 0.0001, 95% confidence interval of difference between the means is 0.5%, 0.7%). Of note, the 3/8-inch NMAS asphalt content is noticeably lower at age eight. For this age, there are only two 3/8-inch NMAS contracts, and one is primarily responsible with an average weighted asphalt content of 4.87%.

3.5.3 *Density*

The overall average weighted density of 3/8-inch NMAS contracts is 93.11% and for 1/2-inch NMAS contracts is 93.18%, a difference of 0.07%. The box and whisker plots (Figure 14) show the average weighted field density in comparison with the age of the contract. Density for 3/8-inch NMAS mixtures were compared using a t-test for two independent samples (H_0 = no difference between density means). Density results fail to reject the null hypothesis at 95% confidence (p-value = 0.528, 95% confidence interval of difference between the means is -0.2%, 0.5%). Of note, the 3/8-inch NMAS density is noticeably lower at age four. For this age, there is only one 3/8-inch NMAS contract with an average weighted density of only 91.19%.

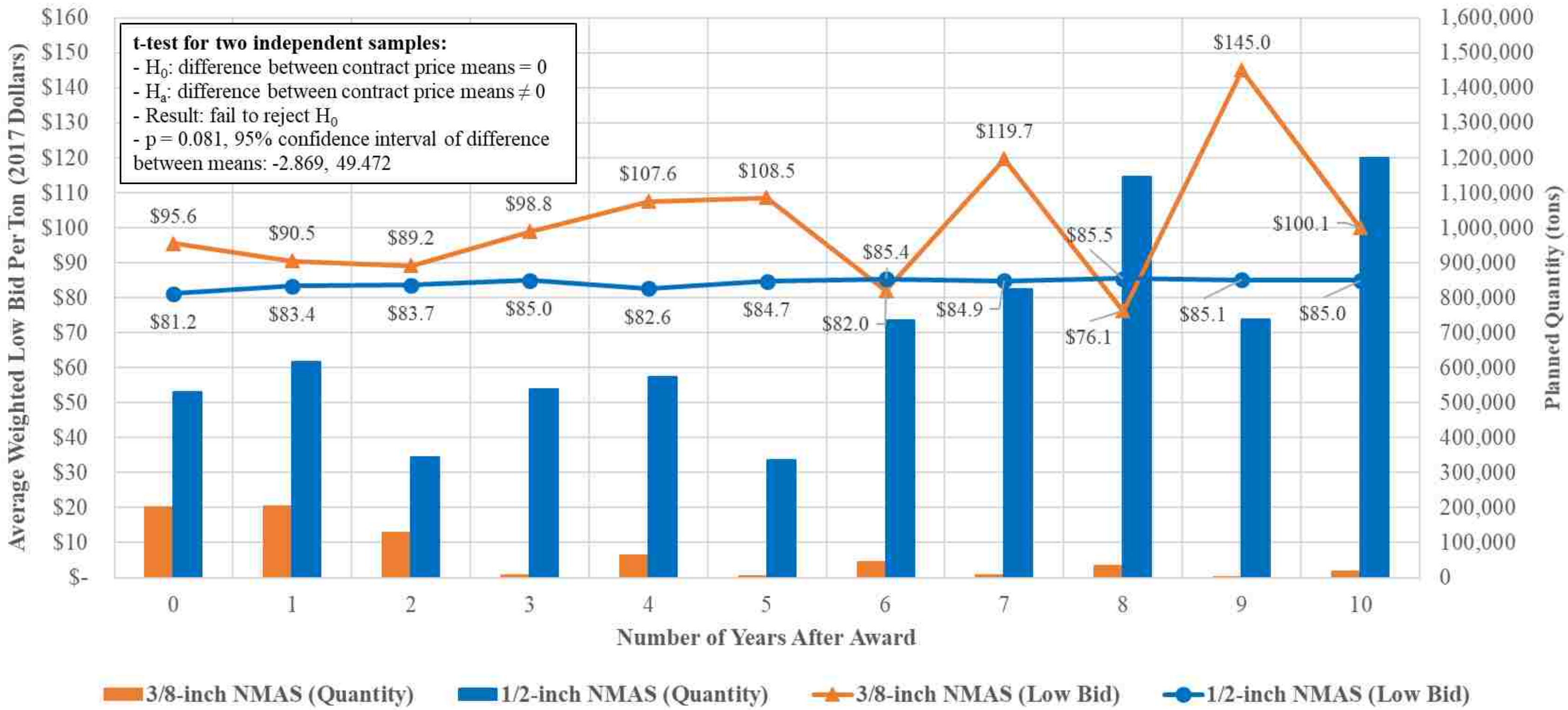
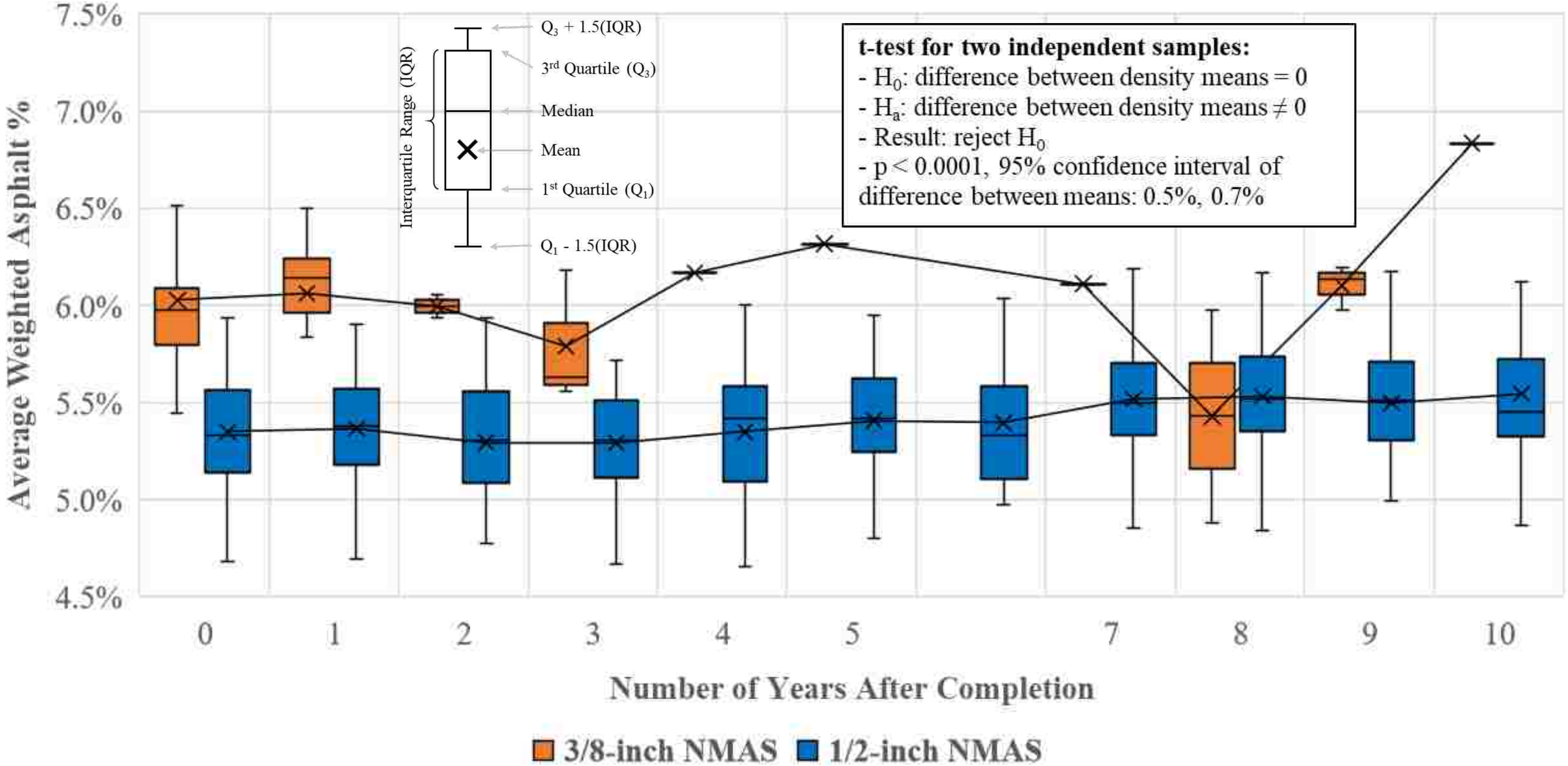
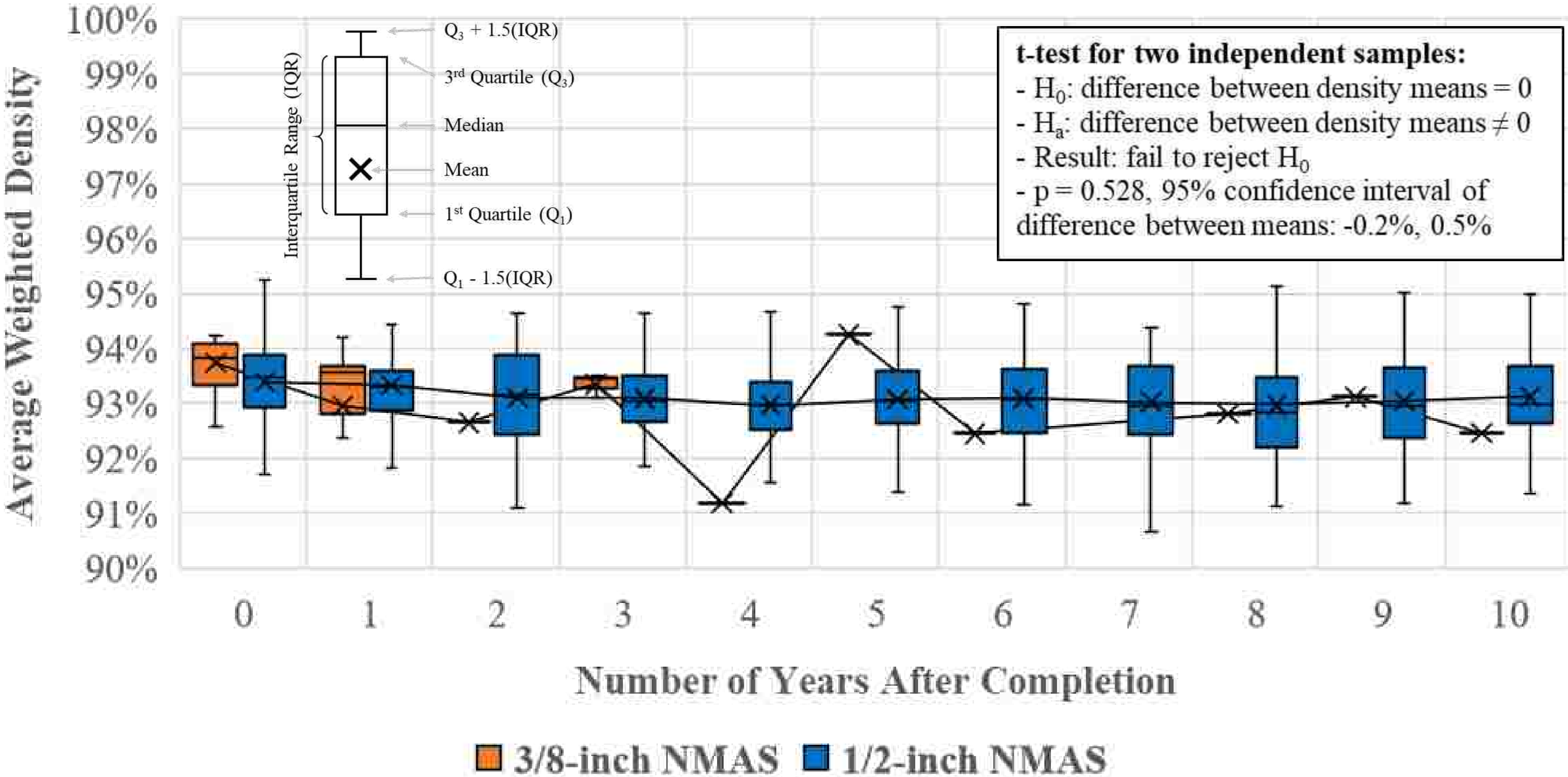


Figure 12. Average Weighted Low Bid Per Ton (2017 Dollars) and Planned Quantity (ton) By Number of Years After Contract Award for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 (Age 10) to 2017 (Age 0)



	Number of Contracts by Years After Completion										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
3/8-inch	10	8	2	3	1	1	0	1	2	3	1
1/2-inch	45	45	44	49	40	46	51	44	53	46	34

Figure 13. Average Weighted Asphalt Content Percentage and Number of Contracts by Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 (Age 10) to 2017 (Age 0)



	Number of Contracts by Years After Completion										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
3/8-inch	10	7	1	3	1	1	1	0	1	1	1
1/2-inch	45	46	45	49	40	48	52	47	59	49	36

Figure 14. Average Weighted Field Density and Number of Contracts by Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 (Age 10) to 2017 (Age 0)

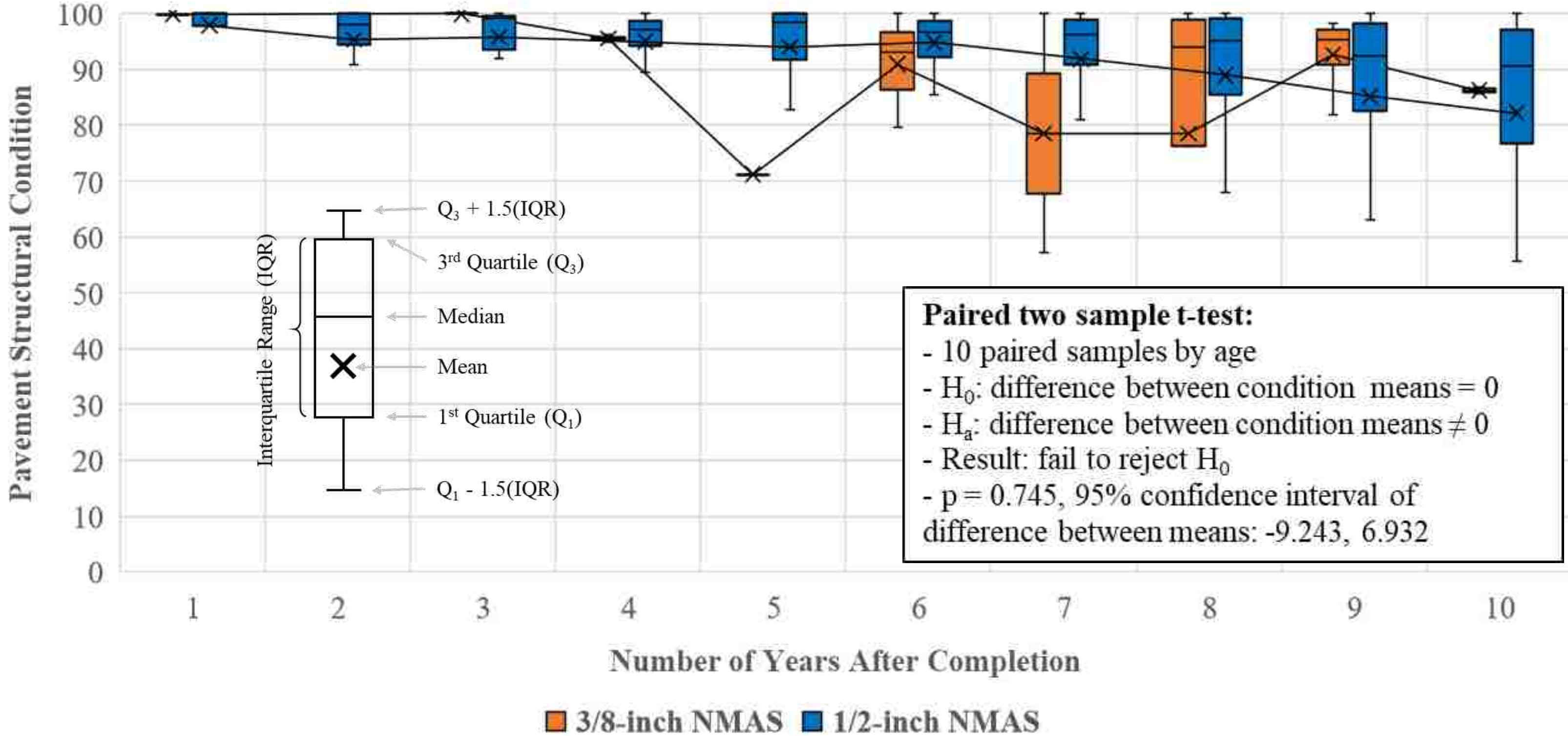
3.5.4 *Pavement condition*

3.5.4.1 **Cracking**

The box and whisker plots (Figure 15) show the average weighted PSC, largely a measure of cracking by contract age for 3/8-inch and 1/2-inch NMAS. Cracking for 3/8-inch NMAS mixtures were compared using a paired t-test (H_0 = no difference between condition means). Cracking results fail to reject the null hypothesis at 95% confidence (p-value = 0.745, 95% confidence interval of difference between the means is -9.243, 6.932). Cracking for 3/8-inch NMAS mixtures with age were compared using a linear regression and results revealed a R^2 coefficient of 0.090, demonstrating a poor fit of the data. The 3/8-inch NMAS condition is noticeably lower at ages five, seven and eight.

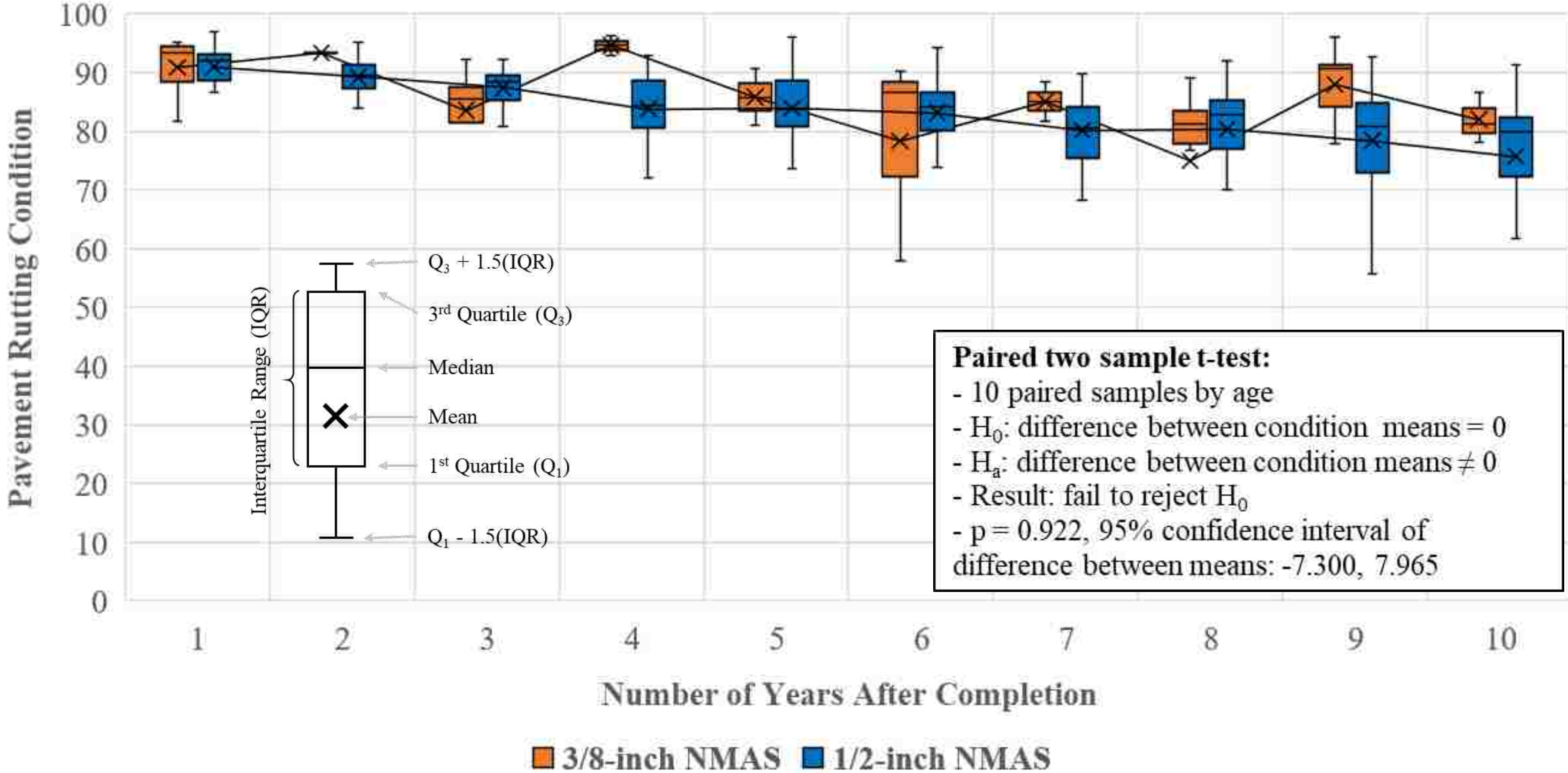
3.5.4.2 **Rutting**

The box and whisker plots (Figure 16) show the average weighted PRC by contract age for 3/8-inch and 1/2-inch NMAS. Rutting for 3/8-inch NMAS mixtures were compared using a paired t-test (H_0 = no difference between condition means). Rutting results fail to reject the null hypothesis at 95% confidence (p-value = 0.922, 95% confidence interval of difference between the means is -7.300, 7.965). Rutting for 3/8-inch NMAS mixtures with age were compared using a linear regression and results revealed a R^2 coefficient of 0.233. The 3/8-inch NMAS condition is noticeably lower at age six.



	Number of Contracts by Years After Completion									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
3/8-inch	1	0	1	2	1	3	2	5	4	2
1/2-inch	4	8	9	30	31	44	33	42	43	40

Figure 15. Average Weighted Pavement Structural Condition and Number of Contracts by Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 (Age 10) to 2016 (Age 1)



	Number of Contracts by Years After Completion									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
3/8-inch	6	1	4	2	2	3	2	6	5	3
1/2-inch	31	31	29	30	33	44	34	43	45	46

Figure 16. Average Weighted Pavement Rutting Condition and Number of Contracts by Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 (Age 10) to 2016 (Age 1)

3.5.4.3 **Location and terrain**

Generally, 3/8-inch and 1/2-inch NMAS contracts exhibit similar cracking and rutting performance in terms of location and terrain. The 3/8-inch NMAS cracking condition is noticeably lower at age 10 for mixtures in Western Washington, age five for mixtures in Eastern Washington, and at age five for mountainous terrain. Conversely, the 3/8-inch NMAS cracking condition is noticeably higher at ages 8-10 for mixtures in Eastern Washington and at age eight in mountainous terrain. The 3/8-inch NMAS rutting condition is noticeably lower at ages three, six, and eight for mixtures in Eastern Washington and at age six for mixtures in mountainous terrain. Conversely, the 3/8-inch NMAS rutting condition is noticeably higher at age five and nine for mixtures in Western Washington and at ages 4, 7, 9, and 10 for mixtures in Eastern Washington. Overall, mixtures exhibit lower cracking and rutting condition values with time in Eastern Washington than in Western Washington. This is consistent with the findings reported in Wen et al. (2016) that the contracts in Eastern Washington generally perform worse. Additionally, the condition data analysis does not reveal a clear trend between condition and terrain. This does not imply that a trend does not exist but rather that the available WSDOT in-service pavement data do not provide evidence to support a performance difference.

3.5.5 ***WAPA survey and WAPA/WSDOT interviews***

3.5.5.1 **WAPA produces mostly 1/2-inch NMAS mixtures**

The amount of 1/2-inch NMAS production exceeded all other mix designs. In response to the question “in 2017, what portion of your project mix designs use the NMAS below?”, the respondent breakdown includes 1/2-inch: 93%, 3/8-inch: 4%, 1-inch: 2% and 3/4-inch: 1%.

3.5.5.2 **WAPA respondents prefer 1/2-inch NMAS mixtures**

The survey asked respondents to select their preferred NMAS and most responses indicated that 1/2-inch NMAS is preferred by WAPA members. In response, 78% preferred 1/2-inch NMAS (11% 3/8-inch NMAS, 11% no preference) citing its lower cost and customer preference. Five of the respondents included a justification supporting their selection. Of the five responses, three use 1/2-inch or 3/8-inch NMAS mixtures because of customer input and two use 1/2-inch NMAS mixtures primarily because of construction/plant efficiency.

Similar to the survey findings, five of seven WAPA members interviewed preferred 1/2-inch NMAS because the cost is lower and they feel it achieves a similar performance level. One interviewee stated that the 3/8-inch NMAS mixes cost about $8 to $10 per ton more than 1/2-

inch NMAS primarily because of the increased crushing costs, increased asphalt content, and the need to control additional fines. During the interviews, three of nine WAPA members indicated that the additional RAP crushing required to meet a 3/8-inch NMAS mix design increases costs and is difficult to achieve. To investigate this further, the survey asked respondents to identify observations that distinguish the two NMASs (Figure 17).

3.5.5.3 **About 30% of respondents prefer 3/8-inch NMAS mixtures**

One WAPA interviewee preferred 3/8-inch NMAS mixtures because it produces a pavement with decreased permeability without any additional performance issues in comparison to 1/2-inch NMAS pavements. Four of the nine WSDOT interviewees prefer 3/8-inch NMAS mixtures and seven of nine WSDOT interviewees recognize its potential performance advantages. One WSDOT interviewee stated that the focus of WSDOT's 3/8-inch NMAS contracts is primarily on the South Central, Eastern, and Northwest regions. The benefits of the 3/8-inch NMAS mixtures include decreased permeability and lower standard deviations of HMA mixture tests (e.g. density). WSDOT also indicated that the 3/8-inch NMAS projects are not necessarily lower risk in comparison to 1/2-inch NMAS projects. The contractor learning curve for 3/8-inch NMAS mixtures is steep and the predicted benefits may take time to achieve.

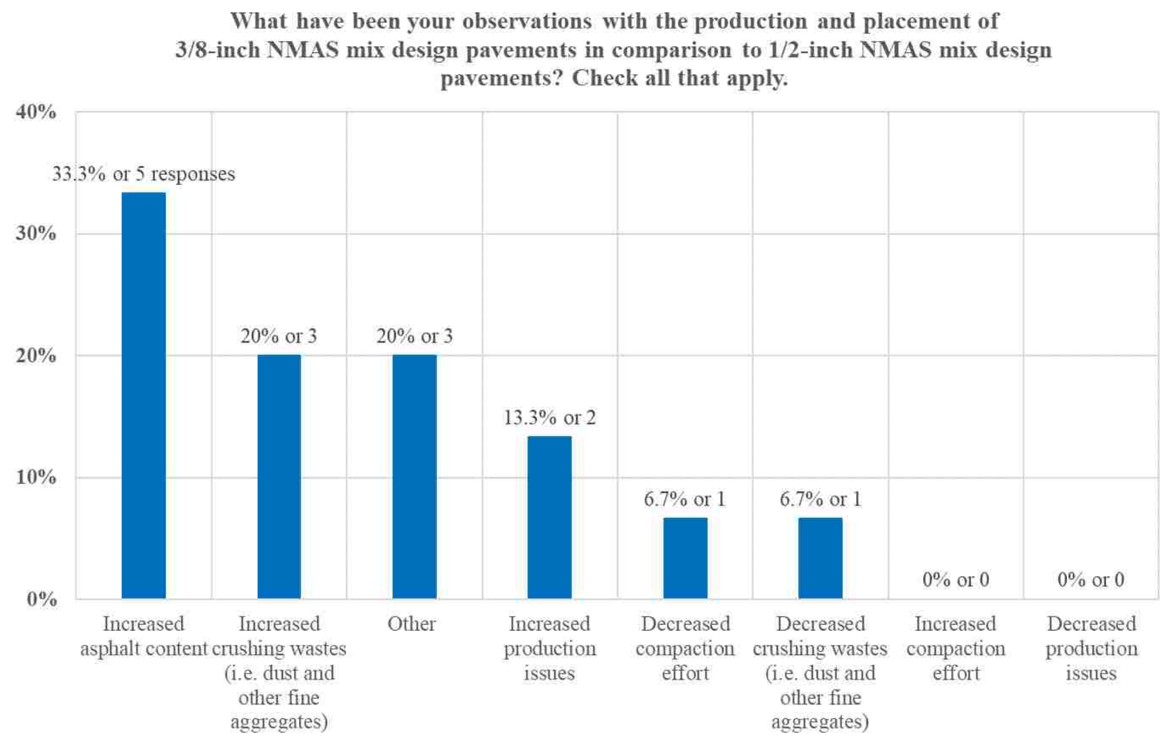


Figure 17. WAPA Survey Response Results by Percentage and Individual Responses for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures

3.6 Discussion

3.6.1 *Limitations*

The purpose of the chapter is to use this field and performance data to characterize 3/8-inch NMAS mixtures in relation to a baseline of 1/2-inch NMAS mixtures. This method uses actual field data and its usefulness relies on quality data. Also, there are many uncontrolled variables (e.g. construction quality, underlying pavement/soil conditions, etc.) that could influence dependent performance variables beyond density and mix design (e.g. NMAS) data. Although industry perspectives can assist in results interpretation, this method is likely to only identify very broad, strong trends and sometimes expected trends are not seen above the noise of unmeasured variables. Many of the qualities of a good pavement as well as 3/8-inch NMAS mixture benefits identified in the literature such as decreased permeability and reduced compactive effort are not captured within WSDOT's quantitative data.

3.6.2 *3/8-inch NMAS construction costs are about $8 per ton more*

The construction cost analysis weighted by quantity reveals that 3/8-inch NMAS mixtures cost $92.75 per ton and the 1/2-inch NMAS mixtures cost $84.46 per ton (Figure 12). The statistical evidence suggests that there is not sufficient evidence to conclude that 3/8-inch NMAS mixtures produce a different cost than 1/2-inch NMAS mixtures. However, the $8 per ton cost difference is reinforced by survey and interview responses which noted that 3/8-inch NMAS pavements cost about $8 to $10 more per ton as a result of increased asphalt content and crushing costs. One of the case studies in Aschenbrener et al. (2017) found that 3/8-inch NMAS mixtures would exhibit a higher price.

3.6.3 *3/8-inch NMAS asphalt content is about 0.7% higher*

The 3/8-inch NMAS mixtures exhibit a higher field measured asphalt content of 6.1% versus 5.4% for 1/2-inch NMAS (Figure 13). The statistical analysis suggests that the difference between these means is statistically significant. This is consistent with the surveys, interviews, and literature since 3/8-inch NMAS mixtures require a higher asphalt content to coat an increased surface area. Additionally, the increased asphalt content for 3/8-inch NMAS mixtures is consistent with the higher cost per ton data.

3.6.4 *3/8-inch NMAS field densities are similar*

The 3/8-inch NMAS mixtures exhibit a field density of 93.11% versus 93.18% for 1/2-inch NMAS. The statistical evidence suggests that there is not sufficient evidence to conclude that 3/8-inch NMAS mixtures produce a different density than 1/2-inch NMAS mixtures (Figure 14). This finding does not align with the expected outcome (i.e. the 3/8-inch NMAS mixtures would produce higher field densities) in the survey and interviews. This observation does not account for compactive effort, which is not recorded with field density measurements. However, because WSDOT uses the same minimum lift thickness for both mixtures, the 3/8-inch NMAS likely requires less compactive effort to achieve the desired field density.

3.6.5 ***3/8-inch NMAS performs similarly over time***

3.6.5.1 **Cracking**

The statistical analysis of the weighted structural condition average by age of the 3/8-inch NMAS versus the 1/2-inch NMAS mixtures fails to reject that the difference between the means is zero. As a result, there is not sufficient statistical evidence to conclude that 3/8-inch NMAS mixtures produce a different overall average weighted structural condition than 1/2-inch NMAS mixtures. This finding does not align with the literature which states that a smaller NMAS exhibits decreased cracking. This does not imply that the literature is incorrect, but rather that the available WSDOT in-service pavement data do not provide evidence to support the literature.

The 3/8-inch NMAS contracts exhibit noticeably lower structural values at ages five, seven, and eight (Figure 15). Low values during these years are driven by three contracts totaling 7.1 lane miles in Eastern Washington. The low number of 3/8-inch NMAS samples provides more weight to individual contracts. There is no corroborating evidence in the data that these low values are due to NMAS. A comparison by tons of mix (versus contracts) during these three years yields a similar PSC of 89.6 for 3/8-inch NMAS mixtures versus 88.8 for 1/2-inch NMAS mixtures.

Conversely, the 3/8-inch NMAS contracts show similar cracking performance to the 1/2-inch NMAS contracts at ages 1 to 4, 6, and 9 to 10 (Figure 15). At ages 9 and 10, the 3/8-inch NMAS mixtures show slightly higher performance with an average weighted PSC of 91.8 versus 85.4 for 1/2-inch NMAS mixtures, yielding a lower average equivalency cracking in the wheel path by about 0.6%. The 3/8-inch NMAS subset of these two years includes six contracts (four Western Washington and two Eastern Washington) covering about 31 lane miles, all of which are on flat/rolling terrain.

3.6.5.2 **Rutting**

The statistical analysis of weighted rutting condition average by age of the 3/8-inch NMAS versus the 1/2-inch NMAS fails to reject that the difference between the means is zero. As a result, there is not sufficient statistical evidence to conclude that 3/8-inch NMAS mixtures produce a different overall average weighted rutting condition than 1/2-inch NMAS mixtures. This finding provides evidence that smaller NMAS mixtures can exhibit similar rutting resistance as larger NMAS mixtures.

The 3/8-inch NMAS contracts exhibit noticeably lower rutting values at age six (Figure 16) because of one small contract (2.4 lane miles) with a low value (PRC of 58.0) in Eastern Washington. The low number of 3/8-inch NMAS samples provides more weight to individual contracts. There is no corroborating evidence in the data that this low value is due to NMAS. A comparison by tons of mix yields a lower PRC of 67.7 for 3/8-inch NMAS versus 81.2 for 1/2-inch NMAS mixtures, a rutting difference of 0.10 inches.

Conversely, the 3/8-inch NMAS contracts show similar rutting performance to the 1/2-inch NMAS contracts at ages 1 to 5 and 7 to 10 (Figure 16). At ages 9 and 10, the 3/8-inch NMAS mixtures show slightly higher performance with an average weighted PRC of 82.9 versus 76.3 for 1/2-inch NMAS mixtures, yielding a lower average rutting depth by about 0.05 inches. The 3/8-inch NMAS subset of these two years includes eight contracts (five Western Washington and three Eastern Washington) covering about 33.9 lane miles, all of which are on flat/rolling terrain.

3.7 Conclusion

This paper investigates the performance of 3/8-inch NMAS mixtures in comparison to 1/2-inch NMAS mixtures in Washington State by synthesizing WSDOT cost, mix design, QA, and performance data for contracts completed between 2007 and 2017 as well as industry perspectives on the topic. The 3/8-inch NMAS mixtures cost more because of increased asphalt content and crushing and have not shown significant performance benefits on a statewide or Eastern versus Western Washington level over the last 10+ years. The conclusions are:

- **The construction bid price of 3/8-inch NMAS mixtures exceeds 1/2-inch NMAS mixtures by about $8 per ton**;
- **The overall weighted average for field measured asphalt content of 3/8-inch NMAS mixtures exceeds 1/2-inch NMAS mixtures by about 0.7%;**

- **The overall average weighted field density for 3/8-inch and 1/2-inch NMAS mixtures is about 93%.** As 3/8-inch NMAS mixtures use increases in Washington, the field density may increase because they require less compactive effort at the same surface lift thickness;
- **There is no statistical evidence that there is a difference between the weighted cracking and rutting performance means.** Alternatively, the data show that performance of the 3/8-inch NMAS contracts may be trending higher in older pavements (ages 9 and 10) but it is not statistically significant. This trend is worth monitoring for future analysis.

The utility of the cost, mix design, field, and performance data method presented in this paper (1) analyzes data over a uniquely long period of time (10+ years) and (2) uses the data to compare with literature findings and industry perspectives. Second, the numerous variables not analyzed (e.g. weather, paving conditions, underlying pavement condition, etc.) necessarily make the standard of proof quite high to show significant differences between the two NMASs being compared. As a result, several analyses (construction cost, density, and performance) show no significant differences. This does not imply that there are not differences, but rather there is not enough evidence to identify them. Conversely, one analysis showed statistically significant differences (asphalt content) which may be a helpful data point to inform policy and specification development. While sometimes expected trends are not seen above the noise of uncontrolled variables, those that are seen constitute strong evidence to be accounted for in policy and specification decisions. Notably, reasons for paving 3/8-inch NMAS mixtures from the literature were not universally confirmed (e.g. decreased permeability and compactive effort). This could be because of the coarse nature of the comparison or because there may be no real difference as constructed.

3.8 Acknowledgments

The authors would like to thank WSDOT and WAPA for their support and contributions to this effort. The views in this paper are those of the authors and do not reflect the official views and policies of WSDOT.

3.9 Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request. The data includes Unit Bid Analysis, SAM, and WSPMS.

3.10 Other Considerations

The preceding narrative, figures, and table in this chapter meet ASCE journal submission length requirements. The following section covers additional in-service pavement data considerations that do not fit the paper length requirements but deserve analysis.

3.10.1 *Voids in mineral aggregate (VMA)*

Another topic that provides insight into the performance of HMA pavements is voids in mineral aggregate (VMA) for contracts completed between 2007 and 2017. At a design air voids of 4%, "increasing aggregate specific surface while increasing minimum VMA will improve both fatigue resistance and rut resistance" (Christensen and Bonaquist 2006). The WSDOT specifications establish a minimum VMA for each NMAS, 15% for 3/8-inch NMAS and 14% for 1/2-inch NMAS; however, VMA was not subject to bonus or penalty pay from 2007 to 2017 (WSDOT 2018d).

WSDOT uses SAM to store QA data which includes which includes VMA field results. The analysis uses contract age (Eq.(3)), total contract sample size (tons) (Eq.(4)), and average weighted VMA per contract (Eq.(12)). Table 4 identifies the number of contracts for VMA by NMAS. Overall, 231 of 512 (~45%) contracts fall below the WSDOT VMA specifications.

$$(AWVMA)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (VMA)_{i,j} \tag{12}$$

where,

subscript $k \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWVMA_i$ = average weighted voids in mineral aggregate of contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts, and

$VMA_{i,j}$ = voids in mineral aggregate of mix design j in contract i.

Table 4. Number of Contracts and Tons of Mix by NMAS and Data Source from 2007 to 2017

Parameter	VMA	No. 8	No. 200
Total Contracts	512	527	525
Average Contracts Per Year	47	48	48
3/8-inch NMAS Contracts	29	32	32
Fine-Graded Contracts	7	8	8
Coarse-Graded Contracts	22	24	24
1/2-inch NMAS Contracts	483	495	493
Fine-Graded Contracts	44	45	45
Coarse-Graded Contracts	439	450	448
Total Tons of Mix	9.8M	11.3M	11.5M
Average Tons of Mix Per Year	893K	1.0M	1.0M

The overall average weighted VMA of 3/8-inch NMAS mixtures is 15.3% and for 1/2-inch NMAS contracts is 14.1%, a difference of about 1.2%%. VMA for 3/8-inch and 1/2-inch NMAS contracts were compared using a t-test for two independent samples (H_0 = no difference between VMA means). Results reject the null hypothesis at 95% confidence (p-value < 0.0001, 95% confidence interval of difference between the means is 0.6%, 1.7%). Generally, the VMA field results have slightly decreased in the last 10+ years and the newer contracts (ages zero to three) exhibit the lowest VMA by tons of mix (Figure 18). Given a similar density of both NMASs, a possible interpretation of the slightly lower VMA may be due to a lower effective asphalt content.

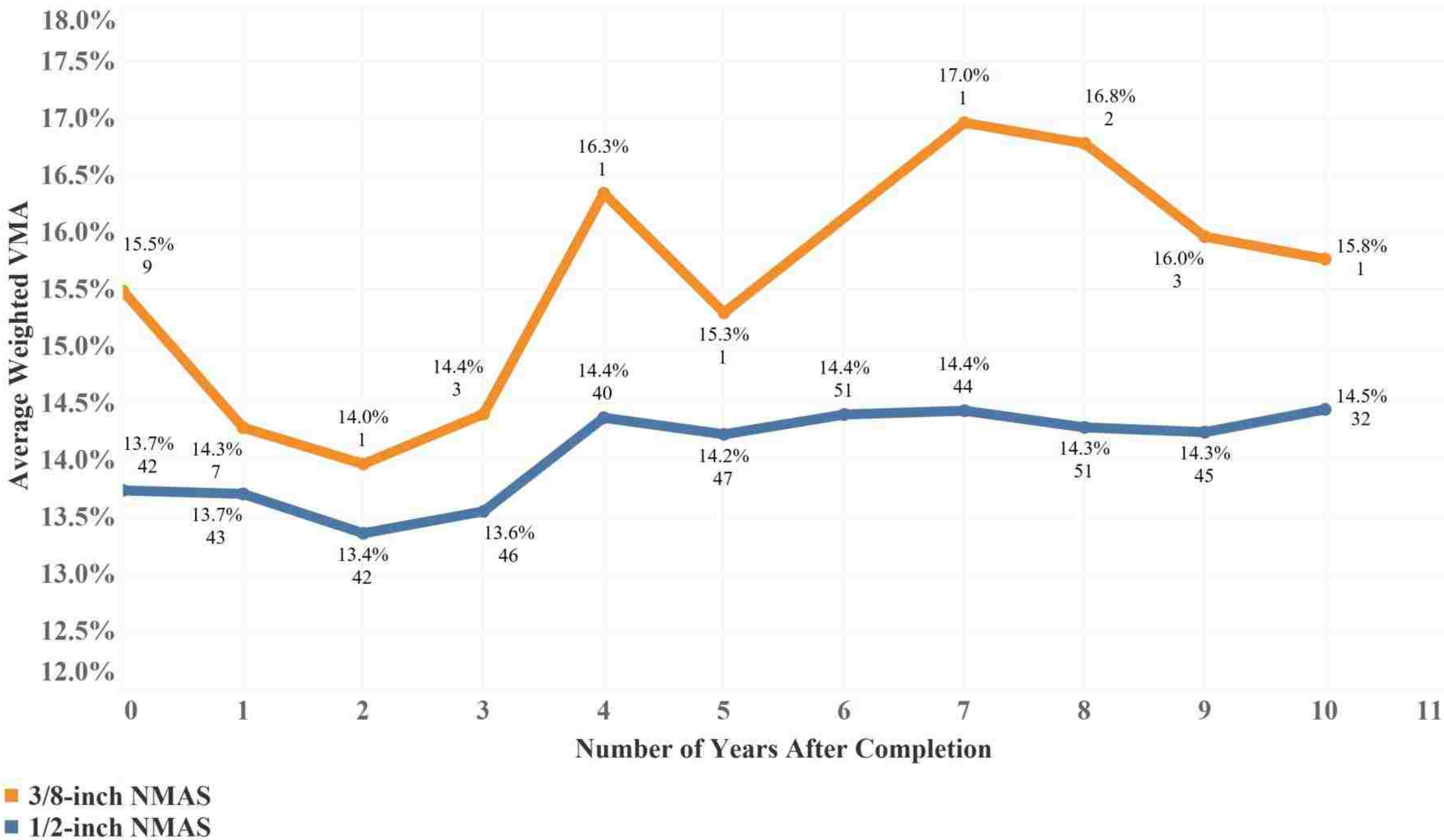


Figure 18. Average Weighted VMA Field Results by Tons of Mix and Number of Contracts Versus Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: VMA (Top), Number of Contracts (Bottom)]

3.10.2 *Gradation*

Mixture gradation provides additional insight into pavement performance, this section analyzes the field data of the No. 8 and No. 200 sieves. Together, these sieve sizes combine for a price adjustment factor (i.e. bonus) of 0.35 or 35% (No. 8: 0.15; No. 200: 0.20), demonstrating the importance WSDOT places on these sieve sizes (WSDOT 2018d).

3.10.2.1 **Gradation (No. 8 sieve)**

The WSDOT No. 8 sieve specifications establish a minimum of 32% and maximum of 67% passing for 3/8-inch NMAS mixtures and a minimum of 28% and maximum of 58% passing for 1/2-inch NMAS mixtures (WSDOT 2018d). For 3/8-inch NMAS mixtures, coarse-graded mixtures contain less than 45% passing the number eight sieve and fine-graded mixtures contain greater than 45% passing the number eight sieve (NAPA and FHWA 2001). For 1/2-inch NMAS mixtures, coarse-graded mixtures contain less than 40% passing the number eight sieve and fine-graded mixtures contain greater than 40% passing the number eight sieve (NAPA and FHWA 2001). When compacted to the same final density, fine-graded mixtures tend to be "easier to compact" (more compaction for the same compactive effort), exhibit increased resistance to permeability, and exhibit similar rutting performance in comparison to coarse-graded mixtures (Aschenbrener et al. 2017).

The WSDOT specifications establish a minimum surface lift thickness for each NMAS to ensure sufficient compaction (WSDOT 2018d). The minimum thickness for 3/8-inch NMAS is 1.2 inches, yielding a t/NMAS of 3.2 and 1.8 inches for 1/2-inch NMAS yielding a t/NMAS of 3.6 (WSDOT 2018b). Despite the allowable minimum surface lift thickness, WSDOT generally paves at the same surface thickness (1.8 inches) for both NMASs. Consequently, the 1/2-inch NMAS coarse-graded mixture, WSDOT's most used mix, yields a t/NMAS that is slightly below the recommended t/NMAS of four. WSDOT uses SAM to store QA data which includes the No. 8 sieve field results. The No. 8 sieve analysis uses contract age (Eq.(3)), total contract sample size (tons) (Eq.(4)), and average weighted No. 8 gradation results per contract (Eq. (13)). Table 4 identifies the number of contracts for the No. 8 sieve by NMAS. The overall average weighted No. 8 sieve field results of 3/8-inch NMAS mixtures is 41.46% and for 1/2-inch NMAS mixtures is 35.03%, a difference of about 6.4%. Generally, the No. 8 sieve field results have slightly increased in the last 10+ years (Figure 19) which may be an indication of more fine-graded WSDOT mixtures.

$$(AWG_{\#8})_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (G_{\#8})_{i,j} \tag{13}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWG_{\#8i}$ = average weighted No. 8 sieve gradation results of contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts, and

$G_{\#8i,j}$ = No. 8 sieve gradation results of mix design j in contract i.

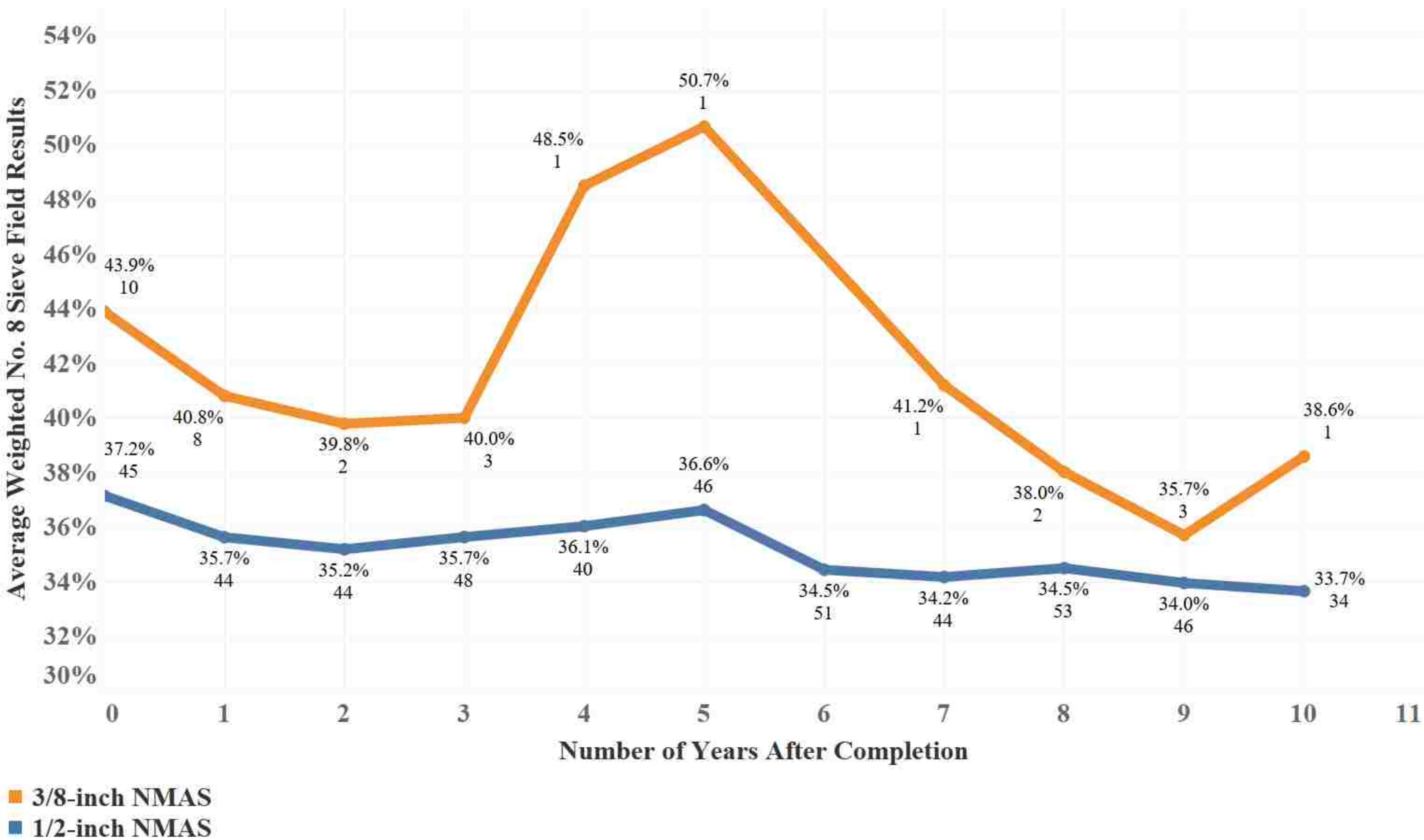


Figure 19. Average Weighted No. 8 Sieve Field Results by Tons of Mix and Number of Contracts Versus Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: No. 8 Sieve Results (Top), Number of Contracts (Bottom)]

3.10.2.2 **Gradation (No. 200 sieve)**

The WSDOT No. 200 sieve specifications establish a minimum of 2% and maximum of 7% for both NMASs (WSDOT 2018d). WSDOT uses SAM to store QA data which includes No. 200 field results. The No. 200 sieve analysis uses contract age (Eq.(3)), total contract sample size (tons) (Eq.(4)), and average weighted field gradation results per contract (Eq.(14)). Table 4 identifies the number of contracts for the No. 200 sieve by NMAS.

$$(AWG_{\#200})_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (G_{\#200})_{i,j} \tag{14}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWG_{\#8i}$ = average weighted No. 200 sieve gradation results of contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts, and

$G_{\#200i,j}$ = No. 200 sieve gradation results of mix design j in contract i.

The overall average weighted No. 200 sieve field results of 3/8-inch NMAS mixtures is 6.2% and for 1/2-inch NMAS mixtures is 5.8%, a difference of 0.4%. Generally, the No. 200 sieve field results have slightly increased in the last 10+ years particularly with the 3/8-inch NMAS mixtures (Figure 20).

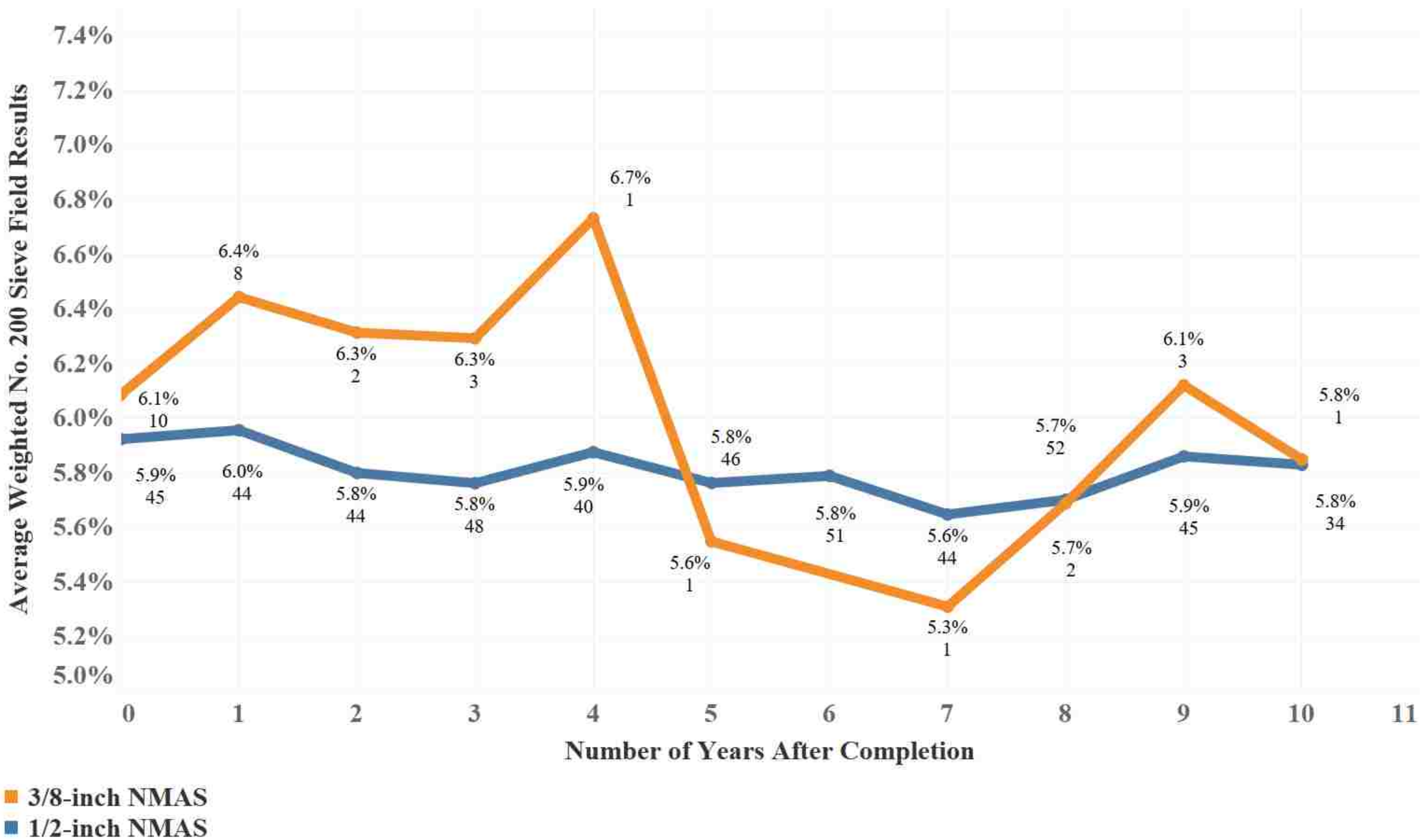


Figure 20. Average Weighted No. 200 Sieve Field Results by Tons of Mix and Number of Contracts Versus Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: No. 200 Sieve Results (Top), Number of Contracts (Bottom)]

3.10.3 *Traffic load*

Another consideration relevant to NMAS and performance is the amount of pavement traffic experienced over the pavement life. This section analyzes the number of traffic loading (i.e. equivalent single axle loads, ESALs) in the context of cracking and rutting condition to determine if a higher amount of traffic loading decreases performance. The data source for ESALs per lane mile section (Eq.(15)) is the 2017 WSPMS and Table 3 breaks down the number of contracts.

$$(AWESAL)_i = \frac{1}{L_i} \sum_{k=1}^{Q_i} \left(\lambda_{i,k}\right) * (ESAL)_{i,k} \tag{15}$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(ESAL)_{i,k}$ = number of ESALs after major rehab of segment j in contract i, and

$(AWESAL)_i$ = average weighted ESAL value of contract i.

3.10.3.1 **Cracking condition**

The average number of ESALs after the last major rehabilitation per lane mile for 3/8-inch NMAS mixtures is about 2.7 million and for 1/2-inch NMAS mixtures is about 2.7 million. The R^2 coefficient is low for both mixtures, 0.069 for 3/8-inch NMAS contracts and 0.0007 for 1/2-inch NMAS contracts (Figure 21).

3.10.3.2 **Rutting condition**

The average number of ESALs after the last major rehabilitation per lane mile for 3/8-inch NMAS mixtures is about 2.3 million and for 1/2-inch NMAS mixtures is about 2.3 million. The R^2 coefficient is low for both mixtures, 0.0007 for 3/8-inch NMAS contracts and 0.021 for 1/2-inch NMAS contracts (Figure 22).

For both cracking and rutting, the results do not show any apparent trends between NMAS, condition, and number of ESALs.

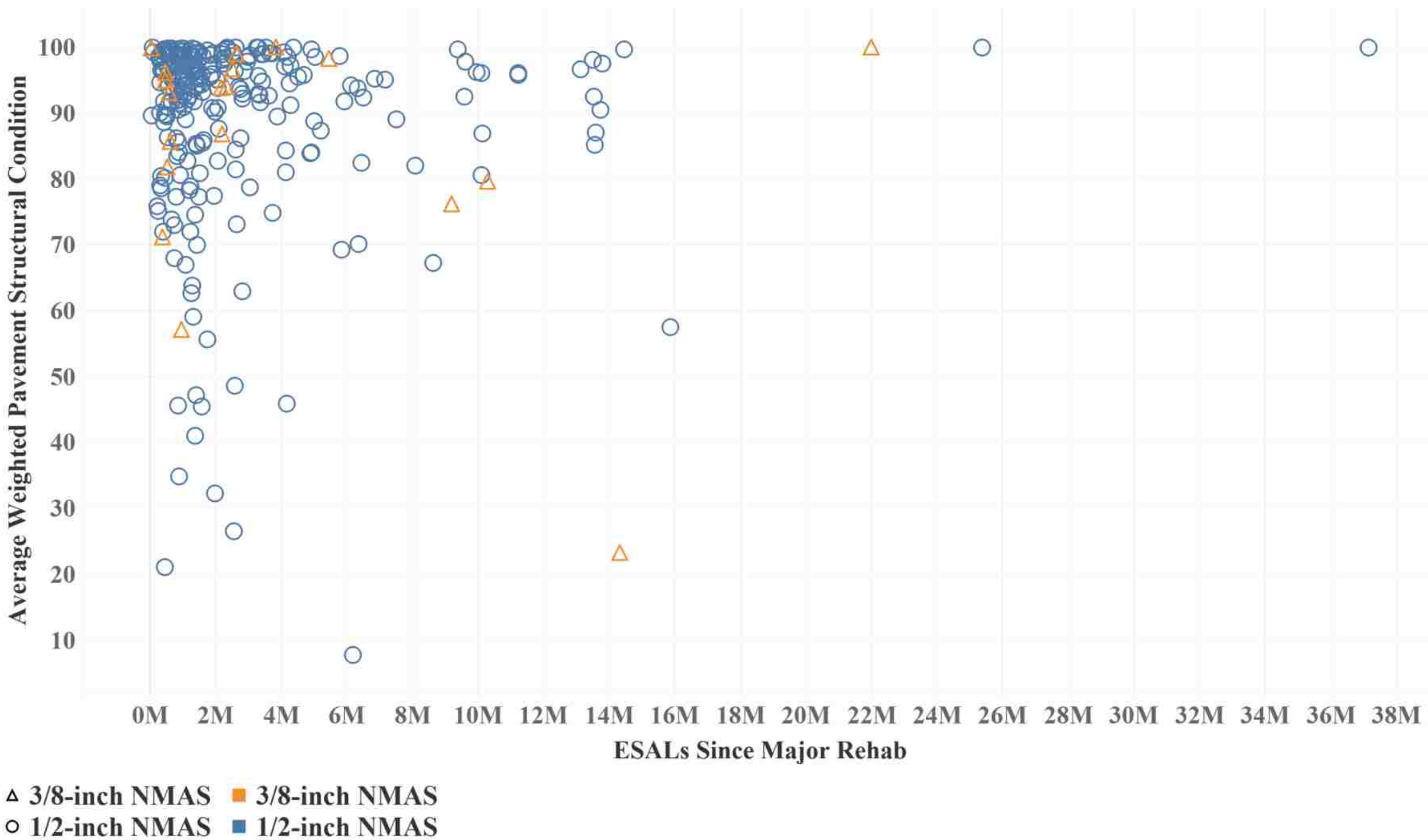


Figure 21. Average Weighted Pavement Structural Condition Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016

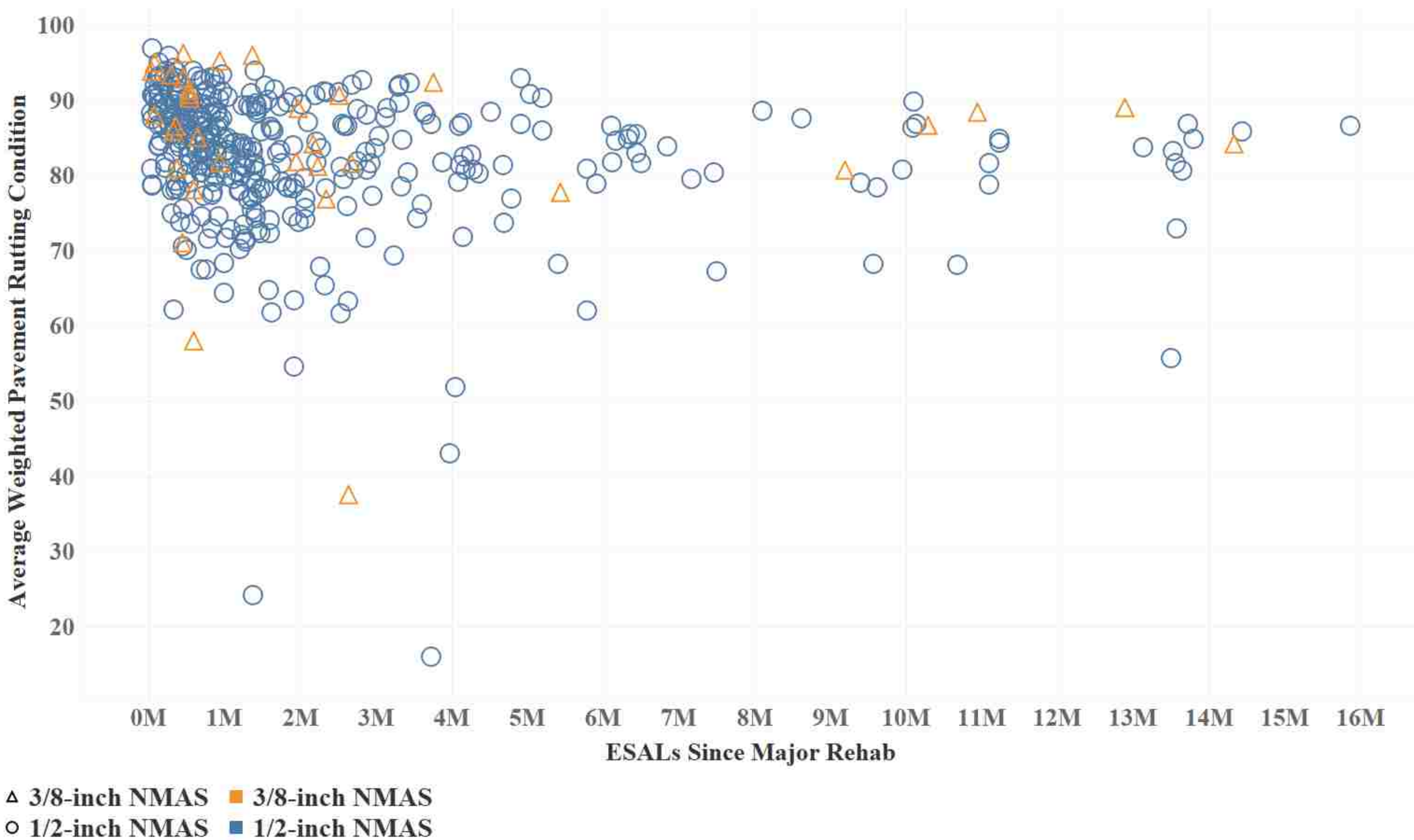


Figure 22. Average Weighted Pavement Rutting Condition Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016

3.10.4 ***Additional location and terrain figures***

The pages limitations of the ASCE article precluded the inclusion of the location and terrain figures (Figure 23-Figure 26) in the context of cracking and rutting performance. These support the results in sections 3.5.4.3.

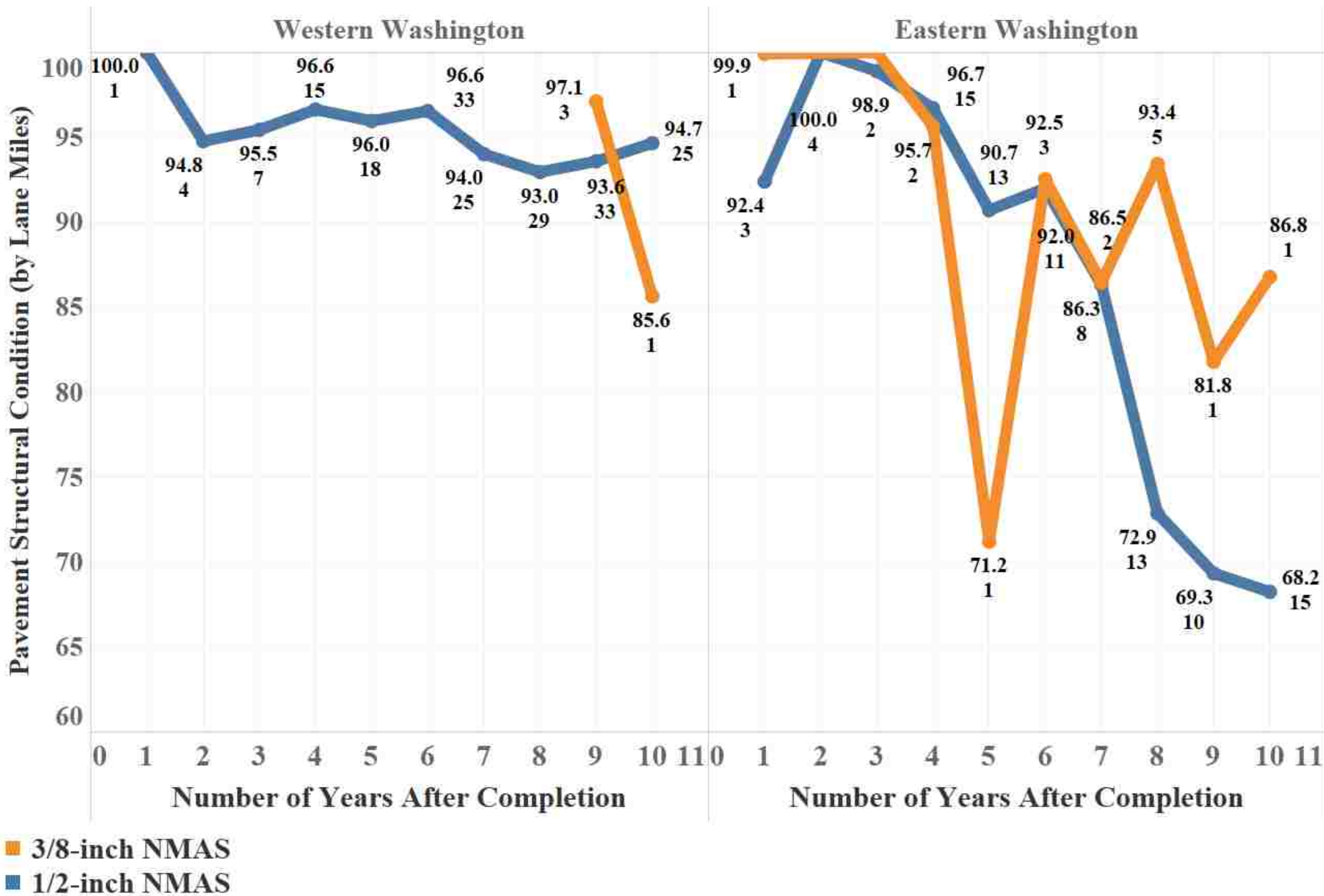


Figure 23. Average Weighted Pavement Structural Condition by Tons of Mix and Location for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PSC (Top), Number of Contracts (Bottom)]

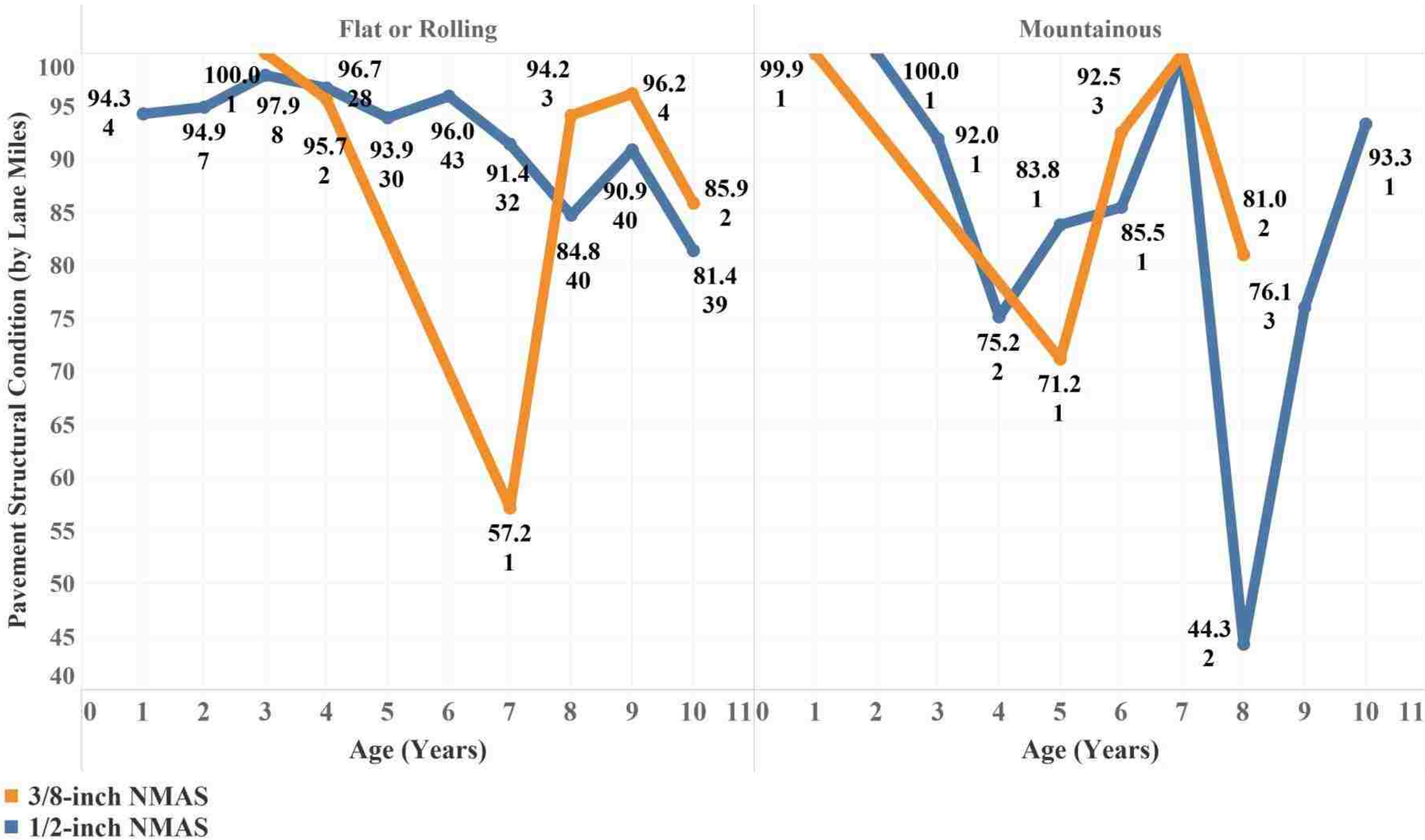


Figure 24. Average Weighted Pavement Structural Condition by Tons of Mix, Terrain, and Number of Contracts for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PSC (Top), Number of Contracts (Bottom)]

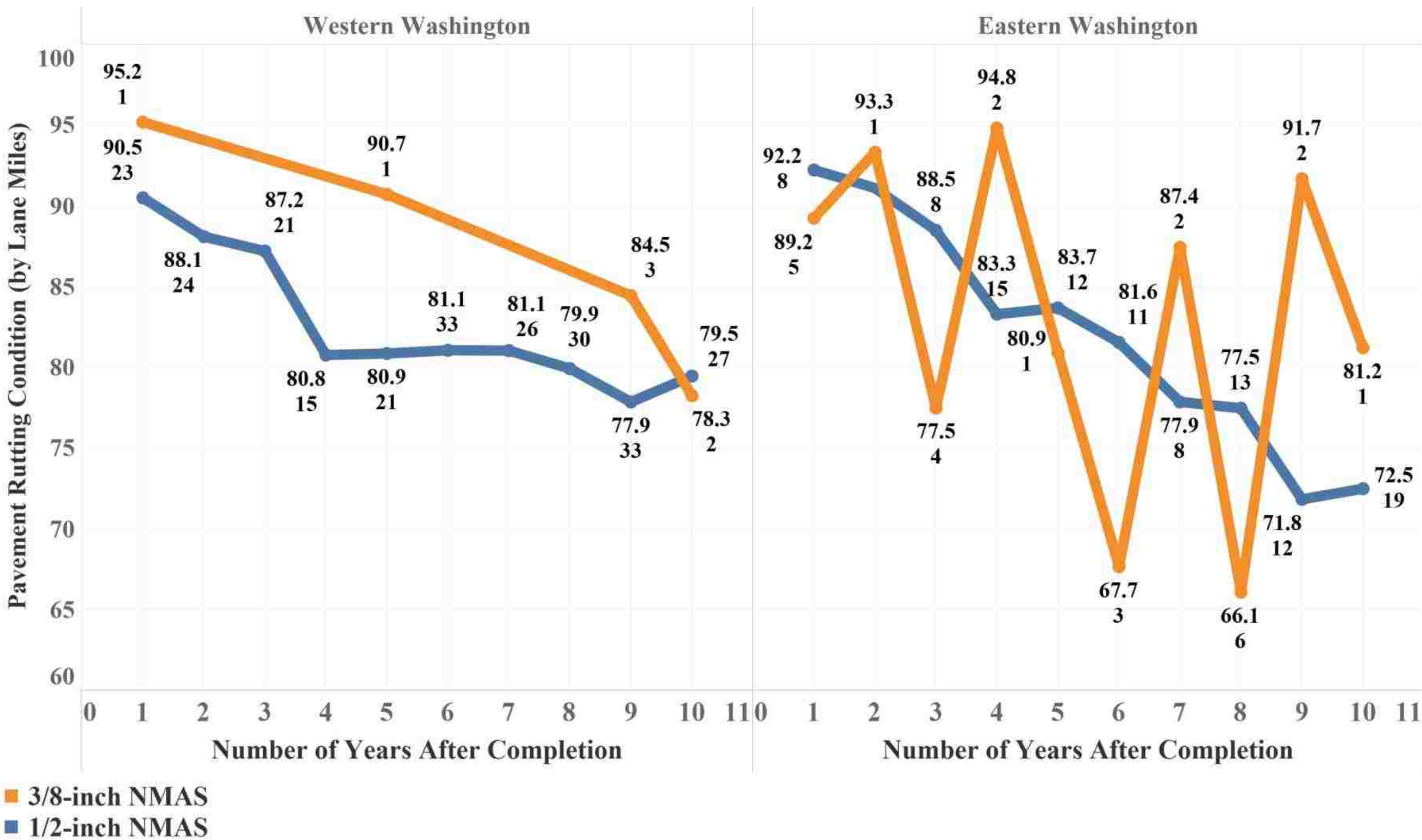


Figure 25. Average Weighted Pavement Rutting Condition by Tons of Mix, Location, and Number of Contracts for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PRC (Top), Number of Contracts (Bottom)]

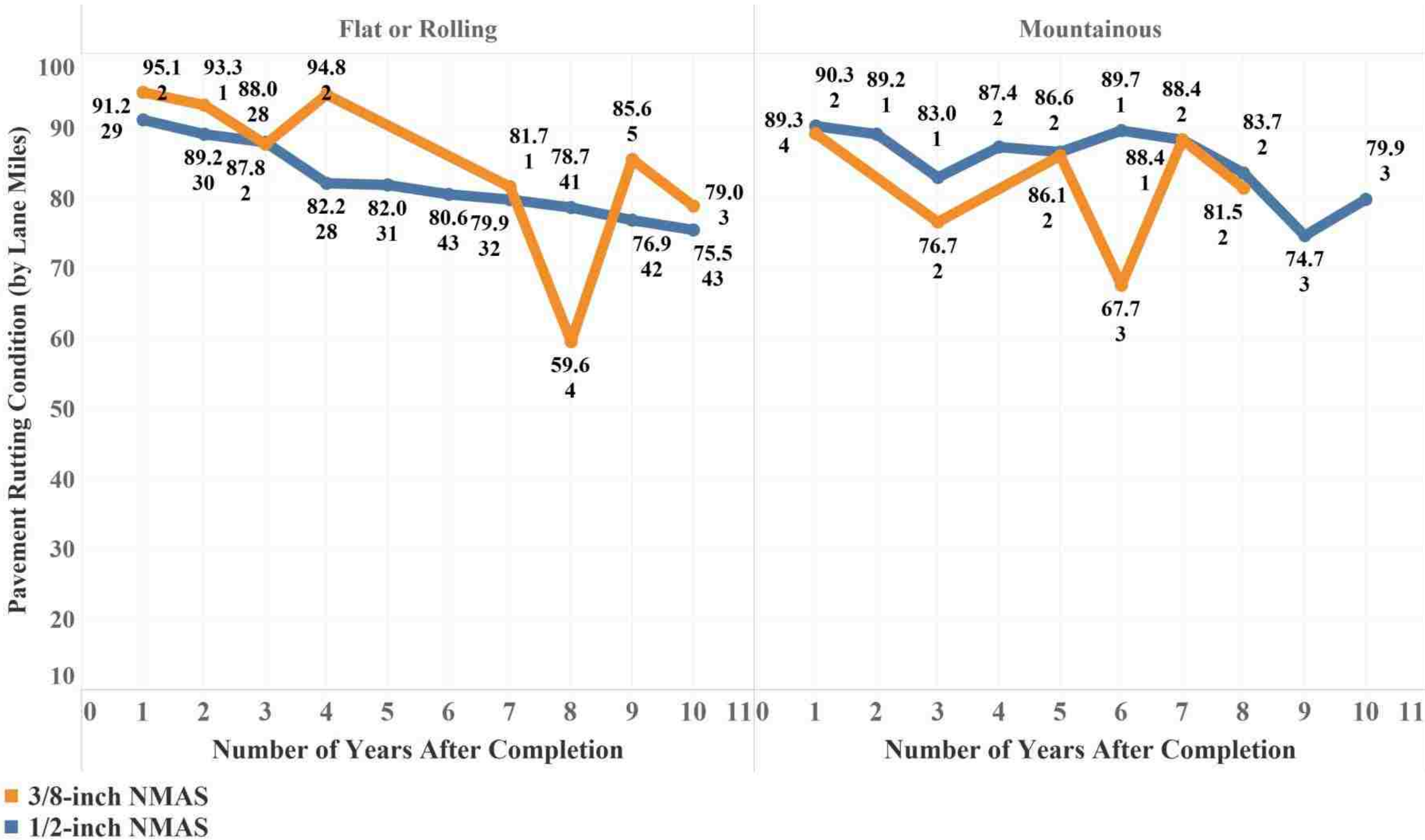


Figure 26. Average Weighted Pavement Rutting Condition by Tons of Mix, Terrain, and Number of Contracts for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PRC (Top), Number of Contracts (Bottom)]

Chapter 4. Performance of Asphalt Pavement Mixtures with Elevated In-Place Density and Other Mixture Characteristics in Washington State

4.1 Preface

The in-service pavement data approach introduced in Chapter 1 describes using cost, mix design, construction, and performance data to inform pavement specifications and policy. This chapter uses the approach with preselected analysis parameters to analyze the linkage of elevated field density and field performance of Washington State Department of Transportation (WSDOT) pavements. Field performance of pavements with elevated density is of particular interest to WSDOT since its lower specification limit will be 92% of theoretical maximum density in 2020. Findings from the research indicate that pavements with elevated field density exhibit longer service life and decreased permeability (Aschenbrener et al. 2017; Tran et al. 2016; Linden et al. 1989).

This study is from a manuscript intended to be submitted for publication in the American Society of Civil Engineers (ASCE) Journal of Materials, Journal of Transportation Engineering, Part B: Pavements, or some other appropriate journal.

4.2 Abstract

This paper investigates the relationship between in-place field density and key mix design, quality assurance, and pavement condition data for Washington State Department of Transportation (WSDOT) pavements from 2007 through 2017. Current national and WSDOT efforts to raise in-place density are intended to improve pavement life based on laboratory and theoretical relationships that show higher density is likely to result in longer pavement life.

At WSDOT's historical 91% theoretical maximum density (TMD), the overall average weighted density for all WSDOT mixtures is about 93% of TMD and the data do not show any clear trends between density and asphalt content/performance. However, fine-graded mixtures may be trending higher than coarse-graded mixtures in terms of cracking performance particularly for the older mixtures. Also, of the contracts with an average weighted density of 94% or higher, none are poorly performing (≤ 50 cracking/rutting condition value). Additionally, the financial incentive to change current practice from a 91% of TMD to a 92% of TMD appears to cost about $26 thousand per contract.

Author keywords: Asphalt; Pavement; Density; Performance; Mix Design; Construction; Pavement Management System; Quality Assurance.

4.3 Introduction

The Washington State Department of Transportation (WSDOT) uses hot mix asphalt (HMA) density data as a primary indicator for pavement performance and WSDOT uses the data to determine contract financial incentives (i.e. pay factors and bonuses). Previous studies indicate that an increase in density can increase pavement performance at certain thresholds (e.g., Aschenbrener et al. 2017; Tran et al. 2016; Linden et al. 1989). However, Willoughby and Mahoney (2007) found that a density "link between design, construction, and pavement performance" has not yet been identified to validate density and performance literature findings in WSDOT's data architecture as currently constructed. By 2020, WSDOT's density specification will change its lower specification limit (LSL) to 92% of theoretical maximum density (TMD) in hopes of extending Washington State's HMA service life.

4.3.1 *Research scope and objectives*

This section presents the research scope and objectives, followed by a discussion of what the literature says on density and then a description of the relevant WSDOT standards. This paper tests the hypothesis that elevated in-place density improves pavement service life by using 10+ years of data on WSDOT's in-service pavements. This paper compares WSDOT field density data using mix design, field quality assurance (QA), and pavement management system (PMS) data. To supplement this field data, this paper gathers industry perspectives from the WSDOT staff and Washington Asphalt Pavement Association (WAPA) members through the use of a survey and interviews. The paper addresses the following three questions:

1) What is the financial incentive for contractors to change practices in response to WSDOT's raising of the lower specification limit from 91% of theoretical maximum density (TMD) to 92% of TMD?
2) How does measured field density and field performance data compare with published literature on field performance related to density?
3) Are there any related mix design parameters (e.g. fine-graded versus coarse-graded) that show an identifiable relationship to field performance?

The hypothesis is that there will be significant financial incentive for contractors to change current construction practices to meet the 92% density lower specification limit. Additionally, mixtures with higher density exhibit reduced cracking and rutting, and fine-graded mixtures exhibit reduced cracking and similar rutting. To test the hypotheses, this study analyzes the following mix design, QA, and performance components of mixtures with density data placed on the WSDOT road network from 2007 to 2017:

- In-place density of WSDOT mixtures with pavement age;
- Pay factor and price adjustment comparison of WSDOT mixtures at a 91% and 92% density lower specification limit;
- Asphalt content of WSDOT mixtures with pavement age;
- Cracking and rutting versus density of WSDOT mixtures with pavement age.

4.3.1.1 **Potential use of large linked field and performance**

The WSDOT pavement data sets used in the study are: (1) Statistical Analysis of Materials (SAM) and (2) Washington State PMS (WSPMS) for contracts completed between 2007 and 2017. A description of each data set is included in later sections. While processing, integration, and analysis of these in-service pavement data sets are done manually for this paper (~1,500 person-hours), recent advances in data storage capabilities can automate such efforts. This work demonstrates how a large amount of field and performance pavement data over a 10+ period can be used and provides insight into the data's abilities, limitations, and value. Further, these linked data sets can be used to better understand the relationship between actual in-service performance and mix design/construction variables. Since this type of data is subject to numerous unmeasured variables, interpretation and feedback from WSDOT and industry are used to provide further insight into observed trends.

4.3.2 ***Summary of reported benefits of increased density and other mixture characteristics from the literature***

The Federal Highway Administration (FHWA) recently launched an increased in-place density initiative to improve the durability of HMA pavements nationwide (Aschenbrener et al. 2017). As part of this effort, Aschenbrener et al. (2017) and Tran et al. (2016) have published excellent literature on influencing factors that impact density. What follows is a summary of several of the major mix design and field influencers on performance identified in these publications.

4.3.2.1 **Performance**

With all other factors held constant, increased in-place field density results in higher performance. Tran et al. (2016) contend that a 1% density increase can extend the asphalt pavement service life by about 10 to 30% for state highway agencies with a density threshold less than 92% of TMD. In the earliest known source of a specific relationship between density and pavement life, Linden et al. (1989) indicate that “a 1% increase in air voids over the base air-void level of 7% [93% of TMD] tends to produce about a 10% loss in pavement life.” Similarly, findings from a 2015 New Jersey DOT report show that HMA pavements experience “an approximate 10% increase in asphalt mixture service life for a 1% decrease in in-place air voids” (Tran et al. 2016).

4.3.2.2 **Asphalt content**

Given a successfully tested mix design, an increased asphalt content may increase field density and increase pavement performance. Aschenbrener et al. (2017) found that 4 of 10 state highway agencies increased in-place density by slightly increasing the optimum asphalt content. It is important to note that these SHAs also altered the HMA mix design to account for the increased asphalt content through various actions such as lowering the number of gyrations, lowering the design air voids, and increasing the voids in mineral aggregate (VMA) (Aschenbrener et al. 2017).

4.3.2.3 **Coarse versus fine gradation**

For 3/8-inch NMAS mixtures, coarse-graded mixtures contain less than 45% passing the number eight sieve and fine-graded mixtures contain greater than 45% passing the number eight sieve (NAPA and FHWA 2001). For 1/2-inch NMAS mixtures, coarse-graded mixtures contain less than 40% passing the number eight sieve and fine-graded mixtures contain greater than 40% passing the number eight sieve (NAPA and FHWA 2001). When compacted to the same final density, fine-graded mixtures tend to be “easier to compact” (more compaction for the same compactive effort), exhibit increased resistance to permeability, and exhibit similar rutting performance in comparison to coarse-graded mixtures (Aschenbrener et al. 2017).

4.3.2.4 **Lift thickness and nominal maximum aggregate size (NMAS)**

Aschenbrener et al. (2017) state that a greater lift thickness increases the ability to compact the HMA pavement to the desired field density. Further, to achieve the required field density, the HMA mixture recommendations include a minimum lift thickness to NMAS ratio (t/NMAS) of three or higher with fine-graded mixtures and four or higher with coarse-graded mixtures (Aschenbrener et al. 2017).

4.3.2.5 **Permeability**

Mixtures constructed at increased density typically results in lower permeability contributing to pavements with increased performance (Aschenbrener et al. 2017). Aschenbrener et al. (2017) state that a field density of 93% to 94% or higher reduces the impacts of permeability on pavement performance. Additionally, coarse-graded mixtures with a field density of about 94% or less increases the pavement's vulnerability to permeability (Aschenbrener et al. 2017).

4.3.3 ***Relevant WSDOT specifications***

4.3.3.1 **NMAS and lift thickness specifications**

The WSDOT specifications establish a minimum surface lift thickness for each NMAS to ensure sufficient compaction (WSDOT 2018d). The minimum thickness for 3/8-inch NMAS is 1.2 inches, yielding a t/NMAS of 3.2 and 1.8 inches for 1/2-inch NMAS yielding a t/NMAS of 3.6 (WSDOT 2018c). Despite the allowable minimum surface lift thickness, WSDOT generally paves at the same surface thickness (1.8 inches) for both NMASs. Consequently, the 1/2-inch NMAS coarse-graded mixture, WSDOT's most used mix (Table 5), yields a t/NMAS that is slightly below the recommended t/NMAS of four.

4.3.3.2 **Asphalt content and density specifications**

From 2007 to 2017, WSDOT's specifications required an asphalt content tolerance of ± 0.5% from the approved Job Mix Formula (JMF) and required a lower specification limit of 91% of TMD as measured by the core calibrated nuclear gauge (WSDOT 2018d).

4.3.3.3 **Pay process**

WSDOT uses a statistical evaluation for most of the asphalt mixture it places. For compaction, each lot receives a corresponding pay factor and compaction price adjustment based on density test results. Price adjustments range from a 5% bonus to a 25% penalty or even complete lot rejection without pay (WSDOT 2018d). Consequently, these pay factors significantly influence owner/contractor decision and behavior. In particular, because of how the pay factor calculation is made, Muench and Mahoney (2001) found that the average pay factor for WSDOT HMA construction is about 1.02. Further, about half of the WAPA personnel interviewees stated that with the density specification at 91% of TMD, their target density was about 93% to receive a bonus.

Table 5. Number of Contracts by Location, Lane Miles, and Tons of Mix With Density Values by Data Source [density, asphalt content, PSC (Pavement Structural Condition), and PRC (Pavement Rutting Condition)] for WSDOT Asphalt Pavement Mixtures Completed Between 2007 and 2017

Parameter	Density	Asphalt Content	PSC	PRC
Total Contracts	543	504	261	338
Average Contracts Per Year	49	46	26	34
Fine-Graded Contracts	50	50	16	27
Coarse-Graded Contracts	453	453	230	298
3/8-inch NMAS Contracts	27	27	4	11
1/2-inch NMAS Contracts	516	477	257	327
Eastern Washington Location Contracts	N/A	N/A	87	106
Western Washington Location Contracts	N/A	N/A	174	232
Total Lane Miles	N/A	N/A	2,891	3,997
Average Lane Miles Per Year	N/A	N/A	289	400
Total Tons of Mix	8.3M	11.4M	N/A	N/A
Average Tons of Mix Per Year	757K	1.0M	N/A	N/A

#N/A: data not available or not used in the analysis

4.4 Method

4.4.1 *Data collection and processing*

This study collects and processes data from the following WSDOT data sources: (1) SAM and (2) WSPMS for contracts with field density data (some contracts do not have density data in SAM) completed between 2007 and 2017. The SAM QA data (density, pay factor/price adjustment, asphalt content) and the WSPMS data (performance) allows the analysis to compare the published literature on mix design and other mixture characteristics with WSDOT's actual mix design and field data. Once collected, the analysis processes the data from each source by linking the data using contract number and sometimes mix design and lot number. The analyses only use 1/2-inch and 3/8-inch mixtures, excluding a small subset of other mixtures (e.g. no NMAS). Each analysis excludes most bridge deck and all chip seal contracts; however, seven of the bridge deck contracts with field density and large tonnage data were retained. The data subsections describe the calculations for each component. All of the statistical tests (i.e. t-tests, linear regression, etc.) are parametric and assume that the distribution of the populations are normal. Table 5 provides a summary of the number of contracts, lane miles, and tons of mix by data source from 2007 to 2017.

The general calculation approach for density, pay factor/price adjustment, asphalt content, and pavement condition in this paper uses tons of mix per contract or lane miles per contract to weight each contract's data. This method reduces unwanted bias towards contracts with a small/large tonnage size or contracts with a small/large number of lane miles measured. Also, by aggregating the data by contract, this approach tracks the data by location.

4.4.1.1 **Density**

WSDOT uses an in-house system, SAM, to store QA data which includes contract statistical evaluation, pay factor, and some mix design data for each HMA parameter. This paper uses field density data extracted from SAM data for HMA contracts completed between 2007 and 2017 to compare with published literature on density. The density analysis integrates the data using contract and mix design numbers, removing contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). The analysis uses number of years after completion (Eq.(16)), total contract sample size (Eq.(17)), and average weighted density (Eq.(18)). Additionally, a statistical t-test for two independent samples is performed on the average weighted density. The density analysis also tracks all contracts that do not meet WSDOT specifications.

$$\text{Number of Years After Completion (i.e. Contract Age)} = 2017 - Y_i \tag{16}$$

$$\text{Total Contract Sample Size (tons)} = \sum_{i=1}^{N}\sum_{j=1}^{M_i} s_{i,j} \tag{17}$$

$$\rho_i = \frac{1}{S_i}\sum_{j=1}^{M_i} (d_{i,j}) * \left(s_{i,j}\right) \tag{18}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

M_i = total distinct number of mix designs included in contract i,

N = total number of contracts,

Y_i = completion year of contract i,

ρ_i = average weighted density of contract i,

$d_{i,j}$ = field density of mix design j of contract i,

$s_{i,j}$ = sample size of mix design j of contract i, and

S_i = sample size of contract i, summed across all M_i contracts.

4.4.1.2 **Pay factor and price adjustment**

This QA analysis uses WSDOT's SAM database to investigate density pay factor and price adjustment (i.e. bonus) data for HMA contracts completed between 2007 and 2017. This paper uses SAM to compare density pay factor and price adjustment data with the 91% density LSL versus WSDOT's new 92% density LSL. The pay factor analysis integrates the data using contract, lot, and sublot numbers, removing contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). For the 91% density specification, the pay factor and bonus data for all contracts and lots is given. For the 92% density specification, the analysis uses updated pay factor (Eq.(19)) and compaction price adjustment (i.e. bonus) (Eq.(20)).

$$\left(Q_L\right)_i = \frac{(X_m)_i - LSL}{S_i} \tag{19}$$

$$(CPA)_i = [0.40 * (CPF_i - 1.00)] * Q_i * UP_i \tag{20}$$

where,

$(Q_L)_i$ = Lower Quality Index for lot i (from WSDOT's quality level table),

$(X_m)_i$ = Arithmetic compaction mean for lot i,

LSL = Lower Specification Limit (92% density),

S_i = Standard Deviation for lot i,

$(CPA)_i$ = Compaction Price Adjustment (i.e. bonus) for lot i,

CPF_i = Composite Pay Factor for lot i (from WSDOT's pay factor table),

Q_i = Quantity in lot i, and

UP_i = Unit Price of HMA in lot i (from WSDOT's Unit Bid Analysis/SAM).

4.4.1.3 **Asphalt content**

For contracts with only density data (some contracts do not have density data in SAM) completed between 2007 and 2017, this paper uses WSDOT's SAM database to investigate field measured asphalt content, comparing the results with published literature on density and asphalt content. The analysis integrates the data using contract and mix design numbers for contracts, removing contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS).

The analysis uses contract age (Eq.(16)), total contract sample size (tons) (Eq.(17)), average weighted asphalt content per contract (Eq.(21)), average weighted JMF (Eq.(22)), and average JMF difference (Eq.(23)). Additionally, a statistical t-test for two independent samples is performed on the average weighted asphalt content. The statistical analysis also performs a linear regression on the average weighted density and the average weighted asphalt content. The JMF difference is used to determine contracts not within WSDOT asphalt specifications.

$$(AWAC)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (AC)_{i,j} \tag{21}$$

$$(AWJMF)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (JMF)_{i,j} \tag{22}$$

$$(\Delta JMF)_i = (AWAC)_i - (JMF)_i \tag{23}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWAC_i$	= average weighted asphalt content of contract i,
$s_{i,j}$	= sample size of mix design j of contract i,
S_i	= sample size of contract i, summed across all M_i contracts,
$AC_{i,j}$	= asphalt content of mix design j in contract i,
$JMF_{i,j}$	= Job Mix Formula (JMF) of mix design j in contract i,
$(AWJMF)_i$	= average weighted JMF of contract i, and
$(\Delta JMF)_i$	= Job Mix Formula (JMF) difference for contract i.

4.4.1.4 **Contracts not within specifications**

About 99% of the asphalt content and density averages conformed to WSDOT specifications demonstrating that the pavements are mostly within specifications.

- **Density.** Five of the 543 (0.9%) contract averages were below the WSDOT 91% minimum density lower specification limit. All of these contracts were small, 2,541 tons (0.03% of total tonnage), exhibiting little influence overall. Additionally, the contracts out of specification did not correspond to any noticeable decrease in pavement performance;
- **Asphalt Content.** Four of the 504 (0.8%) contract averages were within the WSDOT asphalt content ±0.5% tolerance. All of these contracts were small, 4,592 tons (0.04% of total

tonnage), exhibiting little influence overall. The contracts with out of specification asphalt content averages did not correspond to any noticeable decrease in pavement performance.

4.4.1.5 **Pavement condition**

The WSDOT WSPMS database uses three indices to describe pavement condition which includes structural, rutting, and roughness condition data. For contracts with only density data completed between 2007 and 2017 (some contracts do not have density data in SAM), this analysis focuses on structural and rutting condition index values, not roughness index values since roughness is typically a lagging indicator of cracking (Li et al. 2004). The index values of structural and rutting condition values do not account for raveling. Uhlmeyer et al. (2016) and Wen et al. (2016) describe these indices (see below) and the index scale ranges from 0 (very poor) to 100 (very good). An index value of 45 to 50 triggers a pavement rehabilitation requirement (Uhlmeyer et al. 2016).

- **Pavement Structural Condition (PSC).** PSC is a cracking index that accounts for longitudinal, transverse, and alligator cracking as well as patching (Uhlmeyer et al. 2016; Kay et al. 1993). Generally, "top-down cracking is a common distress mode" for HMA pavements in Washington State particularly for pavements thicker than about 6.3 inches (Uhlmeyer et al. 2000). Of the 261 contracts with cracking data, the average total pavement thickness is about 9.6 inches and about 89% have a total pavement thickness greater than about 6.3 inches. The rehabilitation trigger index value of 50 represents about "10% equivalency cracking (EC) in the wheelpaths" (Wen et al. 2016; Uhlmeyer et al. 2016; Kay et al. 1993). "Equivalency cracking" represents the amount of "alligator, longitudinal, transverse cracking and patching", see Eq. (24) (Kay et al. 1993). WSPMS does not include a PSC index for HMA that is three years old or less from 2011 to the present (Uhlmeyer et al. 2016). Because of this, the number of contracts with a PSC value is less than the number of PRC contracts (Table 5).

$$PSC = 100 - 15.8 * (\text{Equivalency Cracking})^{0.5} \tag{24}$$

- **Pavement Rutting Condition (PRC).** PRC is a rutting index (Uhlmeyer et al. 2016; Wen et al. 2016). Rutting index ratings of 75, 50, and 25 translate to a rutting depth of about 0.20 inches, 0.35 inches, and at least 0.55 inches, respectively (Pierce et al. 2001).

The WSPMS condition analysis uses a data extraction for contracts completed between 2007 and 2016 which only includes surface data (Table 5). The analysis uses the condition results to compare with published literature on density and performance. The condition analysis excludes 2017 data (pavement age of zero) and removes contracts using other mixtures (3/4-inch NMAS, open-graded friction course, cold in-place recycling, hot in-place recycling, and class A). The cracking and rutting performance analyses use contract number, completion year, NMAS, WSDOT region, contract age (Eq.(16)), lane miles (Eq.(25)), average weighted condition value (Eq.(26)).

$$L_i = \sum_{k=1}^{Q_i} \lambda_{i,k} \tag{25}$$

$$(CV)_i = \frac{1}{L_i} \sum_{k=1}^{Q_i} \left(\lambda_{i,k}\right) * (SCR)_{i,k} \tag{26}$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(CV)_i$ = average weighted condition value of contract i, and

$(SCR)_{i,k}$ = section condition rating of segment j in contract i.

A paired t-test is performed for fine-graded and coarse-graded as well as 3/8-inch and 1/2-inch NMAS mixture condition results to determine if the difference between the average PSC and PRC condition values per year from 2007 to 2016 is statistically significant. In the paired t-test, one expects the means to be very close in the early years as both pavements are performing well. As the pavements age, they might begin to separate. As a result, the paired t-test is not a very strong indicator of anything if the null is not rejected. A paired t-test measures the difference between paired sets of numbers and has no way of accounting for the growth in difference over time. Additionally, a linear regression is performed to determine the R^2 coefficient of gradation/NMAS, average weighted condition, and contract age.

Contract region was extracted manually from the online WSPMS since they were not included in the WSPMS extraction. The WSDOT regions determined the location of the contract (Eastern and Western Washington). Eastern Washington includes the Eastern, North Central, and South Central regions while Western Washington includes the Northwest, Olympic, and

Southwest regions (Wen et al. 2016). Figure 27 shows the location of the WSPMS contract and average weighted density covering all six WSDOT regions. Table 5 identifies the number of contracts by condition and location.

4.4.2 *Survey and interviews*

This section describes how the paper uses a survey and interviews to provide additional interpretation and feedback of the data analyses in the preceding sections.

4.4.2.1 **WAPA survey**

A general survey given to 37 WAPA members from 14 companies (11 asphalt producers, 2 subsidiaries and 1 asphalt testing laboratory) in Washington State provides industry perspective. In partnership with WAPA and WSDOT, the survey asks local participants to offer interpretation, feedback, and common industry reasons in support of the pavement data results. The survey contains 24 questions on a variety of asphalt topics including one relevant density question (see below). The useful survey response rate, a measure of the total number of surveys taken, complete or not, included 18 of 37 individuals (49%).

1. For 2018, WSDOT will increase its minimum density standard from 91.0% to 91.5%. Do you anticipate doing anything differently (e.g., more rollers, more roller passes, slower production, alter mix design, etc.) to account for this change? In other words, we want to know what the impact of this change is on your company/organization.

4.4.2.2 **WAPA interviews**

Interviews with seven WAPA and nine WSDOT people, averaging about one hour per interview, were used to follow up on the survey. These semi-structured interviews capture specific information on a variety of asphalt topics and were meant to uncover, in a conversational manner, industry and owner sentiment not easily expressed in a short survey (e.g. opinions on mix design, construction practices, performance, etc.). The interviewers generated a set of questions for the WAPA members as well as the WSDOT staff and asked all of the interviewees the same questions to maintain consistency. Using a conversational approach, the interviewers asked additional questions depending on the knowledge of the interviewee.

About 5 to 10 minutes of each semi-structured interview questioned the interviewee about density. The interview topics included volumetrics, lift thickness, stockpiling, performance, permeability, cost, placement, 3/8-inch versus 1/2-inch NMAS, and RAP.

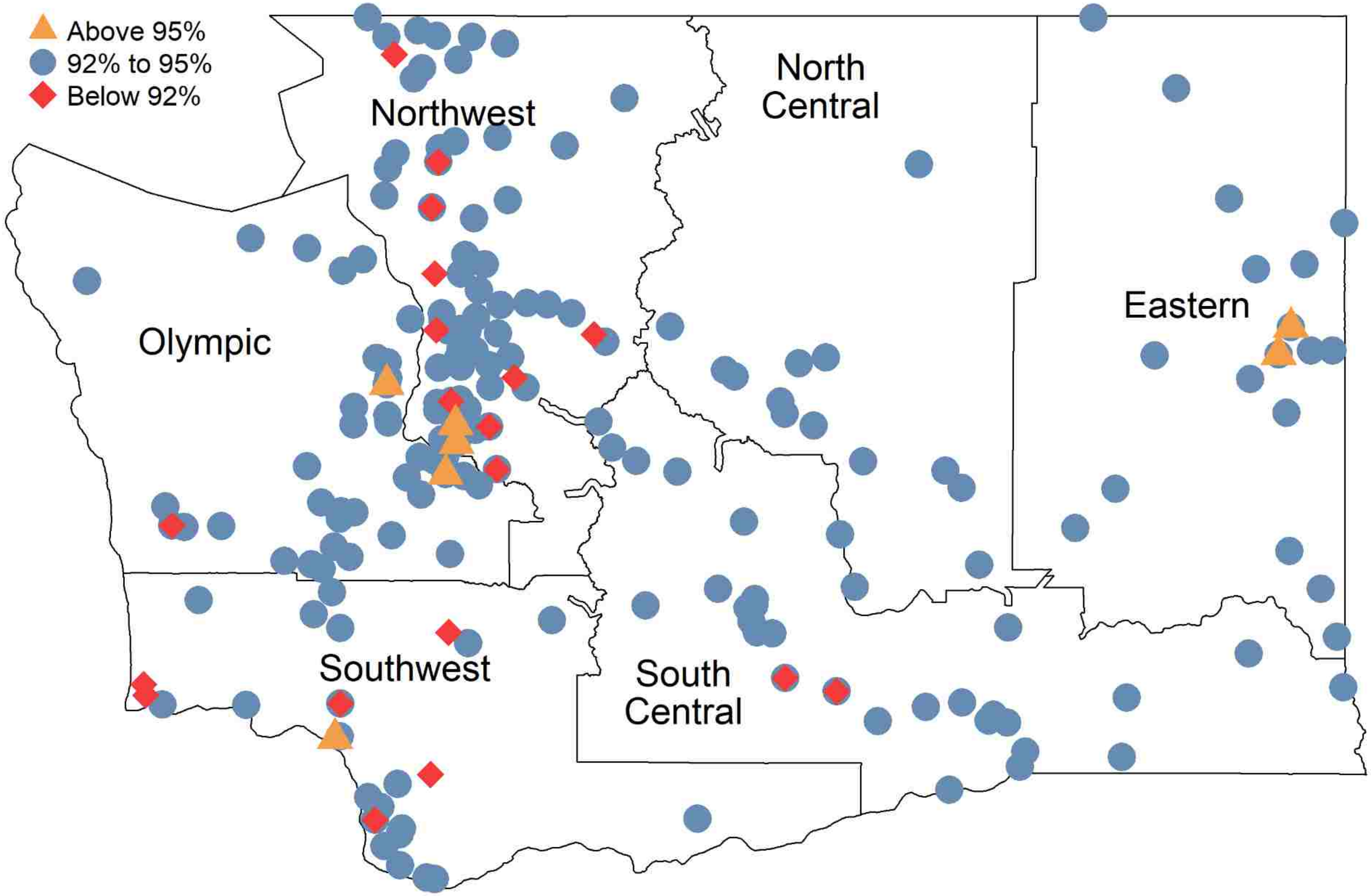


Figure 27. WSPMS Contracts With Density Values by WSDOT Region for Asphalt Pavement Mixtures Completed Between 2007 and 2016

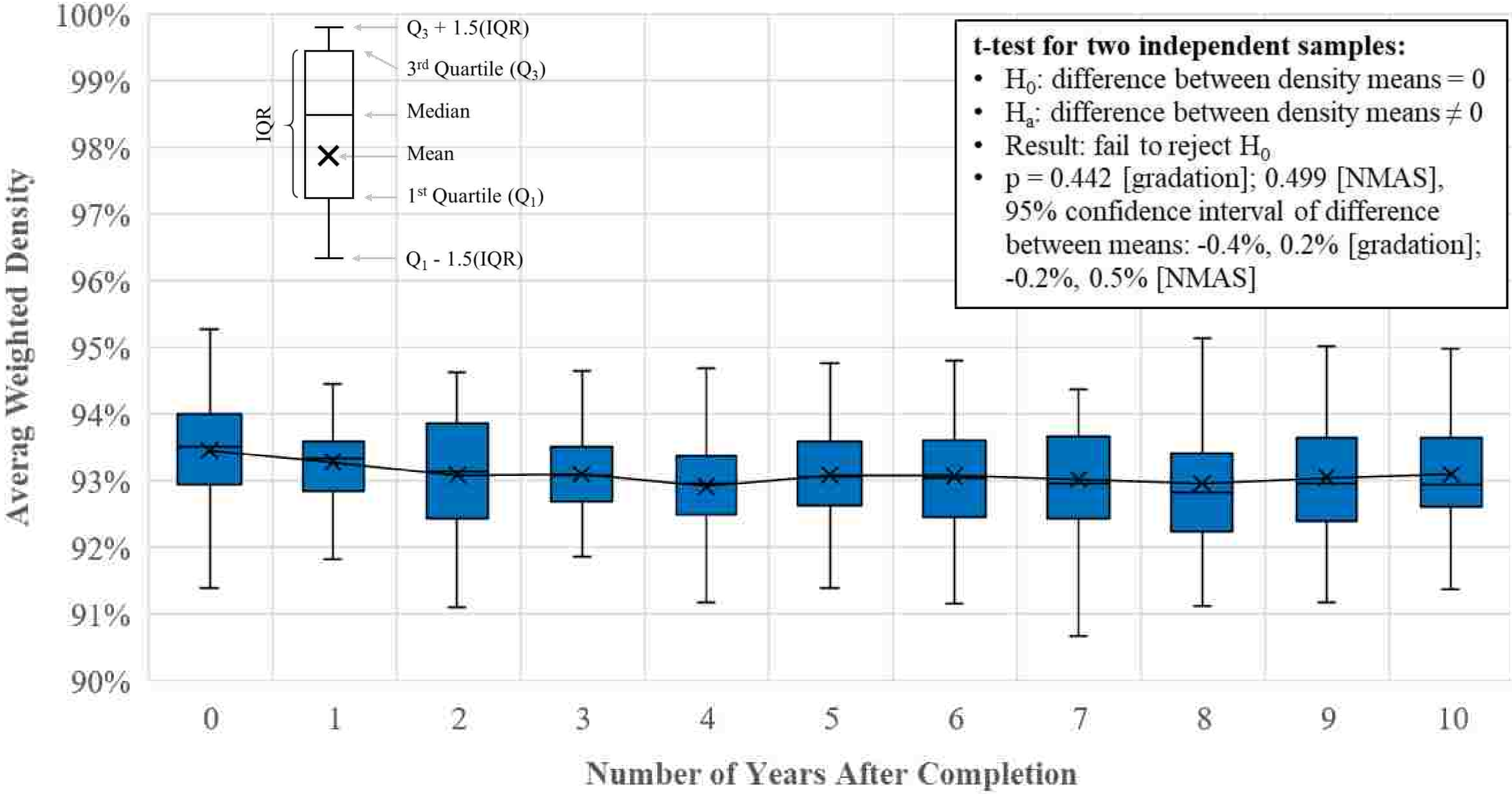
4.5 Results

4.5.1 *Density*

The overall average weighted density for all mixtures from 2007 and 2017is 93.18%. The overall average density of fine-graded mixtures is 93.07% and for coarse-graded mixtures is 93.18%, a difference of 0.11%. The overall average density of 3/8-inch NMAS mixtures is 93.11% and for 1/2-inch NMAS mixtures is 93.18%, a difference of 0.07%. The box and whisker plots (Figure 28) show the average weighted field density in comparison with contract age. Average weighted density for all fine-and coarse-graded as well as 3/8-inch and 1/2-inch NMAS contracts from 2007 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between density means). Density results fail to reject the null hypothesis at 95% confidence (p-value = 0.442 [gradation]; 0.499 [NMAS], 95% confidence interval of difference between the means is -0.4%, 0.2% [gradation]; -0.2%, 0.5% [NMAS]).

4.5.2 *Pay factor and price adjustment*

Using the 91% density LSL, the overall average weighted pay factor is 1.01 and the total price adjustment is about $6.2 million (in 2017 dollars). Conversely, if the new 92% LSL is applied to the same data the result is an overall average weighted pay factor of 0.92 and a total price adjustment of about -$8.1 million (in 2017 dollars), a difference of about 0.10 and $14.3 million (in 2017 dollars). On average, the 91% density LSL yields a price adjustment of about $11,400 per contract ($0.75 per ton) and the 92% density LSL yields a price adjustment of about -$14,800 per contract (-$0.98 per ton), a difference of about $26,200 ($1.72 per ton). Figure 29 shows the pay factor and price adjustment comparison by age.



Number of Contracts by Years After Completion										
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
55	53	46	52	41	49	53	47	60	50	37

Figure 28. Average Weighted Field Density and Number of Contracts by Years After Completion for WSDOT Asphalt Pavement Mixtures, 2007 to 2017

Figure 29. Pay Factor and Price Adjustment Comparison Between 91% Density Lower Specification Limit and 92% Density Lower Specification Limit for WSDOT Asphalt Pavement Mixtures, 2007 to 2017

4.5.3 *Asphalt content*

The overall average weighted asphalt content for all mixtures from 2007 and 2017 is 5.43%. The overall average weighted asphalt content of fine-graded mixtures is 5.42% and for coarse-graded mixtures is 5.43%, a difference of 0.01%. The overall average weighted asphalt content of 3/8-inch NMAS mixtures is 6.07% and for 1/2-inch NMAS mixtures is 5.39%, a difference of 0.68%. Average weighted asphalt content for all fine- and coarse-graded as well as 3/8-inch and 1/2-inch NMAS contracts from 2007 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between density means). Asphalt content results for fine-and coarse-graded contracts fail to reject the null hypothesis at 95% confidence (p-value = 0.341, 95% confidence interval of difference between the means is -0.05%, 0.16%). Asphalt content results for 3/8-inch and 1/2-inch NMAS contracts reject the null hypothesis at 95% confidence (p-value < 0.0001, 95% confidence interval of difference between the means is 0.5%, 0.8%).

The asphalt content data also show no apparent trend between average weighted density and average weighted asphalt content (Table 6). Further, linear regression results between average weighted density and asphalt content show an R^2 coefficient of 0.001.

Table 6. Average Weighted Field Density, Number of Contracts, Total Tons of Mix (Asphalt), and Average Weighted Asphalt Content

Density Interval (% of TMD)	Contract Count	Total Asphalt Tons of Mix	Average Weighted Asphalt Content
≤ 91%	3	1,483	5.51%
> 91%, ≤ 92%	32	238,392	5.64%
> 92%, ≤ 93%	193	4,576,745	5.41%
> 93%, ≤ 94%	206	5,536,456	5.39%
> 94%, ≤ 95%	59	878,687	5.41%
≥ 95%	10	104,573	5.69%

4.5.4 *Condition*

4.5.4.1 **Cracking**

Figure 30 shows the average weighted structural condition and average weighted density by age for fine-graded and coarse-graded mixtures. Cracking for all fine- and coarse-graded as well as 3/8-inch and 1/2-inch NMAS mixtures from 2007 to 2016 were compared using a paired t-test on average weighted cracking values by tons of mix for each age (H_0 = no difference between condition means). Results fail to reject the null hypothesis at 95% confidence (p-value = 0.108 [gradation]; 0.330 [NMAS], 95% confidence interval of difference between the means is -1.387, 11.181 [gradation]; -19.26, 10.441 [NMAS]). Cracking for all gradation and NMAS mixtures from 2007 to 2016 were compared using a linear regression and results revealed R^2 coefficient values of 0.11 (gradation) and 0.11 (NMAS). The data analysis does not reveal an apparent trend between density and cracking; however, the data show increased cracking with age as well as outliers with noticeably low cracking values.

Although the cracking analysis only includes 16 fine-graded mixtures, it is worth noting that none of these mixes result in a poorly performing mix (Figure 30). A poorly performing mix is a pavement with a condition value ≤ 50, the rehabilitation trigger. The lowest PSC value is 84.1 (age four) with an equivalency cracking of about 1.0% in the wheel path. Similarly, the cracking analysis only includes four 3/8-inch NMAS mixtures but none of these perform poorly. The lowest PSC value is 93.8 (age nine) with an equivalency cracking of about 0.2% in the wheel path. Cracking results for coarse-graded and 1/2-inch NMAS mixtures show 9 of 234 (3.8%) and 9 of 257 (3.5%) poorly performing mixtures, respectively.

Additionally, of the 33 contracts with an average weighted density of 94% or higher, none of the contracts are poorly performing (Figure 30). Only 1 of the 33 contracts (3.0%) exhibit a PSC less than 70 and 27 of 33 contracts (~82%) exhibit a PSC of 90 or higher.

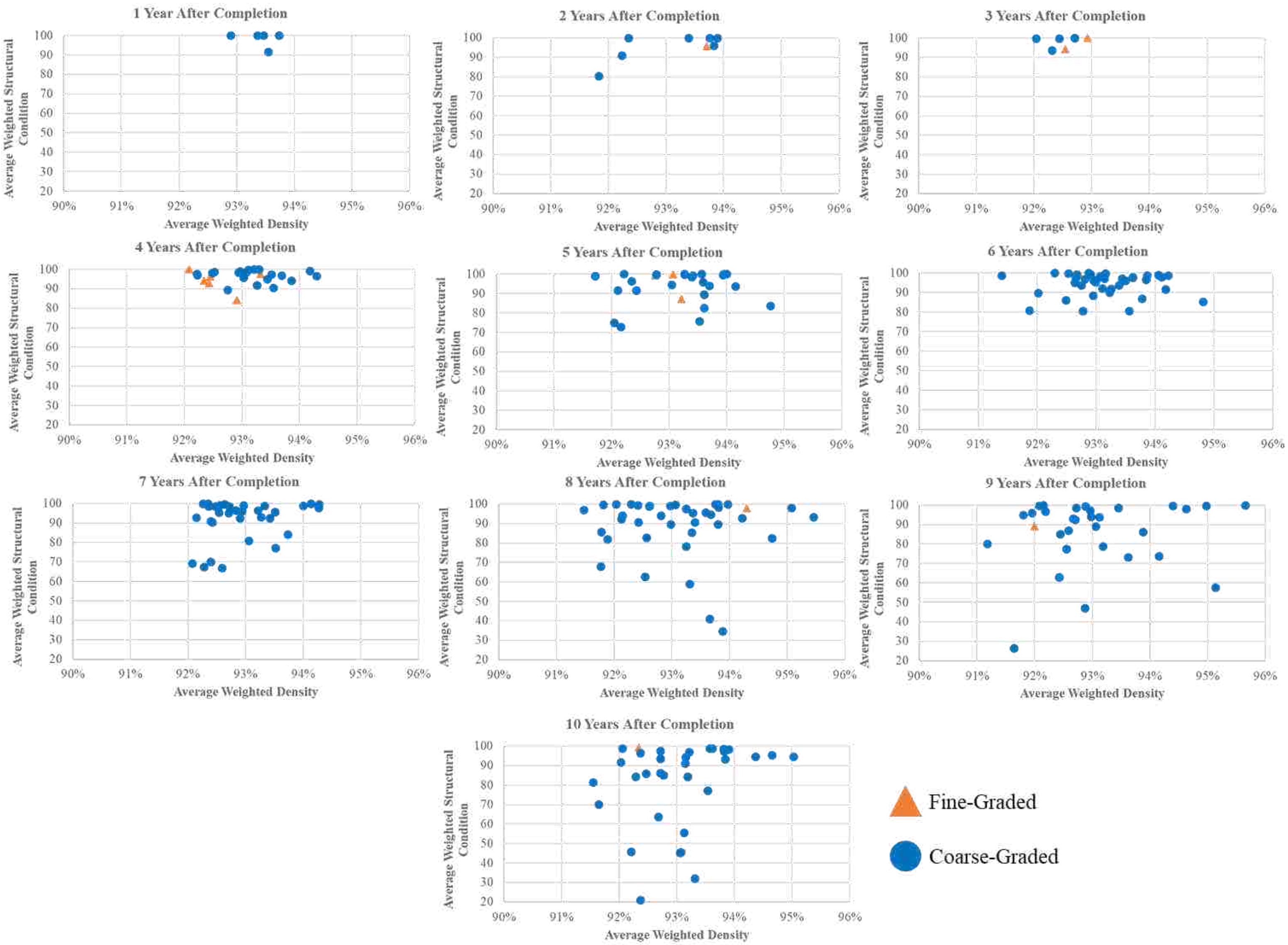


Figure 30. Average Weighted Pavement Structural Condition Versus Average Weighted Density by Number of Years After Contract Completion and Gradation for WSDOT Asphalt Pavement Mixtures, 2007 to 2016

4.5.4.2 **Rutting**

Figure 31 shows the average weighted rutting condition and average weighted density by age for fine-graded and coarse-graded mixtures. Rutting for all fine- and coarse-graded as well as 3/8-inch and 1/2-inch NMAS mixtures from 2007 to 2016 were compared using a paired t-test on average weighted rutting values by tons of mix for each age (H_0 = no difference between condition means). Results fail to reject the null hypothesis at 95% confidence (p-value = 0.350 [gradation]; 0.562 [NMAS], 95% confidence interval of difference between the means is -3.144, 7.759 [gradation]; -8.899, 14.137 [NMAS]). Rutting for all gradation and NMAS mixtures from 2007 to 2016 were compared using a linear regression and results revealed R^2 coefficients of 0.29 (gradation) and 0.31 (NMAS). The data analysis does not reveal an apparent trend between density and rutting; however, the data show increased rutting with age as well as outliers with noticeably low rutting values.

Although the rutting analysis only includes 27 fine-graded mixtures, it is worth noting that none of these mixes result in a poorly performing mix (≤ 50 condition value) (Figure 31). The lowest PRC value is 72.7 (age nine) which is a rutting depth of about 0.20 inches. Rutting results for 3/8-inch NMAS also show no poorly performing mixtures (out of 11). Rutting results for coarse-graded and 1/2-inch NMAS mixtures show 2 of 298 (0.7%) and 2 of 327 (0.6%) poorly performing mixtures, respectively.

Additionally, of the 47 contracts with an average weighted density of 94% or higher, none of the contracts are poorly performing (Figure 31). Only 1 of the 47 contracts (2.1%) exhibit a PRC less than 70 and 33 of 47 contracts (~70%) exhibit a PRC of 80 or higher.

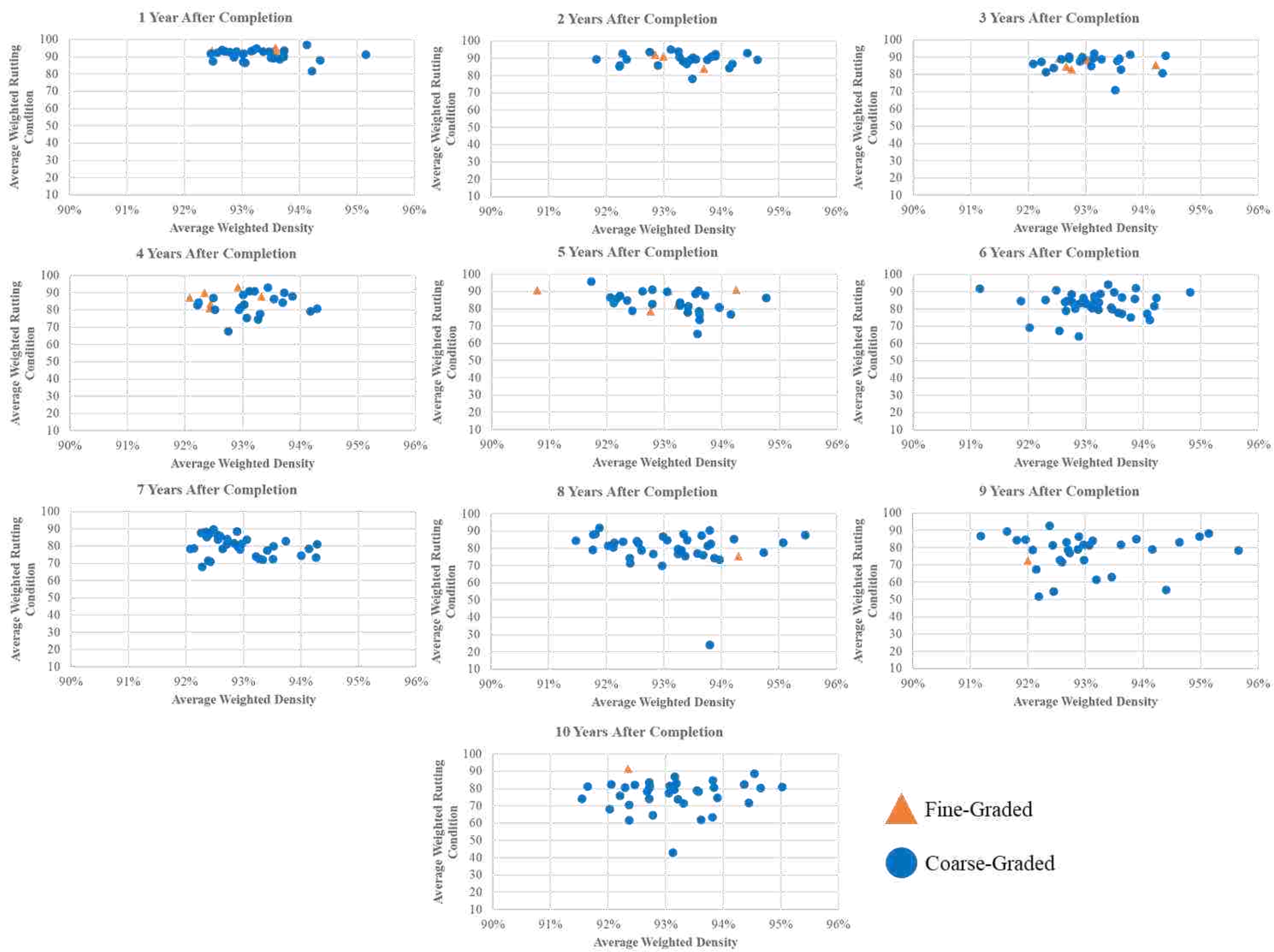


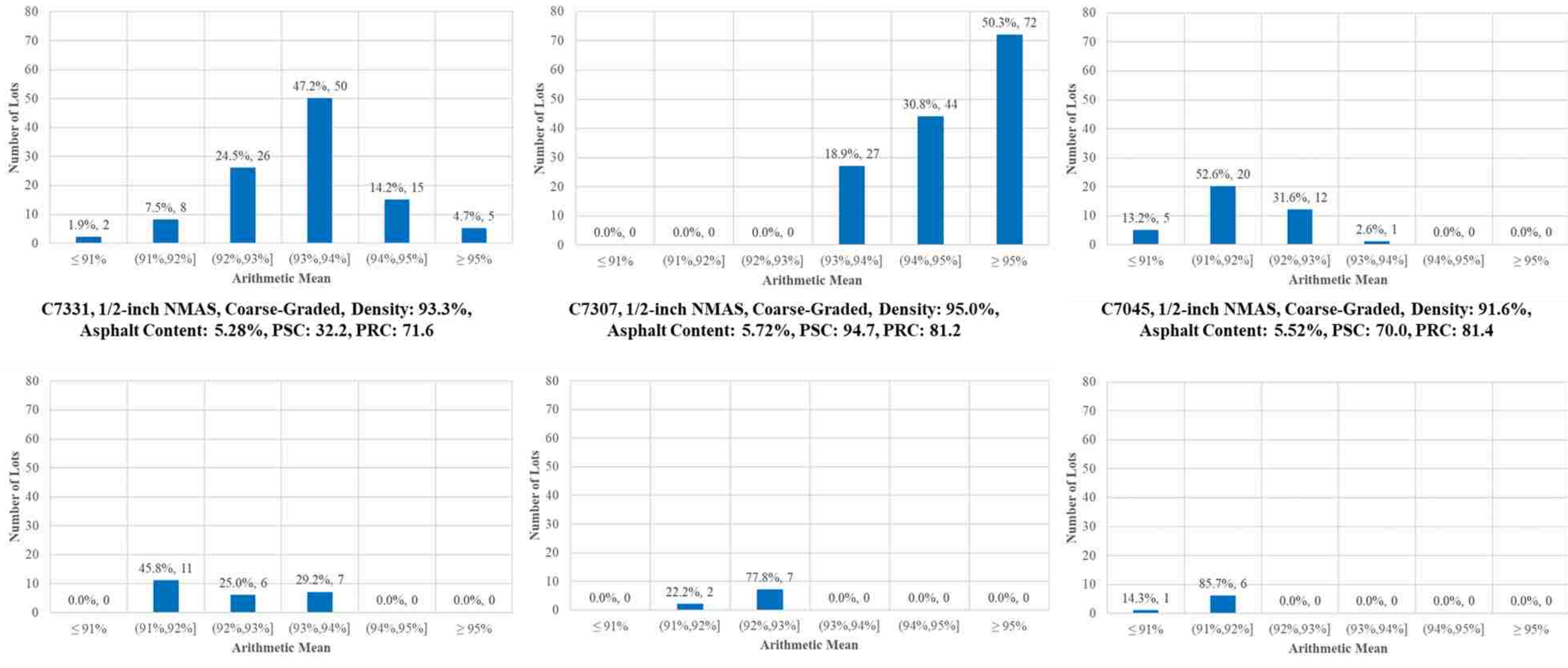
Figure 31. Average Weighted Pavement Rutting Condition Versus Average Weighted Density by Number of Years After Contract Completion and Gradation for WSDOT Asphalt Pavement Mixtures, 2007 to 2016

4.5.4.3 **Older contracts**

Because HMA pavements typically fail or show signs of distress with age, this section explores the data's two oldest years (ages 9-10) to identify any apparent trends between density and condition. Figure 32-Figure 33 show histograms (number of lots versus density mean) for two contracts with relatively poor condition (≤ 50) values [age 9 PSC: 26.5, 47.2; age 10 PSC: 32.2, 21.1], two contracts with relatively good condition (> 50) values [age 9 PSC: 89.1, 99.7; age 10 PSC: 94.7, 99.3], and two contracts with below 92% average density for the entire contract [age 9: 91.2%, 91.8%; age 10: 91.6%, 91.5%]. The contract data show no apparent trend between density and condition. The data also shows that a comparatively high number of lots with less than 92% density drives a low average weighted density per contract. The contracts with low condition have density within specifications but three of the four are less than 93% density. Conversely, the contracts with lower density exhibit condition values above 70.

4.5.4.4 **Location**

Cracking and rutting for all Western and Eastern Washington mixtures were compared using a paired t-test (H_0 = no difference between condition means). Cracking and rutting results fail to reject the null hypothesis at 95% confidence (p-value = 0.064 [cracking]; 0.383 [rutting], 95% confidence interval of difference between the means is -0.674, 18.870 [cracking]; -1.823, 4.251 [rutting]). Of note, cracking performance in Eastern Washington may be trending lower for older contracts, ages 7-10; however, rutting in Eastern Washington is about the same for older contracts. Cracking results for average weighted condition by tons of mix from ages 7-10 in Eastern Washington show conditions of 86.3, 74, 70.5, and 62.7 compared to conditions of 94, 92.6, 93.4, and 94.6 in Western Washington, respectively. Rutting results for average weighted condition by tons of mix from ages 7-10 in Eastern Washington show conditions of 77.9, 77.4, 71.5, and 72 compared to conditions of 81.1, 80.5, 77.8, and 79.5 in Western Washington, respectively.



C7331, 1/2-inch NMAS, Coarse-Graded, Density: 93.3%, Asphalt Content: 5.28%, PSC: 32.2, PRC: 71.6

C7307, 1/2-inch NMAS, Coarse-Graded, Density: 95.0%, Asphalt Content: 5.72%, PSC: 94.7, PRC: 81.2

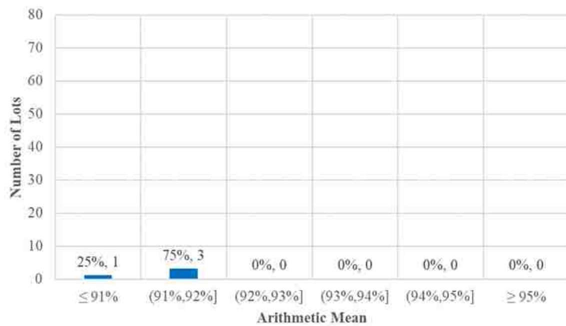
C7045, 1/2-inch NMAS, Coarse-Graded, Density: 91.6%, Asphalt Content: 5.52%, PSC: 70.0, PRC: 81.4

C7252, 1/2-inch NMAS, Coarse-Graded, Density: 92.4%, Asphalt Content: 5.47%, PSC: 21.1, PRC: 61.8

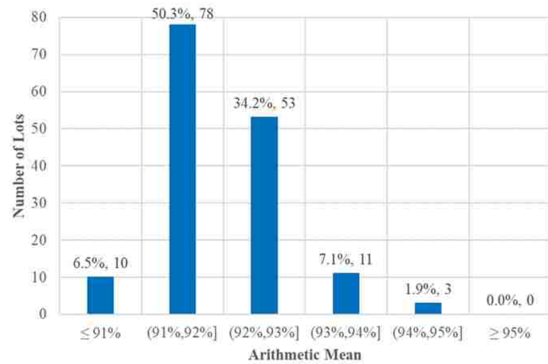
C7240, 1/2-inch NMAS, Fine-Graded, Density: 95.0%, Asphalt Content: 6.12%, PSC: 99.3, PRC: 91.4

C7320, 1/2-inch NMAS, Coarse-Graded, Density: 91.5%, Asphalt Content: 5.55%, PSC: 81.5, PRC: 74.3

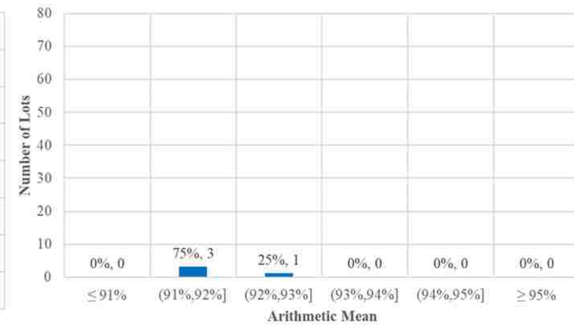
Figure 32. Number of Lots Versus Arithmetic Density Mean for Six WSDOT Asphalt Pavement Mixtures (Two Relatively Poor Condition [Left], Two Relatively Good Condition [Center], and Two Low Density [Right]) Completed in 2007



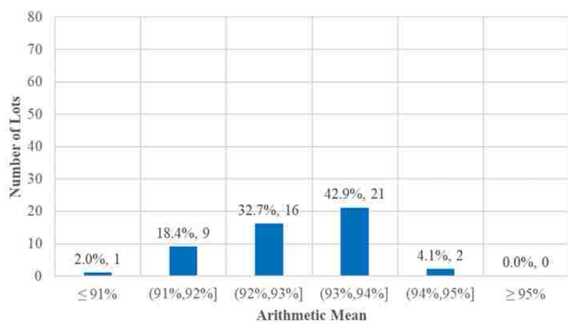
C7447, 1/2-inch NMAS, Coarse-Graded, Density: 91.6%, Asphalt Content: 6.1%, PSC: 26.5, PRC: 89.5



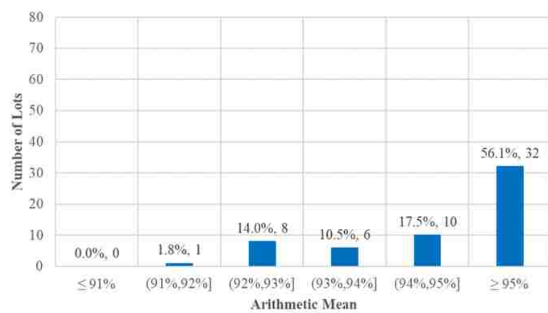
C7551, 1/2-inch NMAS, Fine-Graded, Density: 92.0%, Asphalt Content: 5.65%, PSC: 89.1, PRC: 72.7



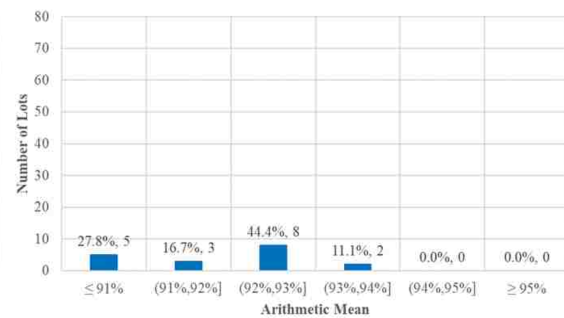
C7452, 1/2-inch NMAS, Coarse-Graded, Density: 91.2%, Asphalt Content: 4.55%, PSC: 80.2, PRC: 86.8



C7445, 1/2-inch NMAS, Coarse-Graded, Density: 92.4%, Asphalt Content: 5.07%, PSC: 47.2, PRC: 79.1



C7457, 1/2-inch NMAS, Coarse-Graded, Density: 95.0%, Asphalt Content: 5.76%, PSC: 99.7, PRC: 91.4



C7524, 1/2-inch NMAS, Coarse-Graded, Density: 91.8%, Asphalt Content: 5.51%, PSC: 95.0, PRC: 84.4

Figure 33. Number of Lots Versus Arithmetic Density Mean for Six WSDOT Asphalt Pavement Mixtures (Two Relatively Poor Condition [Left], Two Relatively Good Condition [Center], and Two Low Density [Right]) Completed in 2008

4.5.5 *WAPA survey and WAPA/WSDOT interviews*

4.5.5.1 **About half of WAPA respondents think increased density improves performance**

Three of the seven WAPA interview respondents (43%) claim that WSDOT's increased density requirement increases performance for HMA pavements. Some of the comments include "in-place density is a key driver to longevity" and that "it [increased density] will help make the road last longer." Additionally, three of the seven WAPA respondents (43%) currently target a 93% field density in their HMA pavements. One of the seven WAPA respondents thought the increased density requirement will not impact performance.

4.5.5.2 **About half of WAPA respondents think increased density requires construction adjustments**

In response to the survey density question, 7 of the 18 WAPA survey respondents (39%) identify some adjustments to meet WSDOT's increased density requirement. Projected adjustments include mix design modifications, increased number of rollers, increased compactive effort, and slower production. Similarly, three of the seven WAPA interview respondents claim that the increased density will require mix design adjustments and four of seven WAPA interview respondents (57%) suggest that the increased density will require construction adjustments such as additional rollers and a slower paving train.

4.6 Discussion

4.6.1 *Limitations*

The purpose of the study is to use WSDOT field and performance data to characterize the influence of density on performance and contractor bonus. This method uses actual field data and its usefulness relies on quality data. Also, there are many unmeasured variables (e.g. construction quality, underlying pavement/soil conditions, etc.) that could influence dependent variables beyond condition (e.g. density, asphalt content) data. Although industry perspectives can assist in results interpretation, this method is likely to only identify very broad, strong trends and sometimes expected trends are not seen above the noise of unmeasured variables. This paper uses and compares findings from the literature, field data, and industry perspectives. At times, the findings from these sources do not all agree.

4.6.2 *Field density is about 93% for all WSDOT HMA mixtures*

The overall average weighted density for fine-graded, coarse-graded, 3/8-inch NMAS, and 1/2-inch NMAS mixtures is about 93% density. The t-test for two independent samples of the contract field density by mixture type fails to reject that the difference between the means is zero (Figure 28). Given a 91% of TMD specification, this 93% in-place density finding aligns with earlier research by Willoughby and Mahoney (2007) which also states that it is easier (higher standard deviation) for contractors to earn a bonus with a higher average field density. Further, about half of the WAPA interviewees target a 93% in-place density to achieve a bonus.

4.6.3 *The 92% density specification produces a financial incentive for contractors to change practices of about $26,200 per contract or about $2 per ton on average*

On average, the 91% density specification yields a bonus of about $11,400 per contract ($0.75 per ton) and the new 92% density specification (without any operational changes) yields a bonus loss of about -$14,800 per contract (-$0.98 per ton), a difference of about $26,200 ($1.72 per ton) (Figure 29). This result confirms some comments in the survey and interviews that the new density specification requires mix design and construction adjustments to secure a bonus at a higher density LSL.

4.6.4 *No clear trends link higher field densities with higher asphalt content*

Linear regression results and Table 6 show no apparent trends between increased density and increased asphalt content. This finding does not align with the literature that states increased asphalt content produces increased density given an adequately adjusted mix design. This does not imply that the literature is incorrect, but rather that there is not available field evidence to support them.

4.6.5 *Fine-graded mixture asphalt content is about the same*

Fine-graded mixtures exhibit a higher field measured asphalt content of 5.42% versus 5.43% for coarse-graded mixtures, a difference of only 0.01%. The statistical analysis (t-test for two independent samples) suggests that there is not a difference between these means. This observation is not consistent with one literature finding which states that fine-graded mixtures have more asphalt (Timm et al. 2006). A possible explanation is that 42 of 50 (84%) fine-graded contracts are 1/2-inch NMAS which contain less asphalt (see next section). Another possible explanation is that state highway agencies may have increased the asphalt content in coarse-graded mixtures in response to the performance concerns about the early Superpave mix designs (FHWA 2010).

4.6.6 ***3/8-inch NMAS mixture asphalt content is about 0.7% higher***

The 3/8-inch NMAS mixtures exhibit a higher field measured asphalt content of 6.07% versus 5.39% for 1/2-inch NMAS mixtures, a difference of about 0.7%. The statistical analysis (t-test for two independent samples) suggests that the difference between these means is statistically significant. This is consistent with the interviews and literature (Newcomb 2009; Christensen and Bonaquist 2006) since 3/8-inch NMAS mixtures require a higher asphalt content to cover an increased surface area.

4.6.7 ***No clear trends link elevated field density and increased performance***

The condition data analysis does not reveal a clear trend between density and cracking/rutting performance (Figure 30-Figure 33). Although the data show increased cracking and rutting with age for all densities, it is difficult to identify any evidence of a strong linkage between density and performance. What can be seen is that for the contracts with an average weighted density of 94% or higher, none of the contracts are performing poorly (≤ 50 condition value), about 80% of those contracts with cracking data exhibit a PSC of 90 or higher, and about 70% of those contracts with rutting data exhibit a PRC of 80 or higher. The absence of a clear trend does not align with literature and some survey/interview comments that elevated field density produces increased performance. This does not imply that the literature and survey/interviews are incorrect, but rather that the available WSDOT in-service pavement data do not provide evidence to support them. It may be that as the analyzed pavements age beyond 10 years (the oldest pavement surface analyzed in this paper) the trend may continue and provide better evidence of differences between fine- and coarse-graded mixtures and 3/8-inch and 1/2-inch NMAS mixtures.

4.6.8 ***Fine-graded mixtures perform similarly to coarse-graded mixtures***

The statistical analysis (paired t-test by age) of cracking and rutting of fine-graded versus coarse-graded mixtures fails to reject that the difference between the means is zero. As a result, there is not sufficient statistical evidence to conclude that fine-graded mixtures produce a different overall average weighted structural and rutting condition than coarse-graded mixtures. This finding does not align with the literature which states that coarse-graded mixtures exhibit increased resistance to permeability (potentially less cracking). This does not imply that the literature is incorrect, but rather that the available WSDOT in-service pavement data do not provide evidence to support the literature. Conversely, this finding provides evidence that fine-graded mixtures can exhibit similar rutting resistance as coarse-graded mixtures.

At a similar density, the structural condition shows that fine-graded mixtures may be trending higher than coarse-graded mixtures in terms of cracking condition particularly for the older contracts, 8-10 years after completion. During this time, the average equivalency cracking in the wheel path for coarse-graded mixtures (0.97%, PSC: 84.4) is about three times higher than fine-graded mixtures (0.27%, PSC: 91.8). Fine-graded mixtures are not likely to have a poor performing mix (Figure 30-Figure 31). It may be that as the analyzed pavements age beyond 10 years (the oldest pavement surface analyzed in this paper) the trend may continue and provide better evidence of differences between fine- and coarse-graded mixtures.

4.6.9 *3/8-inch NMAS mixtures perform similarly over time*

For contracts with just density values, the statistical analysis (paired t-test by age) of cracking and rutting of the 3/8-inch NMAS versus the 1/2-inch NMAS fails to reject that the difference between the means is zero. As a result, there is not sufficient statistical evidence to conclude that 3/8-inch NMAS mixtures produce a different overall average weighted structural and rutting condition than 1/2-inch NMAS mixtures. However, there is some evidence that suggests 3/8-inch NMAS contracts may be trending higher than 1/2-inch NMAS contracts in terms of cracking particularly with older contracts. For example, for contracts ages eight to nine (cracking data not available for age 10), the average weighted cracking condition by tons of mix and equivalency cracking in the wheel path of 3/8-inch NMAS is 94.0 and 0.14% versus 86.1 and 0.77% for 1/2-inch NMAS. It may be that as the analyzed pavements age beyond 10 years (the oldest pavement surface analyzed in this paper) the trend may continue and provide better evidence of differences between 3/8-inch and 1/2-inch NMAS mixtures.

4.6.10 *Location influences performance*

The statistical analysis (paired t-test by age) of cracking and rutting condition of Western and Eastern Washington fails to reject that the difference between the means is zero. As a result, there is not sufficient statistical evidence to conclude that Western Washington mixtures produce a different overall average weighted structural and rutting condition than Eastern Washington mixtures. However, cracking performance in Eastern Washington may be trending lower (more cracking) for older contracts, ages 7-10 since the average weighted cracking condition by tons of mix and equivalency cracking in the wheel path is 73.2 and 2.87% versus 93.0 and 0.19% for

Western Washington. This is consistent with the findings reported in Wen et al. (2016) that the mixtures in Eastern Washington generally perform worse primarily as a result of the extreme climate.

4.7 Conclusion

This study investigates the impacts of (1) density on HMA pavement performance, and (2) mix parameters on density in Washington State by analyzing linked WSDOT mix design, QA, and performance data for mixtures completed between 2007 and 2017 as well as relevant industry perspectives obtained through a survey and series of interviews. All WSDOT mixtures exhibit similar field density and there are no apparent trends between increased density and performance on a statewide or Eastern versus Western Washington level over the last 10+ years. Additionally, unless contractors change current construction practices to meet the 92% density lower specification limit, there will be financial implications. The conclusions are:

- **The overall average weighted field density for all WSDOT HMA mixtures is about 93%.** This finding aligns with earlier research and the WAPA interviews because this average density makes it easier to earn a bonus;
- **The 92% density LSL produces a financial incentive for contractors to change practices of about $26,200 per contract or about $2 per ton on average.** It is unknown if this financial incentive is sufficient to change current practices but survey and interview answers indicate that it is likely. About half of WAPA members feel the increased density LSL requires mix design and construction adjustments;
- **There are no clear trends between increased field density and asphalt content**;
- **The overall average weighted field measured asphalt content for all WSDOT HMA mixtures is 5.43%**;
- **There are no clear trends that link field density and performance.** The data do show that of the contracts with an average weighted density of 94% or higher, none are poorly performing ($\leq$ 50);
- **There is no statistical evidence that there is a difference between cracking and rutting condition means for all mixtures.** The data do show that cracking performance of fine-graded mixtures may be trending higher (less cracking) than coarse-graded mixtures for older contracts, ages 8-10. Additionally, data show that cracking performance of older 3/8-inch NMAS mixtures may be trending higher (less cracking) than 1/2-inch NMAS mixtures for

older contracts, at ages eight to nine (cracking data with density is not available for 3/8-inch NMAS mixtures at age 10).

The utility of the mix design, field, and performance data method presented in this paper (1) analyzes data over a uniquely long period of time (10+ years) and (2) uses the data to compare with literature findings and industry perspectives. The numerous variables not analyzed (e.g. weather, paving conditions, underlying soil/pavement conditions, etc.) necessarily make the standard of proof quite high to show significant differences between density and HMA performance as well as density and other mixture characteristics. As a result, some analyses (e.g. density, performance) showed no significant differences. This does not imply that there are not differences, but rather there is not enough evidence to identify them. Conversely, one analysis showed statistically significant differences (NMAS mixture asphalt content) which may be a helpful data point to inform policy and specification development. While sometimes expected trends are not seen above the noise of uncontrolled variables, those that are seen constitute strong evidence to be accounted for in policy and specification decisions. Notably, reasons for paving at an increased density were not universally confirmed (e.g. increased performance). This could be because of the coarse nature of the comparison or because it is too early in the pavement life to identify significant performance differences.

4.8 Acknowledgments

The authors would like to thank WSDOT and WAPA for their support and contributions to this effort. The views in this paper are those of the authors and do not reflect the official views and policies of WSDOT.

4.9 Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request. The data includes SAM and WSPMS.

4.10 Other Considerations

The preceding narrative, figures, and tables in this chapter approximately meet ASCE journal submission length requirements. This section covers additional in-service pavement data considerations that do not fit the paper length requirements but deserve analysis.

4.10.1 *Voids in mineral aggregate (VMA)*

For mixtures with field density data, another topic that provides insight into the performance of HMA pavements is voids in mineral aggregate (VMA) for contracts completed between 2007 and 2017. At a design air voids of 4%, "increasing aggregate specific surface while increasing minimum VMA will improve both fatigue resistance and rut resistance" (Christensen and Bonaquist 2006). The WSDOT specifications establish a minimum VMA for each NMAS, 15% for 3/8-inch NMAS and 14% for 1/2-inch NMAS; however, VMA was not subject to bonus or penalty pay from 2007 to 2017 (WSDOT 2018b). WSDOT uses SAM to store QA data which includes field measured and the analysis integrates the data using contract and mix design numbers. The analysis uses contract age (Eq.(16)), total contract sample size (tons) (Eq.(17)), and average weighted VMA per contract using (Eq.(27)). Table 7 identifies the number of contracts for VMA by gradation and NMAS. Overall, 275 of 494 (~45%) contracts fall below the WSDOT VMA specifications.

$$(AWVMA)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right)*(VMA)_{i,j} \tag{27}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWVMA_i$ = average weighted voids in mineral aggregate of contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts, and

$VMA_{i,j}$ = voids in mineral aggregate of mix design j in contract i.

Table 7. Number of Contracts and Tons of Mix by NMAS, Gradation, and Data Source from 2007 to 2017

Parameter	VMA	No. 200
Total Contracts	494	501
Average Contracts Per Year	45	46
3/8-inch NMAS Contracts	24	26
1/2-inch NMAS Contracts	470	475
Fine-Graded Contracts	48	50
Coarse-Graded Contracts	446	451
Total Tons of Mix	9.8M	11.4M
Average Tons of Mix Per Year	887K	1.0M

The overall average weighted VMA of 3/8-inch NMAS contracts is 15.3% and for 1/2-inch NMAS contracts is 14.1%, a difference of about 1.2%%. VMA for all fine-and coarse-graded as well as 3/8-inch and 1/2-inch NMAS mixtures from 2007 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between density means). VMA results for gradation fail to reject the null hypothesis at 95% confidence (p-value = 0.454, 95% confidence interval of difference between the means is -0.6%, 0.3%. Conversely, VMA results for NMAS reject the null hypothesis at 95% confidence (p-value < 0.0001, 95% confidence interval of difference between the means is 0.6%, 1.7%).

Generally, the VMA field results have slightly decreased in the last 10+ years but may be trending upward at age zero (Figure 34-Figure 35). Additionally, an analysis of older contracts (ages 9-10) reveals no apparent trends between cracking and rutting condition with VMA (Figure 36-Figure 39). Given a similar density of both NMASs, a possible interpretation of the slightly lower VMA may be due to a lower effective asphalt content.

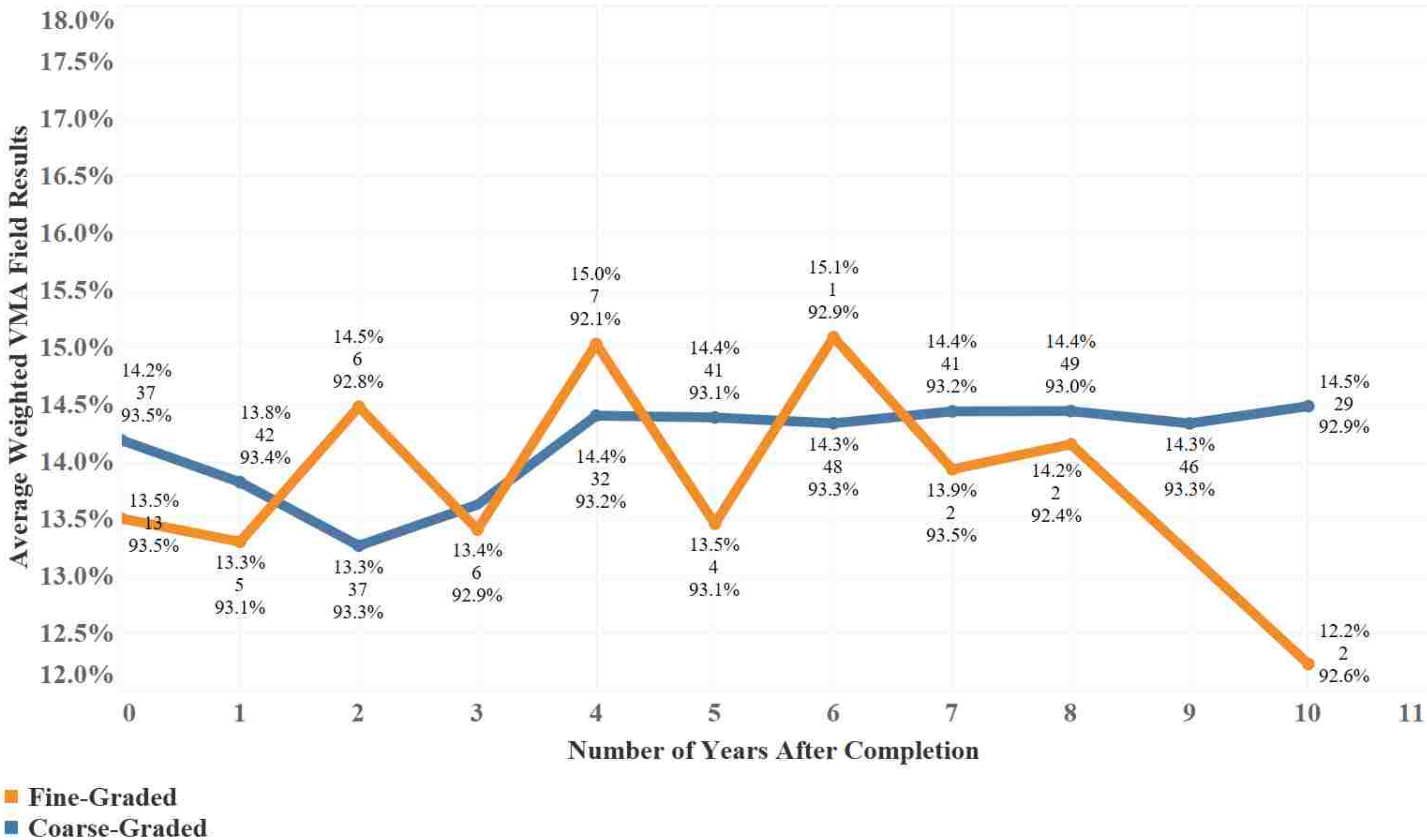


Figure 34. Average Weighted VMA Field Results by Tons of Mix, Number of Contracts, and Average Weighted Density Versus Number of Years After Contract Completion for Fine-Graded and Coarse-Graded NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: VMA (Top), Number of Contracts (Middle), Density (Bottom)]

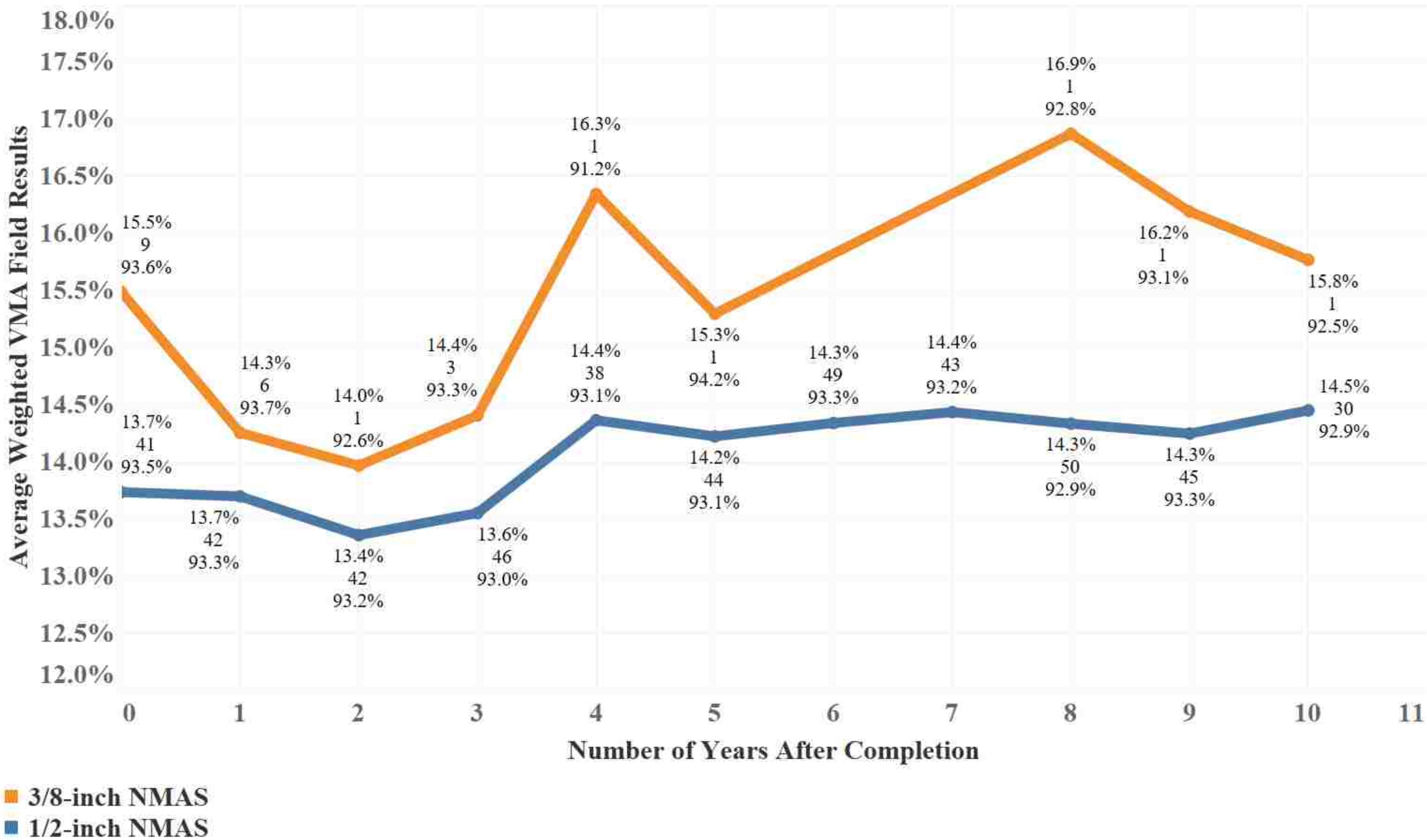


Figure 35. Average Weighted VMA Field Results by Tons of Mix, Number of Contracts, and Average Weighted Density Versus Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: VMA (Top), Number of Contracts (Middle), Density (Bottom)]

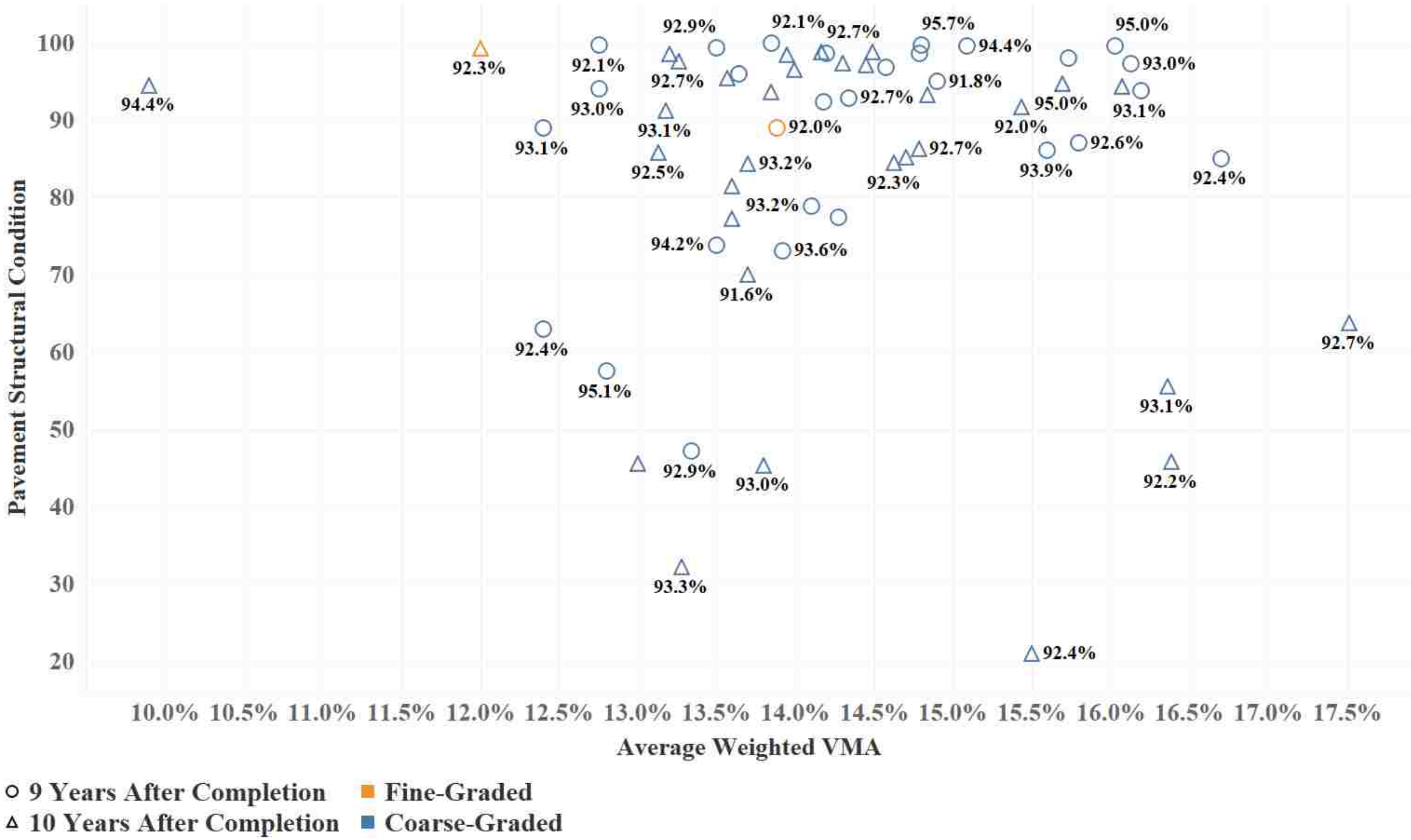


Figure 36. Average Weighted Pavement Structural Condition by Average Weighted Density Versus Average Weighted VMA for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2008

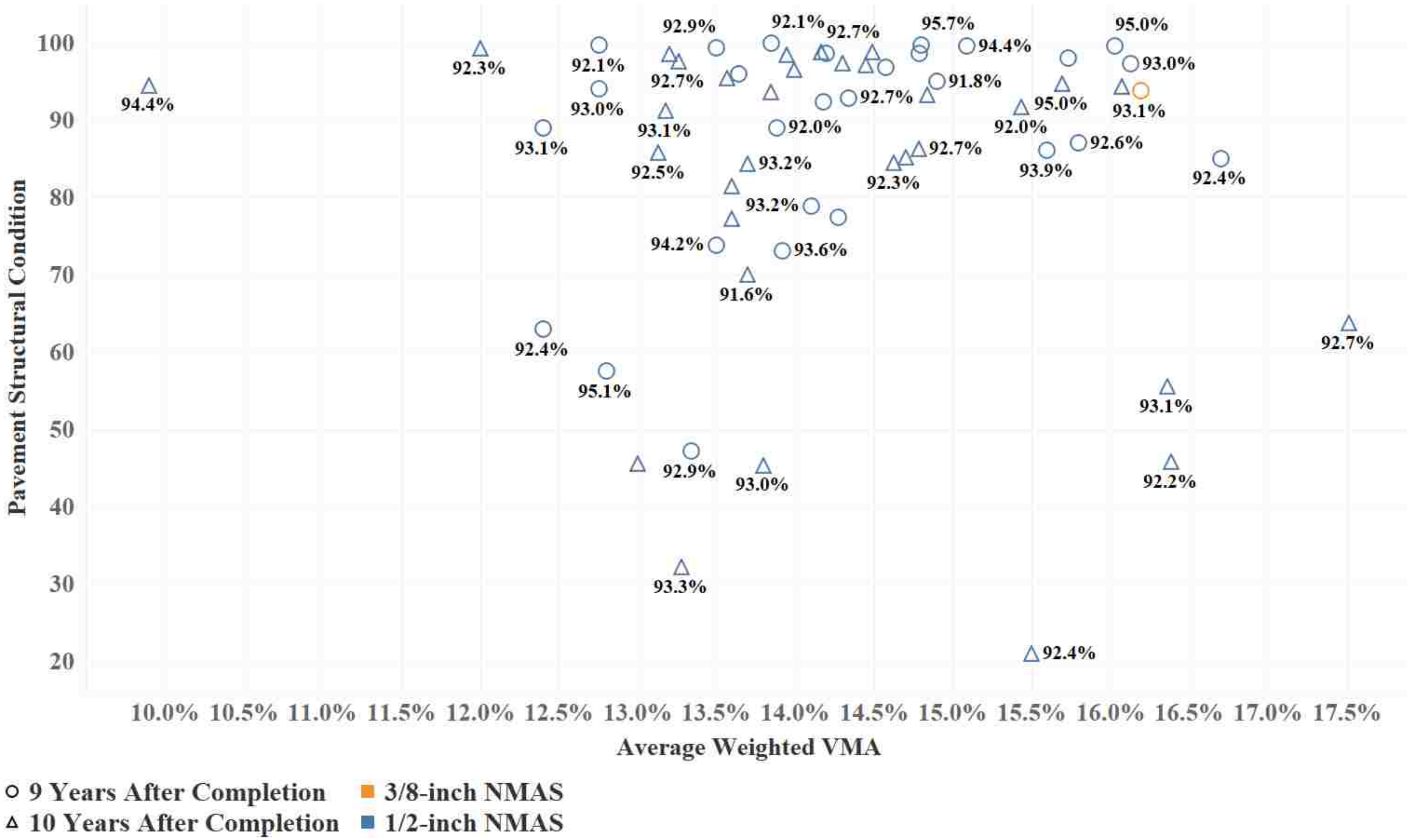


Figure 37. Average Weighted Pavement Structural Condition by Average Weighted Density Versus Average Weighted VMA for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2008

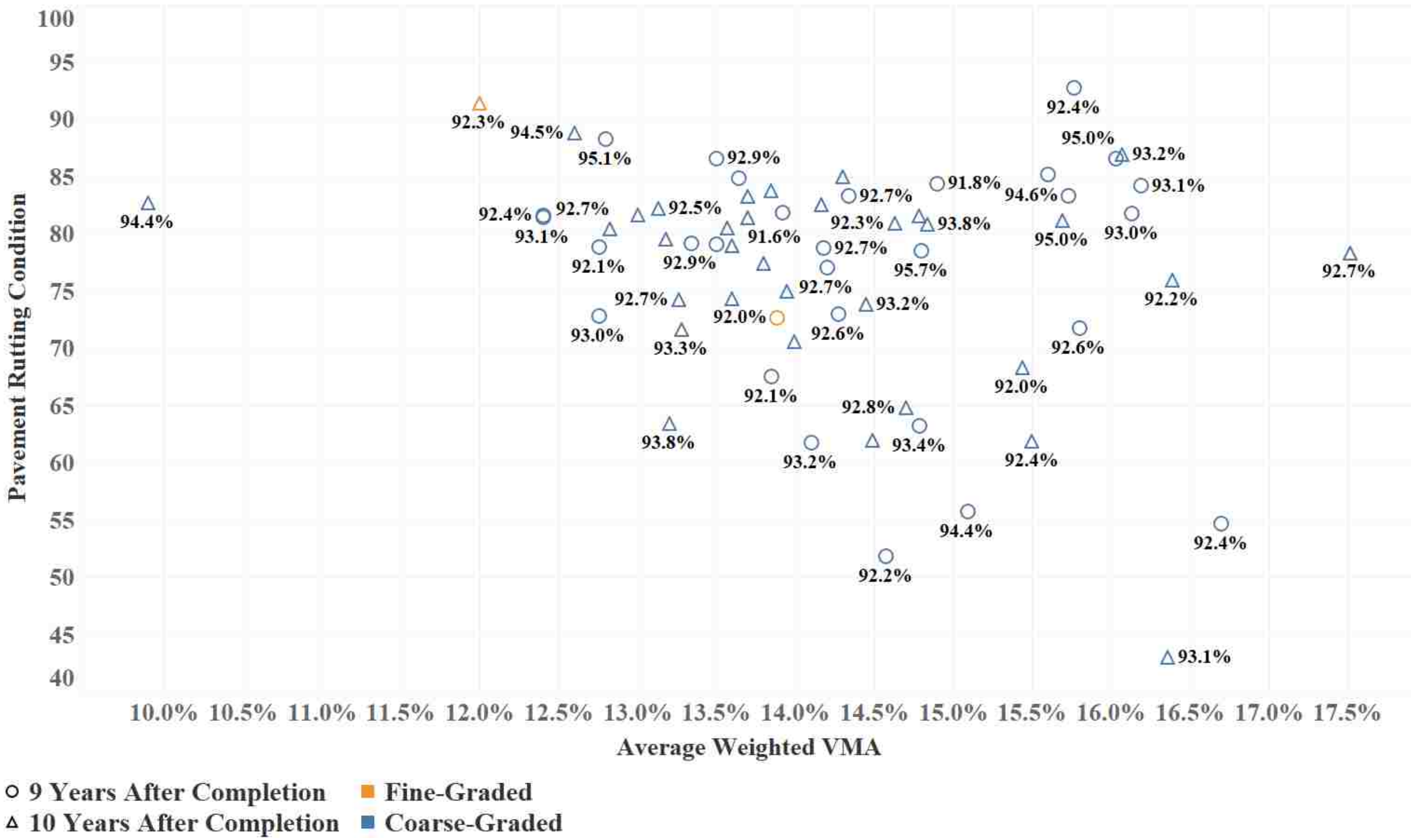


Figure 38. Average Weighted Pavement Rutting Condition by Average Weighted Density Versus Average Weighted VMA for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2008

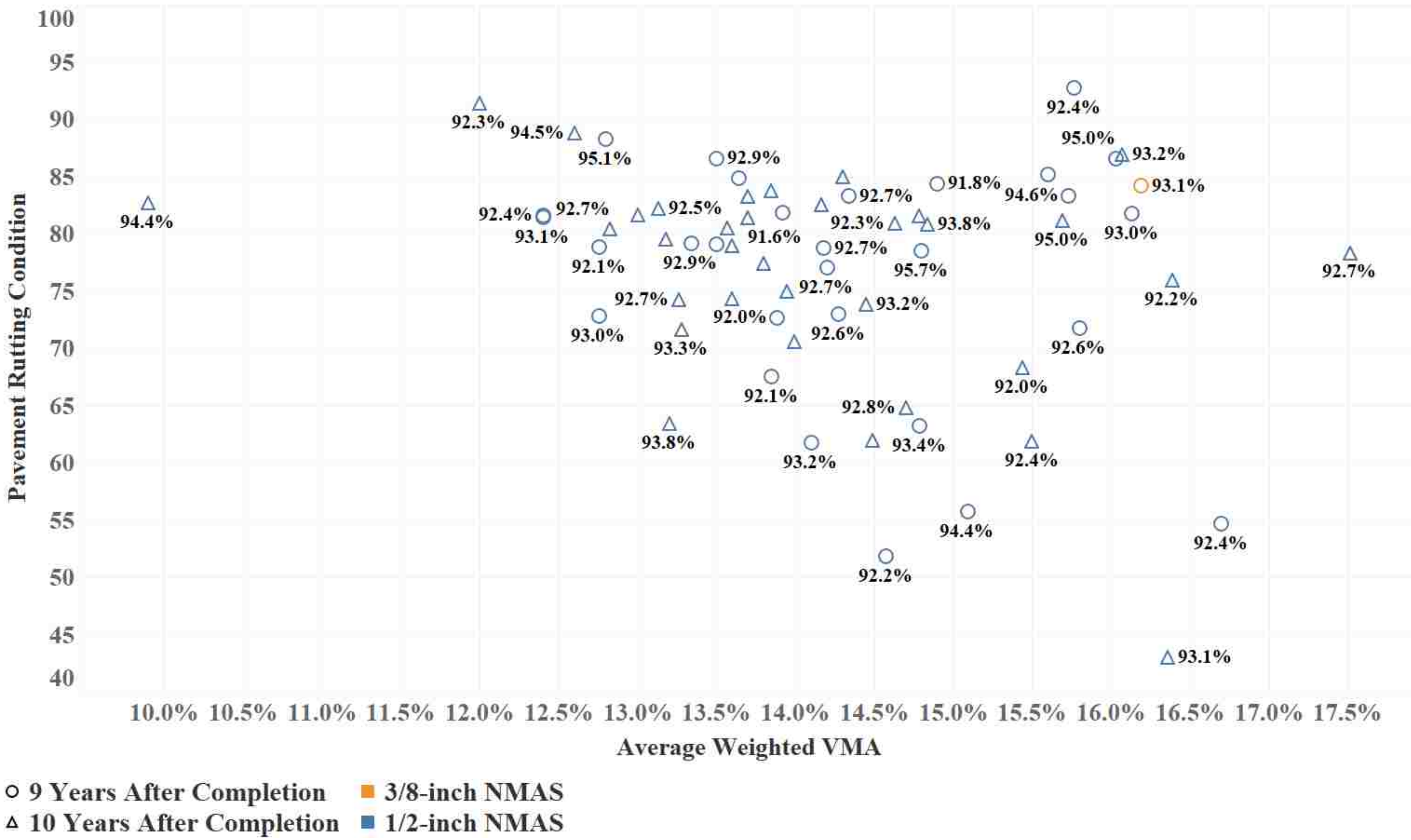


Figure 39. Average Weighted Pavement Rutting Condition by Average Weighted Density Versus Average Weighted VMA for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2008

4.10.2 ***No. 200 sieve***

Mixture gradation provides additional insight into pavement performance and this section analyzes the field data of the No. 200 sieves, a price adjustment factor of 0.20 (WSDOT 2018a). The WSDOT specifications establish a tolerance band of 2 to 7% passing the No. 200 sieve for 3/8-inch and 1/2-inch NMAS mixtures with a job mix formula tolerance of ±2 (WSDOT 2018b). For mixtures with field density data, WSDOT uses SAM to store QA data which includes field measured and the analysis integrates the data using contract and mix design numbers. The analysis uses contract age (Eq.(16)), total contract sample size (tons) (Eq.(17)), and average weighted field gradation results per contract (Eq.(28)). Table 7 identifies the number of contracts for the No. 200 sieve by gradation and NMAS.

$$(AWG_{\#200})_i = \frac{1}{S_i}\sum_{j=1}^{M_i}(s_{i,j})*(G_{\#200})_{i,j} \qquad (28)$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWG_{\#8i}$ = average weighted No. 200 gradation results of contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts, and

$G_{\#200i,j}$ = No. 200 gradation results of mix design j in contract i.

The overall average weighted No. 200 field results of 3/8-inch NMAS mixtures is 6.2% and for 1/2-inch NMAS mixtures is 5.8%, a difference of 0.4%. Generally, the No. 200 field results have slightly increased in the last 10+ years (Figure 40-Figure 41).

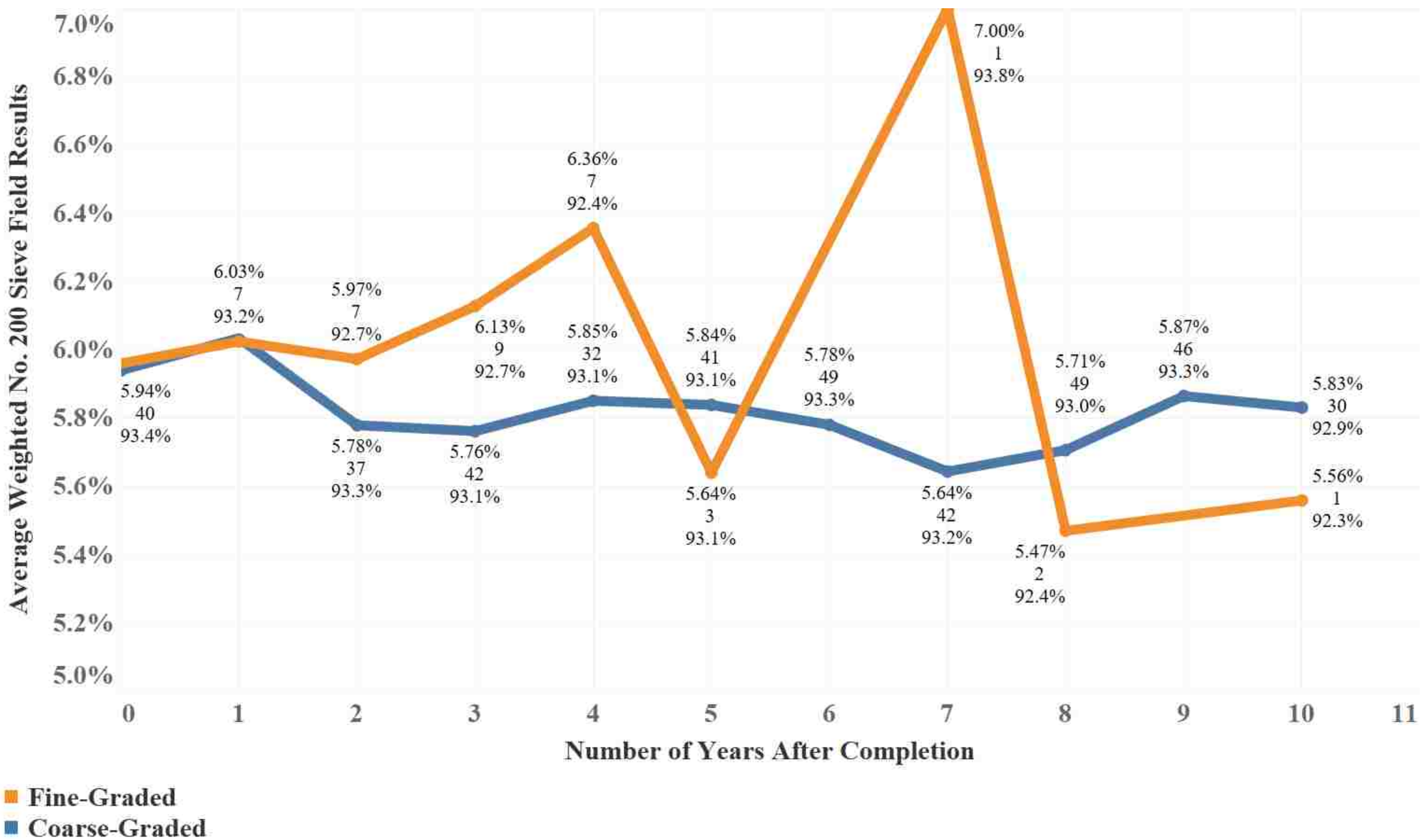


Figure 40. Average Weighted No. 200 Sieve Field Results by Tons of Mix, Number of Contracts, and Average Weighted Density Versus Number of Years After Contract Completion for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: No. 200 Sieve (Top), Number of Contracts (Middle), Density (Bottom)]

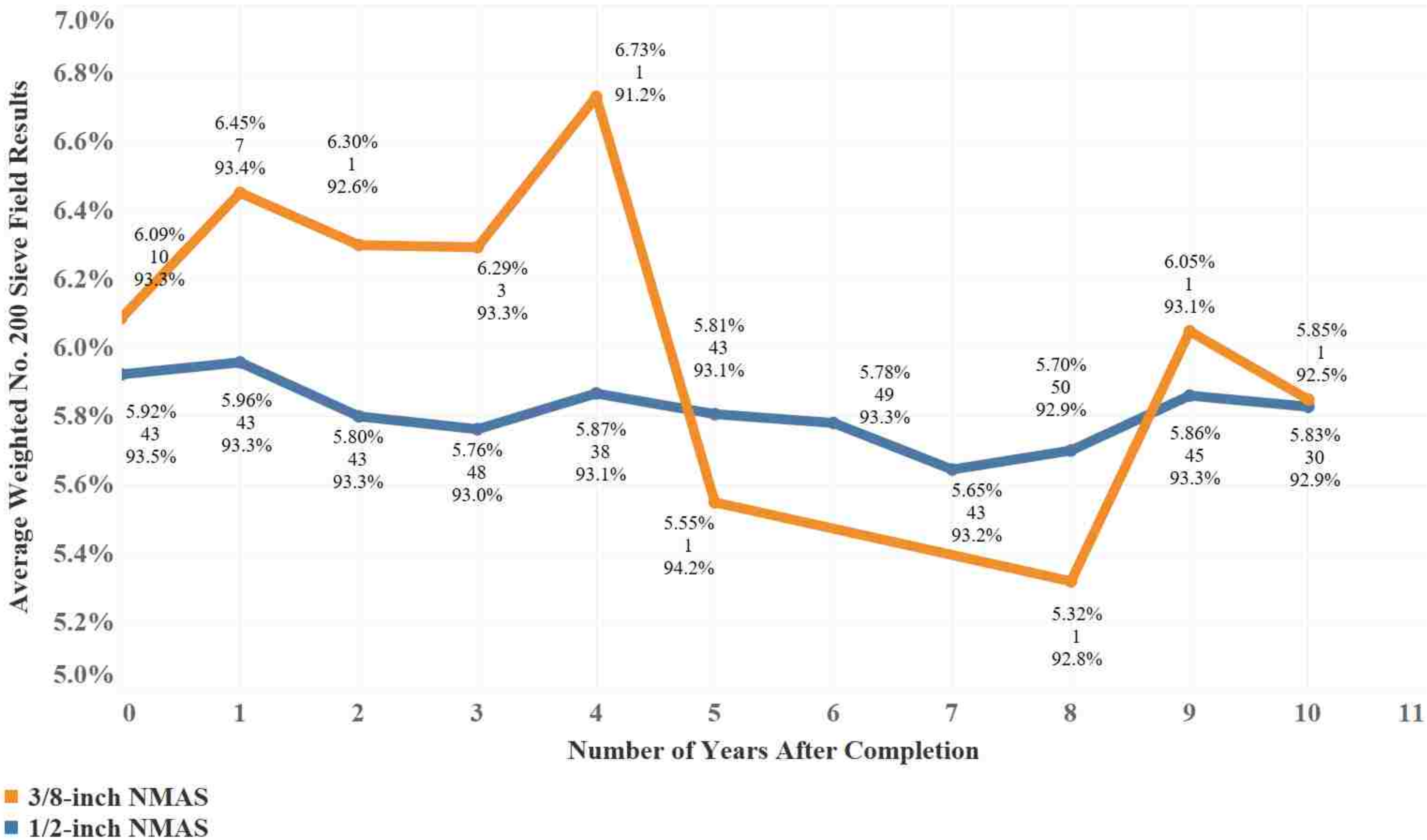


Figure 41. Average Weighted No. 200 Sieve Field Results by Tons of Mix, Number of Contracts, and Average Weighted Density Versus Number of Years After Contract Completion for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2017 [Data Labels: No. 200 Sieve (Top), Number of Contracts (Middle), Density (Bottom)]

4.10.3 ***Condition and density by NMAS***

This section includes the figures (Figure 42-Figure 43) supporting the condition and density by NMAS analysis described in section 4.5.4 and section 4.6.

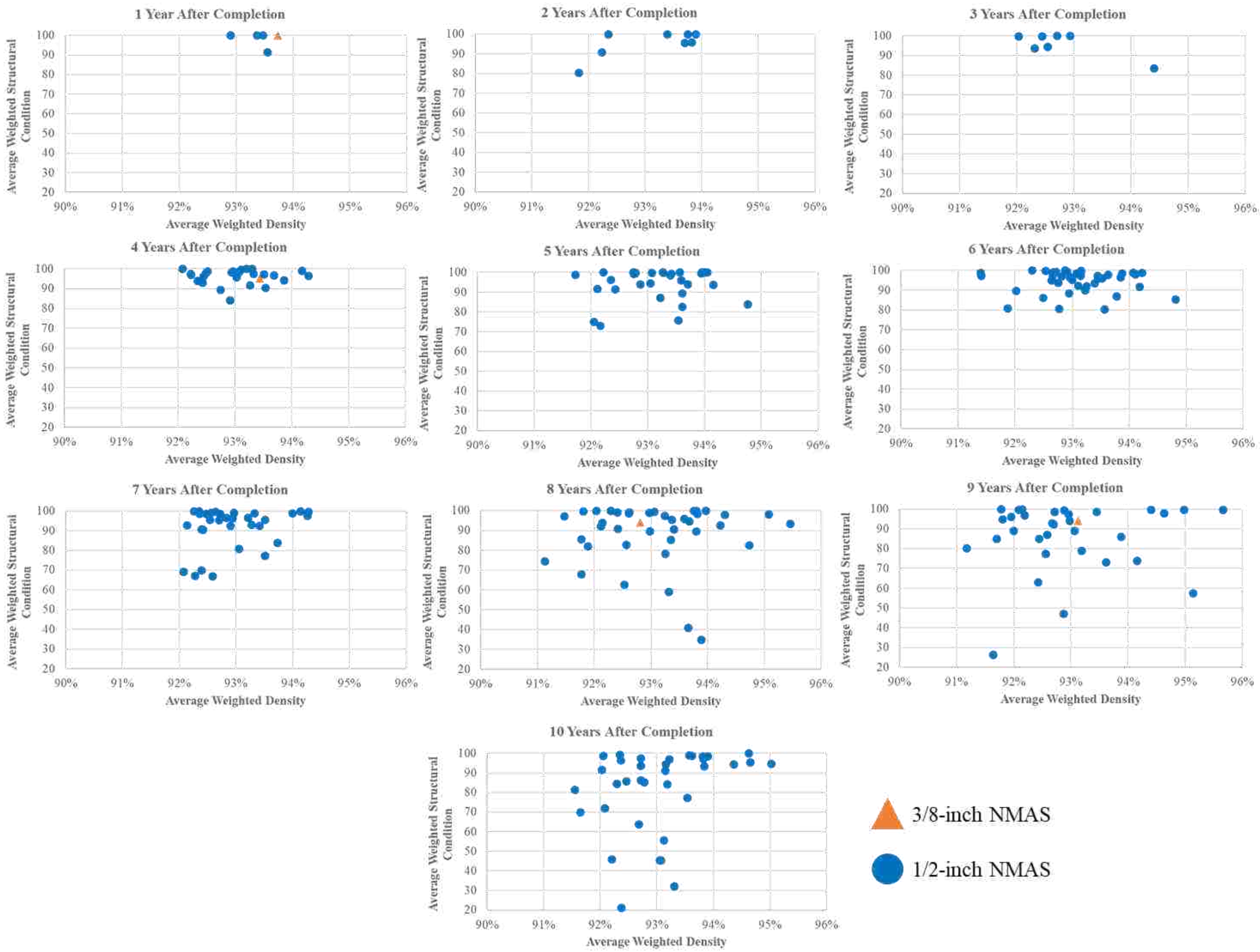


Figure 42. Average Weighted Structural Condition Versus Average Weighted Density by Number of Years After Contract Completion and NMAS for WSDOT Asphalt Pavement Mixtures, 2007 to 2016

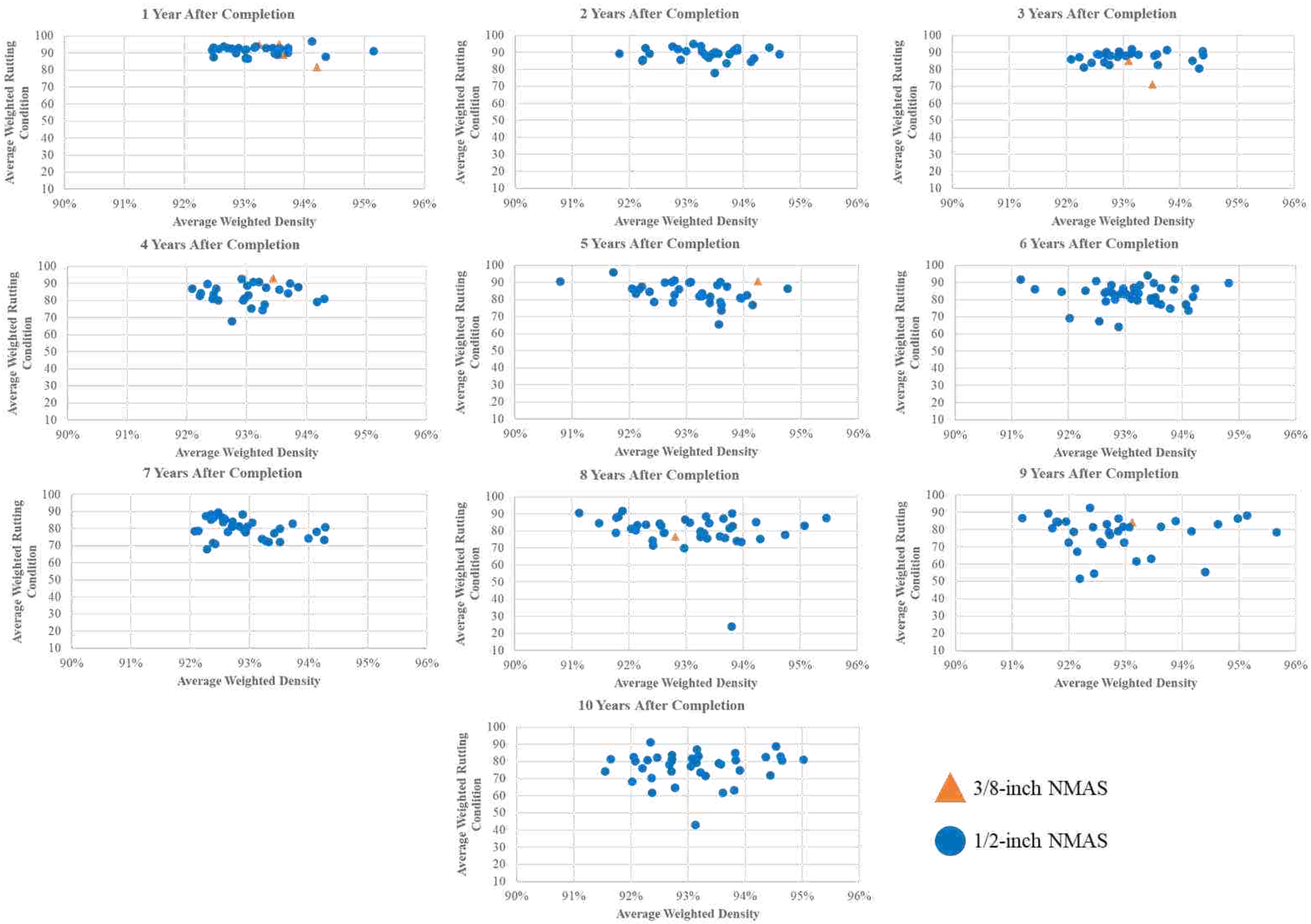


Figure 43. Average Weighted Rutting Condition Versus Average Weighted Density by Number of Years After Contract Completion and NMAS for WSDOT Asphalt Pavement Mixtures, 2007 to 2016

4.10.4 ***Traffic load***

Another consideration for mixtures with field density data relevant to gradation (fine-graded and coarse-graded), NMAS (3/8-inch and 1/2-inch NMAS), and performance is the amount of pavement traffic experienced over the pavement life. This section analyzes the number of traffic loading (i.e. equivalent single axle loads, ESALs) in the context of cracking and rutting condition to determine if a higher amount of traffic loading decreases performance. The analysis uses total lane miles, (Eq.(25)), and number of ESAL after the last major rehabilitation effort to calculate the number of average weighted ESALs per contract (Eq.(29)). The data source for ESALs per lane mile section is the 2017 WSPMS and Table 5 breaks down the number of contracts.

$$(AWESAL)_i = \frac{1}{L_i}\sum_{k=1}^{Q_i}\left(\lambda_{i,k}\right)*(ESAL)_{i,k} \tag{29}$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(ESAL)_{i,k}$ = number of ESALs after major rehab of segment j in contract i, and

$(AWESAL)_i$ = average weighted ESAL value of contract i.

4.10.4.1 **Cracking condition**

For mixtures with density data, the average number of ESALs since the last major rehabilitation per lane mile for fine-graded mixtures is about 2.6 million, for coarse-graded mixtures is about 3.7 million, for 3/8-inch NMAS mixtures is about 2.7 million, and for 1/2-inch NMAS mixtures is about 1.6 million. Similarly, the R^2 coefficient is 0.58 for fine-graded contracts, 0.0014 for coarse-graded contracts, 0.64 for 3/8-inch NMAS contracts, and 0.0020 for 1/2-inch NMAS contracts. It is worth noting that none of the fine-graded or 3/8-inch NMAS contracts are poorly performing (≤ 50 cracking condition value).

4.10.4.2 **Rutting condition**

For mixtures with density data, the average number of ESALs since the last major rehabilitation per lane mile for fine-graded mixtures is about 1.4 million, for coarse-graded mixtures is about 2.2 million, for 3/8-inch NMAS mixtures is about 1.1 million, and for 1/2-inch NMAS mixtures is about 2.1 million. Similarly, the R^2 coefficient is low for all mixtures, 0.010 for fine-graded contracts, 0.017 for coarse-graded contracts, 0.19 for 3/8-inch NMAS contracts, and 0.015 for 1/2-inch NMAS contracts. It is worth noting that none of the fine-graded or 3/8-inch NMAS contracts are poorly performing (≤ 50 rutting condition value).

For both cracking and rutting, the results do not show any apparent trends between density, gradation, NMAS, condition, and ESALs since the last major rehabilitation (Figure 44-Figure 47).

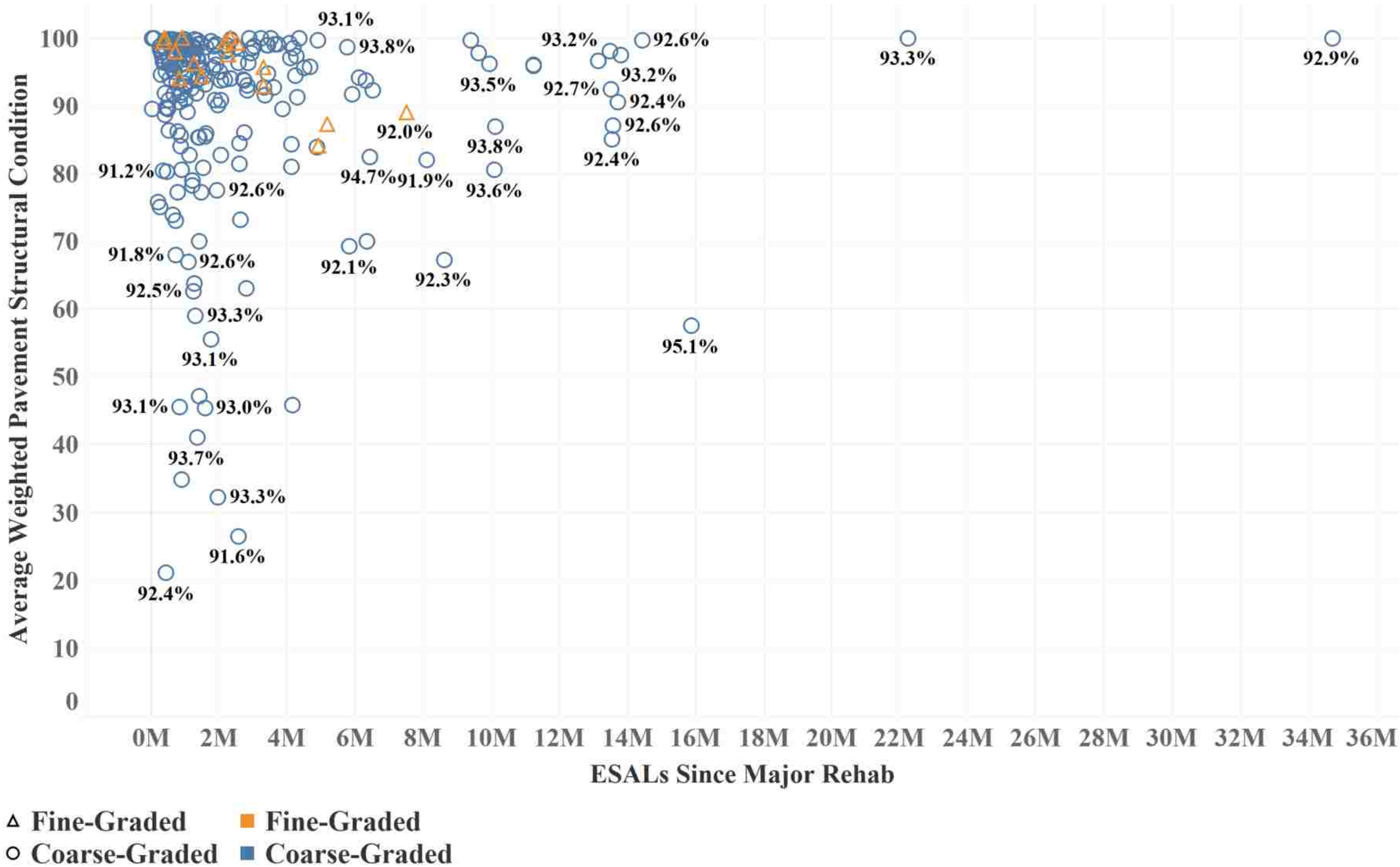


Figure 44. Average Weighted Pavement Structural Condition and Average Weighted Density Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2016

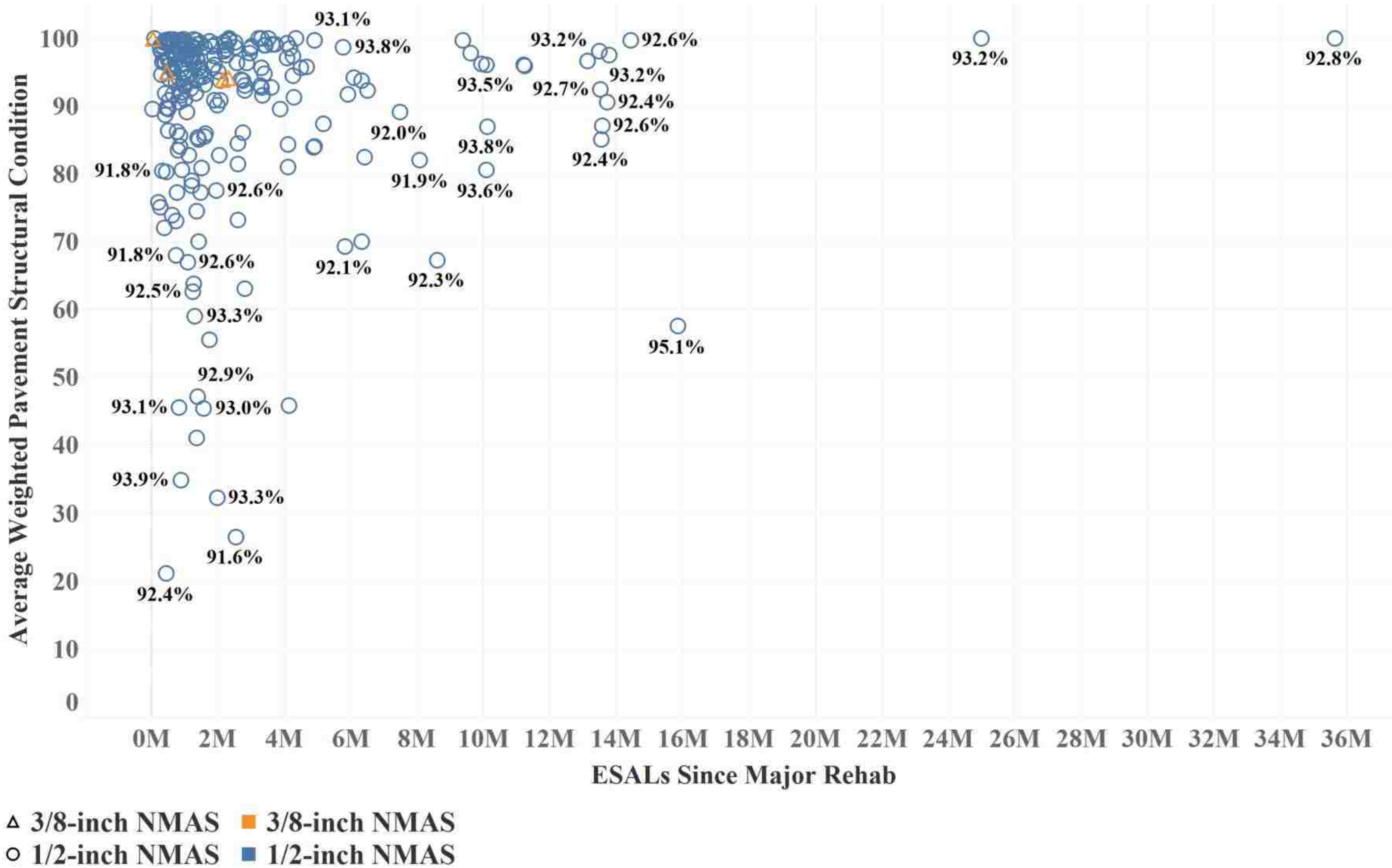


Figure 45. Average Weighted Pavement Structural Condition and Average Weighted Density Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016

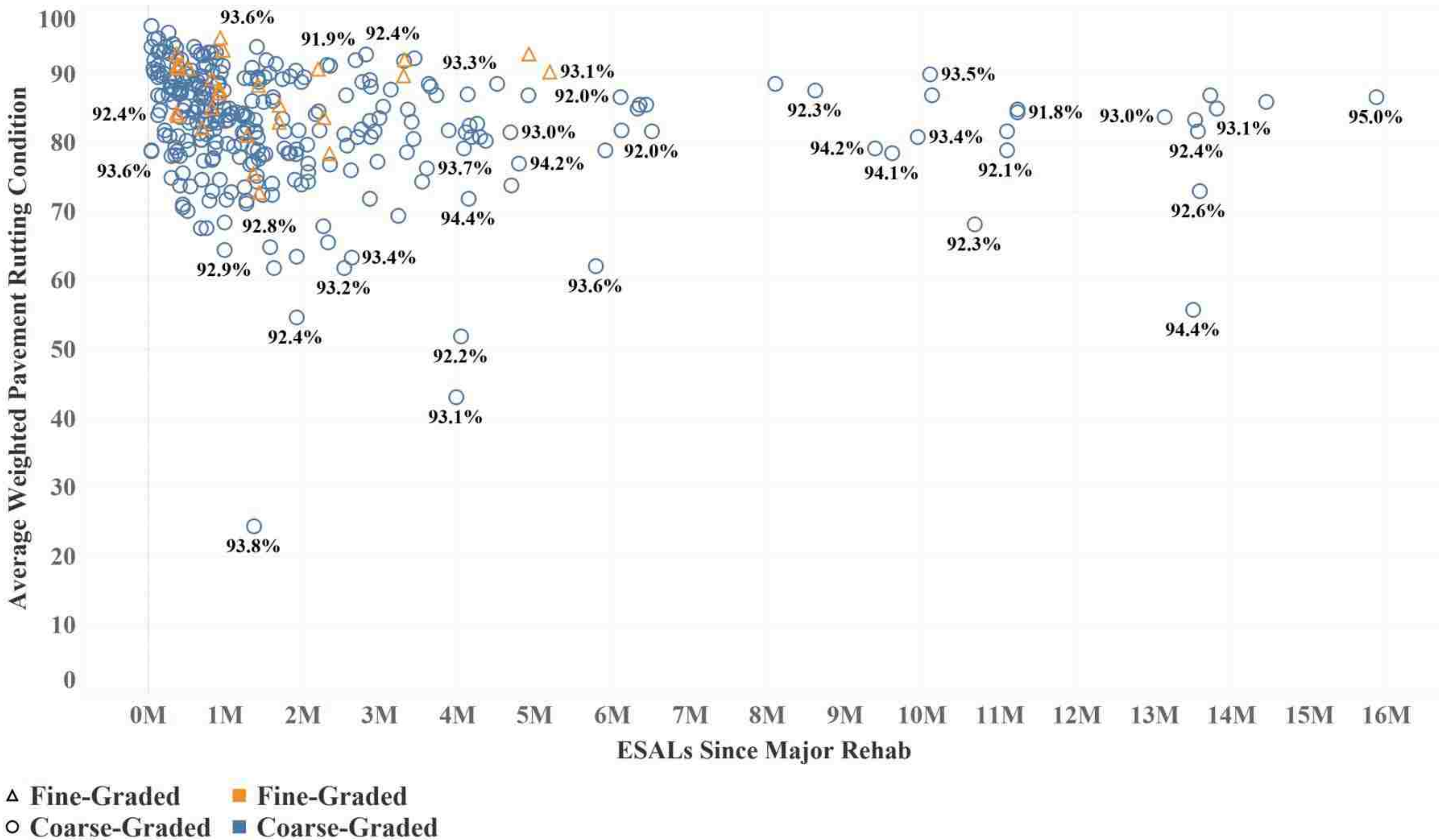


Figure 46. Average Weighted Pavement Rutting Condition and Average Weighted Density Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2016

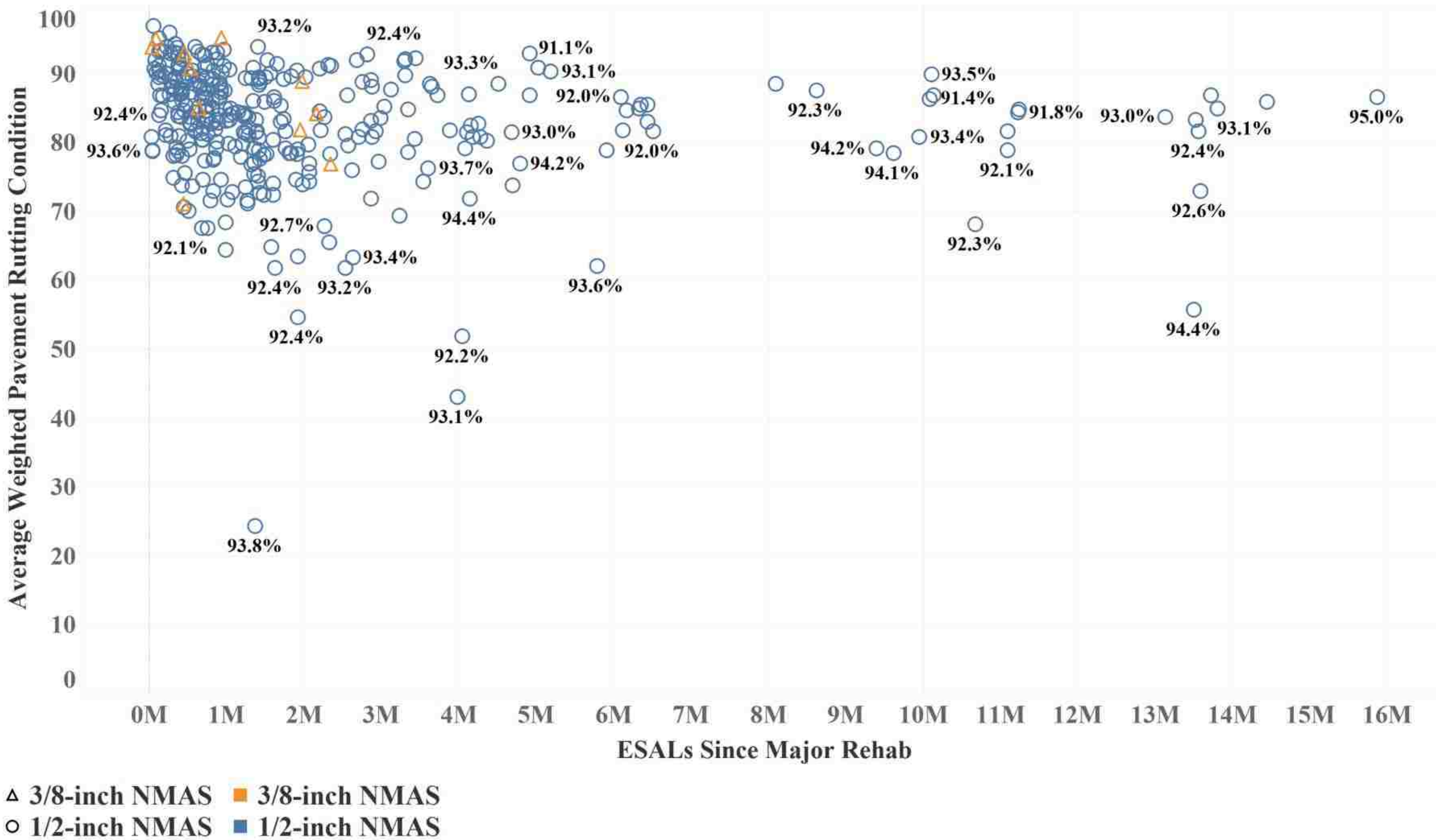


Figure 47. Average Weighted Pavement Rutting Condition and Average Weighted Density Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016

4.10.5 ***Predicted pavement service life and in-place density***

A significant consideration for this study is the relationship between in-place density and pavement service life. Although the data do not include pavement service life, the next best available data option is WSDOT predicted service life (in years) for each pavement section. Using contracts with cracking data (Table 5), WSDOT's predominant failure mode, this section compares the predicted service life per contract with in-place density (Wen et al. 2016). The analysis uses average weighted density (Eq.(18)), total lane miles (Eq.(25)), and average weighted predicted due year (Eq.(30)). A linear regression is performed to determine the R^2 coefficient of predicted due year and in-place density.

$$(AWDY)_i = \frac{1}{L_i}\sum_{k=1}^{Q_i}\left(\lambda_{i,k}\right) * (SDY)_{i,k} \tag{30}$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(AWDY)_i$ = average weighted predicted due year of contract i, and

$(SDY)_{i,k}$ = section predicted due year of segment k in contract i.

The overall average weighted predicted pavement service life for the data is 15.0 years and the R^2 is 0.004 (Figure 48). Consequently, there is no clear trend between in-place density and WSDOT's predicted service life data. This finding does not align with literature and some survey/interview comments that elevated field density produces increased performance. This does not imply that the literature and survey/interviews are incorrect, but rather that the available WSDOT in-service pavement data do not provide evidence to support them.

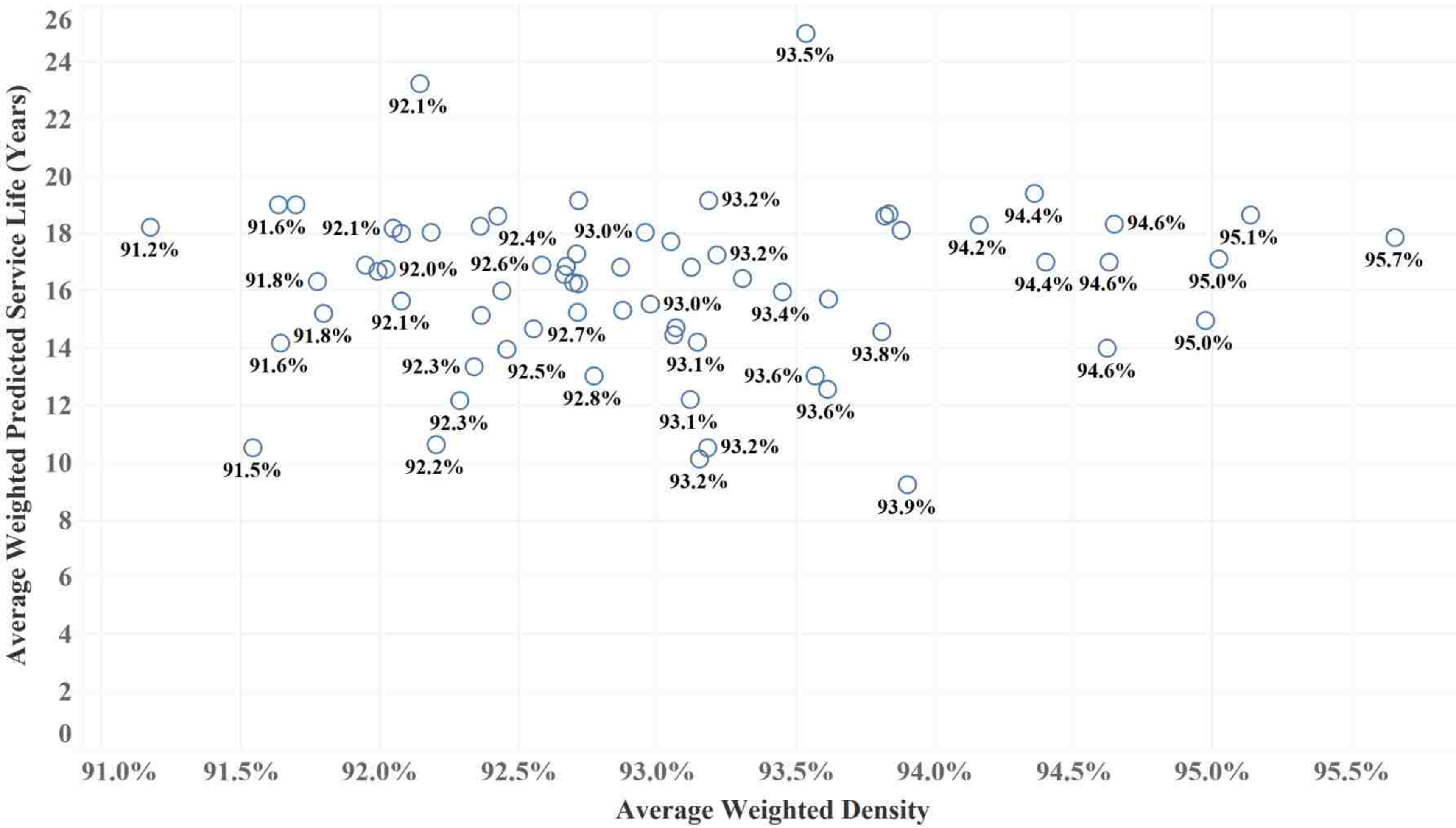


Figure 48. Average Weighted Predicted Service Life (Due Year) Versus Average Weighted Density for WSDOT Asphalt Pavement Mixtures with Cracking Data, 2007 to 2016

4.10.6 *Additional location figures*

The pages limitations of the manuscript precluded the inclusion of the location and terrain figures (Figure 49-Figure 52) in the context of gradation/NMAS with cracking and rutting performance for just contracts with density data. These support the results and discussion in section 4.5 and section 4.6.

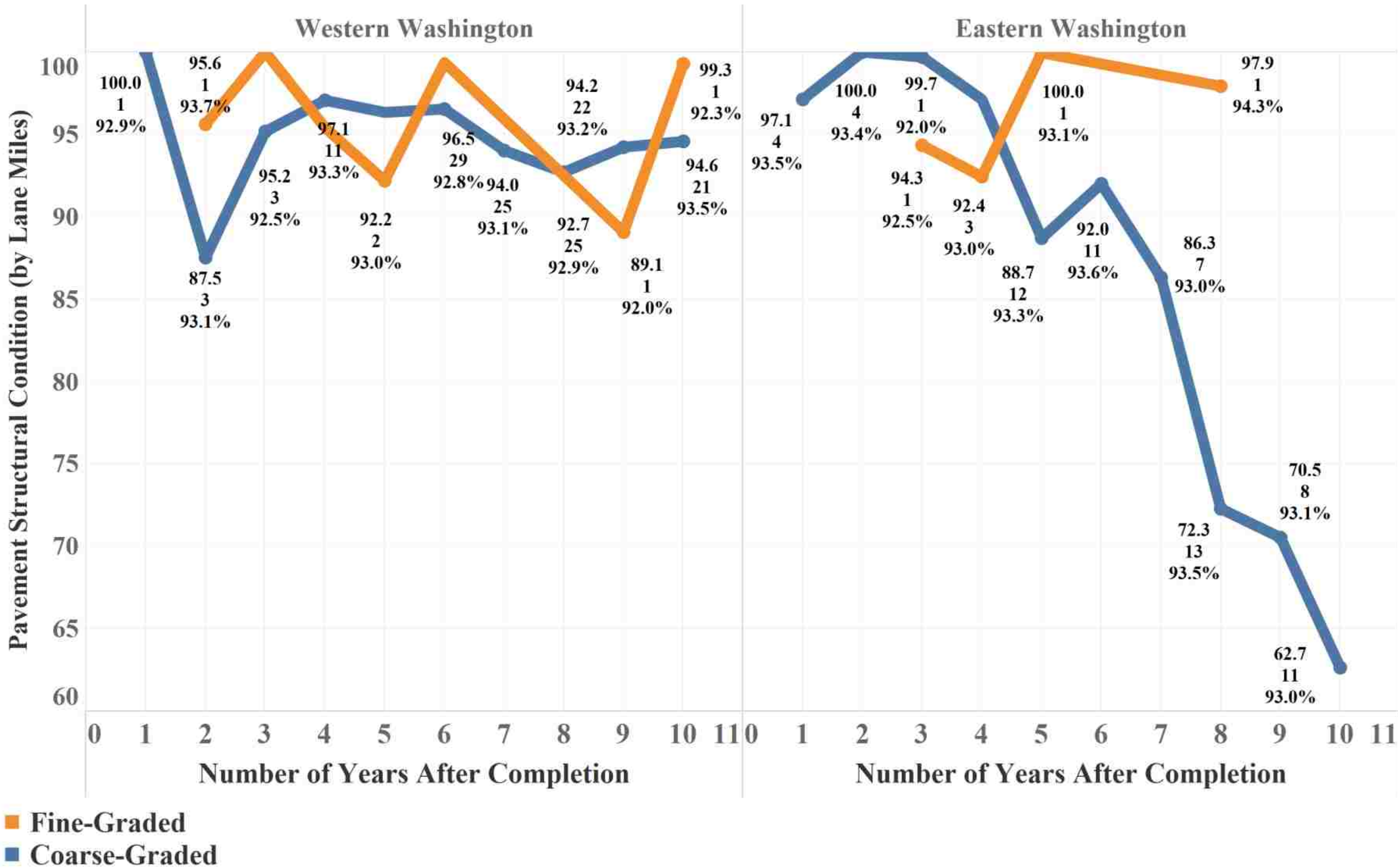


Figure 49. Average Weighted Pavement Structural Condition by Tons of Mix, Location, Number of Contracts, and Average Weighted Density for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PSC (Top), Number of Contracts (Middle), Density (Bottom)]

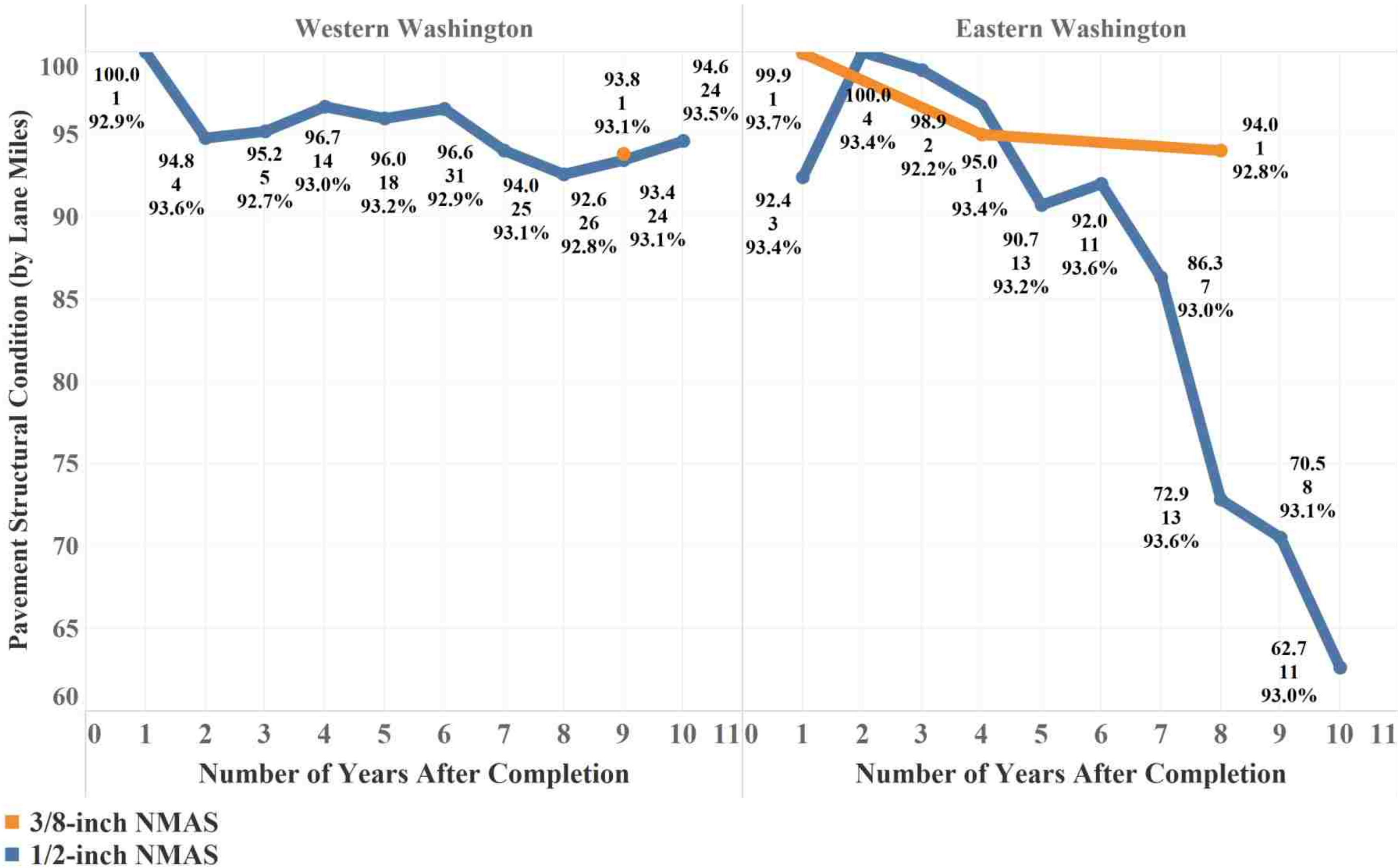


Figure 50. Average Weighted Pavement Structural Condition by Tons of Mix, Location, Number of Contracts, and Average Weighted Density for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PSC (Top), Number of Contracts (Middle), Density (Bottom)]

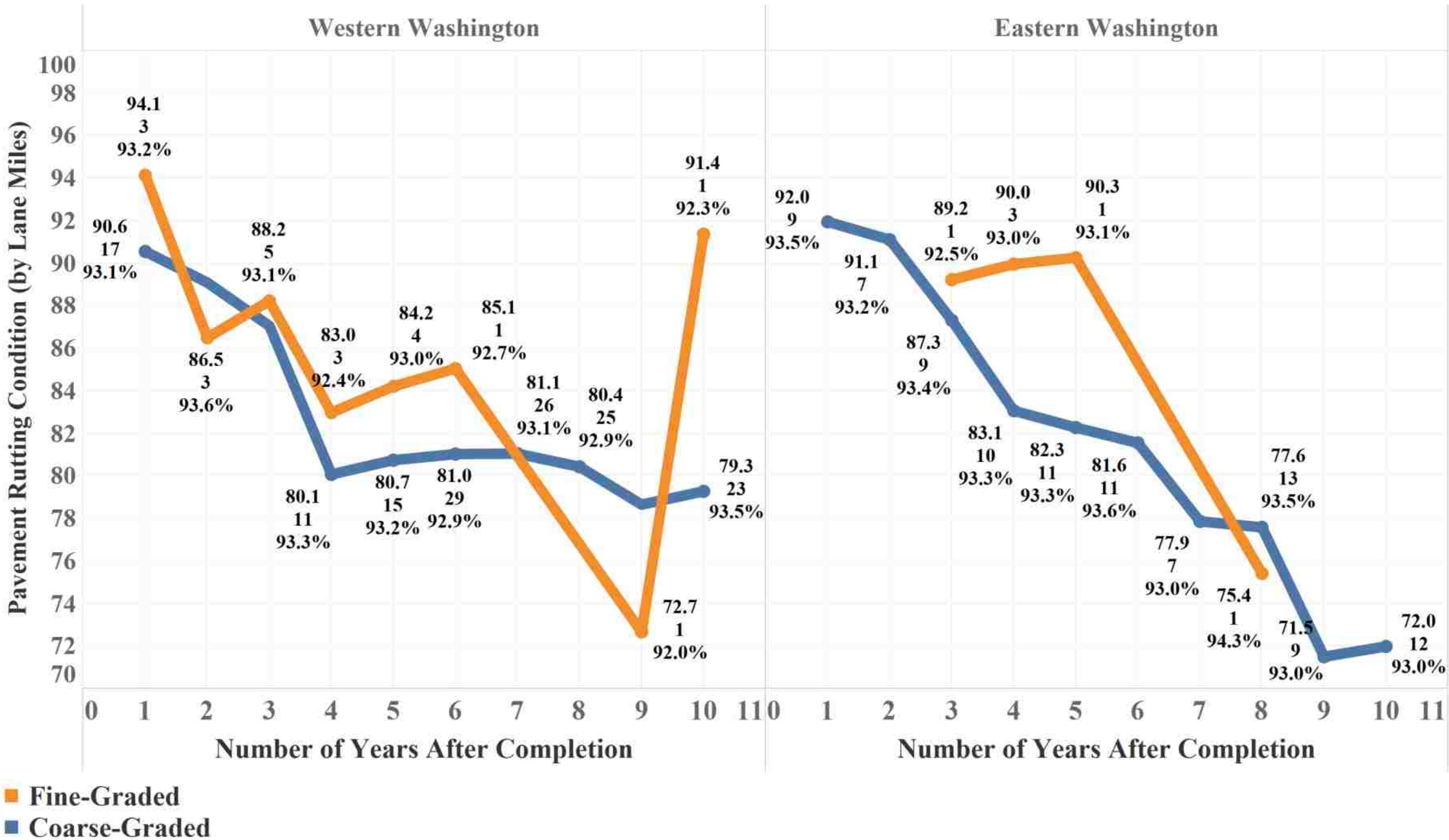


Figure 51. Average Weighted Pavement Rutting Condition by Tons of Mix, Location, Number of Contracts, and Average Weighted Density for Fine-Graded and Coarse-Graded WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PRC (Top), Number of Contracts (Middle), Density (Bottom)]

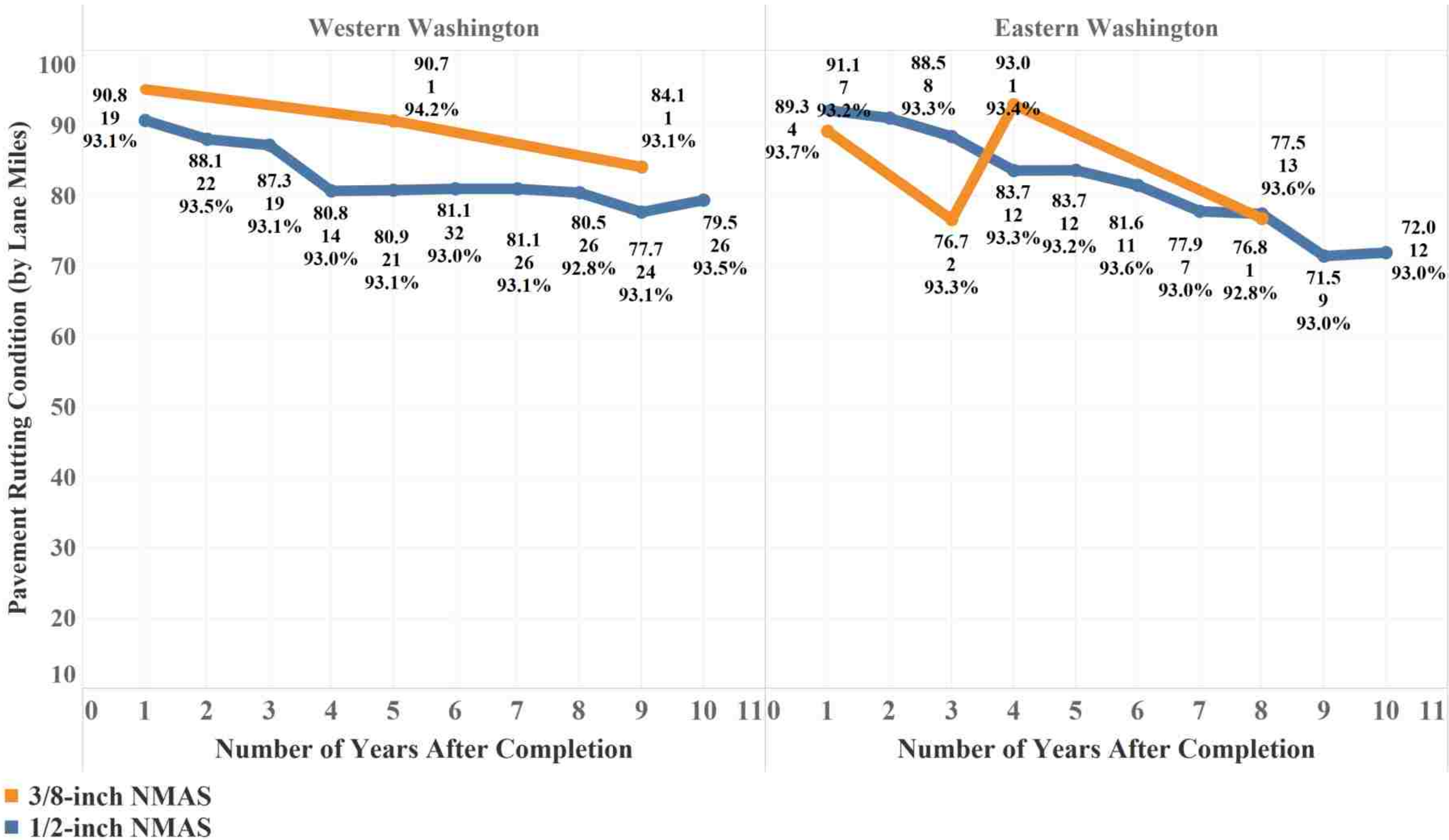


Figure 52. Average Weighted Pavement Rutting Condition by Tons of Mix, Location, Number of Contracts, and Average Weighted Density for 3/8-inch and 1/2-inch NMAS WSDOT Asphalt Pavement Mixtures, 2007 to 2016 [Data Labels: PRC (Top), Number of Contracts (Middle), Density (Bottom)]

Chapter 5. Performance of High Reclaimed Asphalt Pavement Mixtures in Washington State

5.1 Preface

The in-service pavement data approach introduced in Chapter 1 describes using cost, mix design, construction, and performance data to inform pavement specifications and policy. This chapter uses the approach with preselected analysis parameters to analyze the linkage of high-reclaimed asphalt pavement (RAP) mixtures and field performance of Washington State Department of Transportation (WSDOT) pavements. Mixtures containing more than 20% RAP by weight are termed "high-RAP" mixtures because 20% is the WSDOT threshold for adding testing and specification for RAP-containing mixtures. Because high-RAP mixtures are relatively new and long-term performance is unknown, the field performance of high-RAP pavements is of particular interest to WSDOT. WSDOT awarded 35 contracts between 2013-2017 (about 33% RAP per contract, 11% of contracts, and 11% of tonnage during this time). Findings from the research indicate that high-RAP mixtures perform similarly to virgin RAP mixtures with increased rutting resistance; however, "premature cracking" is a concern (Stroup-Gardiner 2016; Timm et al. 2016; West 2009).

This study will be submitted to a peer-reviewed journal, possibly as part of the University of Nevada-Reno's laboratory efforts supporting the WSDOT RAP Reset research effort.

5.2 Abstract

This paper investigates the performance of Washington State Department of Transportation (WSDOT) asphalt mixtures that contain over 20% reclaimed asphalt pavement (RAP) completed between 2013 and 2017 using cost, mix design, field quality assurance, and field pavement management system data. Mixtures containing more than 20% RAP by weight are termed "high-RAP" mixtures because 20% is the WSDOT threshold for adding testing and specification for RAP-containing mixtures.

Current in-service pavement data do not show differences in cracking and rutting performance between high-RAP mixtures and those containing lower amounts of RAP. While the number of WSDOT high-RAP mixtures is limited (35 of 322 mixtures, ~11%, with about 33% RAP per mixture between 2013-2017) there may be some early but unverifiable trends

developing. The construction bid price of high-RAP mixtures slightly exceeds up-to-20%-RAP mixtures by about $5 per ton, likely attributable to the more expensive urban setting in which high-RAP mixtures tend to be used. High-RAP mixture density (93.06%) is slightly lower than up-to-20%-RAP mixtures (93.25%) by about 0.2%.

Author keywords: Asphalt; Pavement; RAP; Performance; Mix Design; Construction; Pavement Management System; Quality Assurance.

5.3 Introduction

Since 1991, the Washington State Department of Transportation (WSDOT) has allowed the use of up-to-20% reclaimed asphalt pavement (RAP) in mix designs without any additional testing (Uhlmeyer 2009). With the first contracts completed in 2013, WSDOT has allowed the use of RAP mixtures beyond 20% by weight ("high-RAP") subject to additional testing and controls. While the pavement community has long accepted asphalt mixtures containing RAP as performing equal to those without (Timm et al. 2016; West 2009), some recent work (Stroup-Gardiner 2016) suggests that mixtures containing higher RAP percentages may not perform as well in some areas (e.g. cracking resistance). This paper describes an investigation of WSDOT's in-place high-RAP mixtures as part of a larger study on RAP mixture performance.

5.3.1 *Research scope and objectives*

This paper compares WSDOT high-RAP pavements to up-to-20%-RAP pavements using linked cost, pavement management system (PMS), mix design, and field quality assurance (QA) data. To supplement this data, this paper gathers industry perspectives from WSDOT staff and Washington Asphalt Pavement Association (WAPA) members through the use of a survey and interviews. The paper asks the following questions:

1) How does the measured field performance data compare with published literature on the relationship between high-RAP and long-term performance?
2) Are there any measured mixture or field parameters [e.g. density, asphalt, voids in mineral aggregate (VMA), etc.] that show an identifiable relationship to field performance between high-RAP and up-to-20%-RAP mixtures?

The hypothesis is that high-RAP mixtures are less expensive and have a similar service life in comparison to up-to-20%-RAP mixtures based on lower virgin asphalt in the mix and similar cracking/rutting resistance. The first accessible records of WSDOT's completed high-RAP mixtures are available beginning in 2013. To test the hypothesis, this paper analyzes the following cost, performance, mix design, and QA components of high-RAP and up-to-20%-RAP mixtures placed on the WSDOT road network from 2013 to 2017:

- Construction cost per ton (adjusted for inflation) of mixtures;
- Cracking and rutting versus density of mixtures with pavement age;
- In-place density of mixtures with pavement age;
- Asphalt content of mixtures with pavement age;
- Voids in mineral aggregate (VMA) of mixtures with pavement age.

5.3.1.1 **Potential use of large linked field and performance data sets**

The WSDOT pavement data sets used in the study are: (1) Unit Bid Analysis, (2) Washington State PMS (WSPMS), and (3) Statistical Analysis of Materials (SAM) for contracts completed between 2013 and 2017. A description of each data set is included in later sections. While processing, integration, and analysis of these in-service pavement data sets is done manually for this paper (~1,500 person-hours), recent advances in data storage capabilities can automate such efforts. This work demonstrates how a large amount of linked field and performance data over a five-year period can be used and provides insight into the data's abilities, limitations, and value. Further, these linked data sets can be used to better understand the relationship between actual in-service performance and cost, mix design, and construction variables. Since this type of data is subject to numerous unmeasured variables and some differences in field measured data, interpretation and feedback from WSDOT and industry are used to provide further insight into observed trends.

5.3.2 ***Overview of reported benefits of high-RAP mixtures from the literature***

Most of the literature indicates that high-RAP mixtures are potentially cheaper and performance is similar to lower RAP mixtures with an increased rutting resistance; however, some of the high-RAP mixture analyses exhibited reduced cracking performance (Stroup-Gardiner 2016; Timm et al. 2016).

5.3.2.1 **High-RAP cost savings**

High-RAP mixtures can be cheaper because they require less aggregate and asphalt binder. Material expenses comprise about "70% of the asphalt mixture cost" (excluding "plant production, transportation, and placement") (Stroup-Gardiner 2016). The use of RAP can generate cost savings because it reduces the amount of aggregate and asphalt binder, the highest cost material (Stroup-Gardiner 2016).

5.3.2.2 **High-RAP performance**

High-RAP mixtures perform similarly to lower RAP mixtures but decreased cracking performance is a concern. Higher amounts of RAP in mixtures present “concerns about overly stiff mixtures resulting from aged binder that could contribute to premature cracking” (Timm et al. 2016). At a design air voids of 4%, “increasing aggregate specific surface while increasing minimum VMA will improve both fatigue resistance and rut resistance” (Christensen and Bonaquist 2006). The research below represents a sampling of the high-RAP analyses in the literature.

- **National Center for Asphalt Technology (NCAT).** An NCAT comparative study synthesized Long Term Pavement Performance (LTPP) data and revealed that high-RAP mixtures (at least 30% in this case) exhibited similar or higher performance to virgin mixtures (West 2009). Another NCAT study of mixtures with 50% RAP exhibited similar or higher performance in comparison to virgin mixtures on the Pavement Test Track (Timm et al. 2016).
- **Florida DOT.** An analysis of projects completed between 1991 and 1999 with mixtures containing 30% to 50% RAP indicates cracking as the primary performance issue (Stroup-Gardiner 2016). Using the same data for mixtures with at least 5,000 tons and available traffic data, the high-RAP mixture performance was mostly superior to the virgin mixtures (Stroup-Gardiner 2016).
- **Iowa DOT.** A high-RAP analysis of three HMA mixtures (30%, 35.5% and 39.2%) revealed that the mixture with the highest RAP initially exhibited a higher cracking performance; however, after about two years the three mixtures performed comparably (Van Winkle et al. 2017).
- **Minnesota DOT.** The Minnesota DOT discovered that the inclusion of RAP decreases rutting; however, about a third of the projects experienced premature cracking (32%) and raveling (39%) (Stroup-Gardiner 2016). Additionally, the projects also exhibited construction issues such as “globs of oil and fines” in the pavement, overly rigid mixtures as well as inconsistencies in the mix (Stroup-Gardiner 2016).

5.3.2.3 **Asphalt content**

In terms of RAP's impact on asphalt content contribution, one study concluded that RAP led to a "significant contribution about 80% of the time, but only partial to little contribution 20% of the time" (Stroup-Gardiner 2016).

5.3.2.4 **VMA**

Stroup-Gardiner (Stroup-Gardiner 2016) described mixed findings on the impacts of increasing recycled material and VMA, "some studies report decreases in VMA with increasing percentages of recycled material … , whereas other studies have reported opposite trends."

5.3.3 ***Relevant WSDOT specifications***

- **High-RAP specifications.** For mixtures containing more than 20% RAP by weight of HMA, WSDOT requires a separate high-RAP stockpile that meets asphalt content and gradation standards (WSDOT 2018d). WSDOT also requires a test section to achieve a pay factor of at least 0.95 for gradation, asphalt binder, VMA, and air voids. Additionally, the test section must also meet the additional test requirements for Hamburg Wheel Track, Indirect Tensile Strength, aggregates, sand equivalent, uncompacted void content, and fracture (WSDOT 2018d).
- **NMAS and VMA specifications.** WSDOT specifications establish a minimum VMA for each NMAS, 15% for 3/8-inch NMAS and 14% for 1/2-inch NMAS. VMA was not subject to bonus or penalty pay from 2013 to 2017 (WSDOT 2018d).
- **Asphalt content.** From 2013 to 2017, WSDOT's specifications required an asphalt content tolerance of ± 0.5% from the approved Job Mix Formula (JMF) (WSDOT 2018d).
- **Density specifications.** From 2013 to 2017, WSDOT's specifications required a lower specification limit of 91% of theoretical maximum density as measured by the core calibrated nuclear gauge (WSDOT 2018d).

5.4 Method

5.4.1 ***Data collection and processing***

This study collects and processes data from the following WSDOT data sources: (1) Unit Bid Analysis, (2) WSPMS, (3) SAM, and for contracts completed between 2013 and 2017. The Unit Bid Analysis data (construction bid price), WSPMS data (performance), and SAM data (density, asphalt content, and VMA) allow the analysis to compare the published literature on high-RAP mixtures with WSDOT's actual mix design and field data. Once collected, the analysis processes the data from each source by linking the data using contract number and sometimes mix design and lot number. The analysis only use 1/2-inch and 3/8-inch mixtures, excluding a small subset of other mixtures (e.g. no NMAS). Each analysis excludes most bridge deck and all chip seal contracts; however, four of the bridge deck contracts with field density and large tonnage data were retained. The data subsections describe the calculations for each component. All of the statistical tests (i.e. t-tests, linear regression, etc.) are parametric and assume that the distribution of the populations are normal. Table 8 provides a summary of the number of high-RAP and up-to-20%-RAP contracts, high-RAP percentage, lane miles, and tons of mix by data source from 2013 to 2017.

The general calculation approach for cost, condition, density, asphalt content, and VMA in this paper uses tons of mix per contract or lane miles per contract to weight each contract's data. This method reduces unwanted bias towards contracts with a small/large tonnage size or contracts with a small/large number of lane miles measured. Also, by aggregating the data by contract, this approach tracks the condition data by location.

Table 8. Number of High-RAP and Up-to-20%-RAP Contracts by Location, Lane Miles, and Tons of Mix by Data Source [density, asphalt content, PSC (Pavement Structural Condition), and PRC (Pavement Rutting Condition)] for WSDOT Asphalt Pavement Mixtures Completed Between 2013 and 2017

Parameter	Cost	PSC	PRC	Density	Asphalt Content	VMA
Total Contracts	322	55	134	247	246	234
Average Contracts Per Year	64	14	34	49	49	45
High-RAP Contracts	35	6	22	37	37	36
High-RAP %	33.3%	35.6%	33.7%	33.3%	33.3%	33.5%
Fine-Graded Contracts	N/A	3	7	14	14	13
Coarse-Graded Contracts	N/A	3	15	23	23	22
9.5-mm NMAS Contracts	3	0	0	3	3	3
12.5-mm NMAS Contracts	32	6	22	34	34	32
Eastern Washington Location Contracts	5	2	3	N/A	N/A	N/A
Western Washington Location Contracts	30	4	19	N/A	N/A	N/A
Up-to-20%-RAP Contracts	287	49	112	210	209	199
Fine-Graded Contracts	N/A	6	11	29	31	28
Coarse-Graded Contracts	N/A	34	82	171	177	171
3/8-inch NMAS Contracts	42	4	13	19	22	18
1/2-inch NMAS Contracts	245	45	99	191	187	181
Eastern Washington Location Contracts	111	26	47	N/A	N/A	N/A
Western Washington Location Contracts	176	23	65	N/A	N/A	N/A
Total Lane Miles	N/A	346	1,351	N/A	N/A	N/A
Average Lane Miles Per Year	N/A	86	135	N/A	N/A	N/A
Total Tons of Mix	3.2M	N/A	N/A	3.6M	4.4M	351K
Average Tons of Mix Per Year	641K	N/A	N/A	715K	883K	70K

#N/A: data not available or not used in the analysis

5.4.2 *Cost*

The cost analysis uses historical cost data on WSDOT's Unit Bid Analysis web page to explore the construction bid price per ton for HMA contracts awarded between 2013 and 2017 in comparison with published on high-RAP and cost (WSDOT 2018c). This data provides the bid history for WSDOT's standard bid items (WSDOT 2018c). To gather this data, the analysis completes a standard item search of HMA between 2013 and 2017. The analysis uses key fields which include the contract numbers, WSDOT standard item numbers, WSDOT region, low bid costs, planned quantity (tons), average weighted low bid (Eq.(31)), and inflation factor (Eq.(32)). The WSDOT regions determined the location of the contract (Eastern and Western Washington). Eastern Washington includes the Eastern, North Central, and South Central regions while Western Washington includes the Northwest, Olympic, and Southwest regions (Wen et al. 2016). All of the costs are adjusted to reflect 2017 U.S. dollars.

The statistical analysis performs a t-test for two independent samples on each contract's average weighted low bid by NMAS per year. The analysis only includes the primary HMA items, 3/8-inch and 1/2-inch NMAS. It does not include the HMA standard items for preleveling, pavement repair, and approach categories.

$$\text{Average Weighted Low Bid} = \frac{1}{P}\sum_{i=1}^{N} b_i * p_i \tag{31}$$

$$\text{Annual Inflation Factor} = \frac{\text{2017 Average Weighted Low Bid}}{\text{Annual Average Weighted Low Bid}} \tag{32}$$

where,

subscript $i \in \{1, \ldots, N\}$ denotes contract i out of N total contracts,

b_i = low bid for contract i (2017 U.S. dollars),

p_i = total planned HMA weight (tons) for contract i, and

P = sum of planned HMA weight (tons) across all N contracts.

5.4.3 *Pavement condition*

The WSDOT WSPMS database uses three indices to describe pavement condition which includes structural, rutting, and roughness condition data. This analysis focuses on structural and rutting condition index values, not roughness index values since roughness is typically a lagging indicator of cracking (Li et al. 2004). The index values of structural and rutting condition values do not account for raveling. Uhlmeyer et al. (2016) and Wen et al. (2016) describe these indices (see below) and the index scale ranges from 0 (very poor) to 100 (very good). An index value of 45 to 50 triggers a pavement rehabilitation requirement (Uhlmeyer et al. 2016).

- **Pavement Structural Condition (PSC).** PSC is a cracking index that accounts for longitudinal, transverse, and alligator cracking as well as patching (Uhlmeyer et al. 2016; Kay et al. 1993). Generally, "top-down cracking is a common distress mode" for HMA pavements in Washington State particularly for pavements thicker than about 6.3 inches (Uhlmeyer et al. 2000). Of the 55 contracts with cracking data, the average total pavement thickness is about 8.7 inches and 46 of 55 contracts (~84%) have a total pavement thickness greater than about 6.3 inches. The rehabilitation trigger index value of 50 represents about "10% equivalency cracking (EC) in the wheelpaths" (Wen et al. 2016; Uhlmeyer et al. 2016; Kay et al. 1993). "Equivalency cracking" represents the amount of "alligator, longitudinal, transverse cracking and patching", see Eq. (33) (Kay et al. 1993). WSPMS does not include a PSC index for HMA that is three years old or less from 2011 to the present (Uhlmeyer et al. 2016). Because of this, the number of contracts with a PSC value is less than the number of PRC contracts (Table 8).

$$PSC = 100 - 15.8 \text{ x } (\text{EC})^{0.5} \quad (33)$$

- **Pavement Rutting Condition (PRC).** PRC is a rutting index (Uhlmeyer et al. 2016; Wen et al. 2016). Rutting index ratings of 75, 50, and 25 translate to a rutting depth of about 0.20 inches, 0.35 inches, and at least 0.55 inches, respectively (Pierce et al. 2001).

The WSPMS condition analysis uses a data extraction for contracts completed between 2013 and 2016 which only includes surface data (Table 8). The analysis uses the condition results to compare with published literature on high-RAP and performance. The condition analysis excludes 2017 data (pavement age of zero) and removes contracts using other mixtures (3/4-inch NMAS, open-graded friction course, cold in-place recycling, hot in-place recycling, and class A). The cracking and rutting performance analyses use contract number, completion year, NMAS, WSDOT region, contract age (Eq.(34)), lane miles (Eq.(35)), and average weighted condition value (Eq.(36)).

$$\text{Number of Years After Contract Completion (i.e. Contract Age)} = 2017 - Y_i \quad (34)$$

$$L_i = \sum_{k=1}^{Q_i} \lambda_{i,k} \tag{35}$$

$$(CV)_i = \frac{1}{L_i} \sum_{k=1}^{Q_i} (\lambda_{i,k}) * (SCR)_{i,k} \tag{36}$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Y_i = completion year of contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(CV)_i$ = average weighted condition value of contract i, and

$(SCR)_{i,k}$ = section condition rating of segment j in contract i.

A paired t-test is performed for high-RAP and up-to-20%-RAP condition results to determine if the difference between the average PSC and PRC condition values per year from 2013 to 2016 is statistically significant. In the paired t-test, one expects the means to be very close in the early years as both pavements are performing well. As the pavements age, they might begin to separate. As a result, the paired t-test is not a very strong indicator of anything if the null is not rejected. A paired t-test measures the difference between paired sets of numbers and has no way of accounting for the growth in difference over time. Additionally, the statistical analysis performs a t-test for two independent samples on the average weighted condition by age. A linear regression is also performed to determine the R^2 coefficient of high-RAP/up-to-20%-RAP, average weighted condition, and contract age.

Contract region was extracted manually from the online WSPMS (not included in the WSPMS extraction) to determine the location of the contract (Eastern and Western Washington). Figure 53 shows the location of the WSPMS contracts by RAP mixture covering all six WSDOT regions. Table 8 identifies the number of contracts by location.

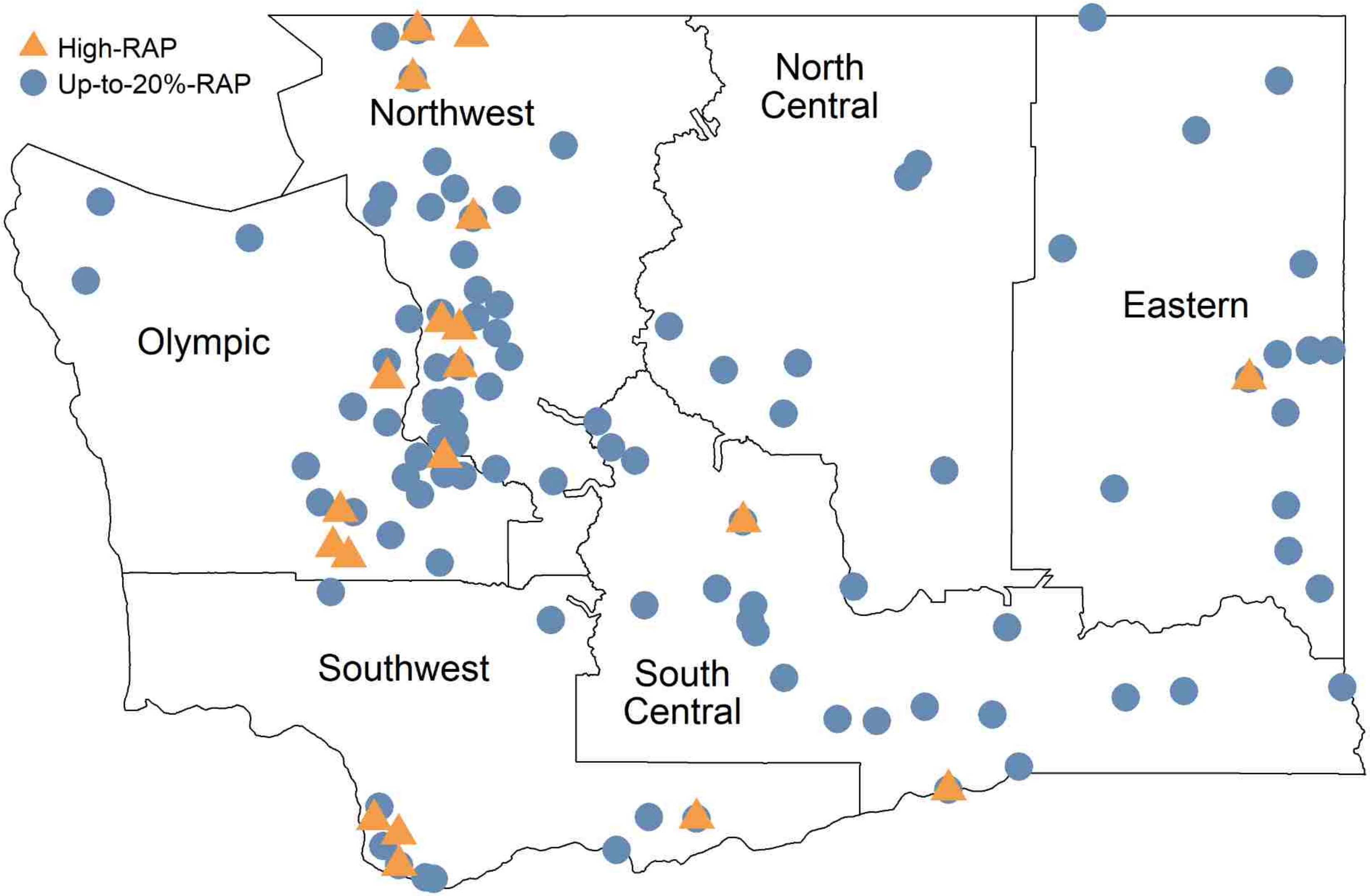


Figure 53. High-RAP and Up-to-20%-RAP WSPMS Contracts by WSDOT Region for Asphalt Pavement Mixtures Completed Between 2013 and 2016

5.4.4 ***Density***

WSDOT uses an in-house system, SAM, to store QA data which includes contract statistical evaluation, pay factor, and some mix design data for each HMA parameter. This paper uses field density data extracted from SAM data for HMA contracts completed between 2013 and 2017 to compare with published literature on density and RAP. The density analysis integrates the data using contract and mix design numbers, removing contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). The analysis uses contract age (Eq.(34)), total contract sample size (Eq.(37)), and average weighted density (Eq.(38)). Additionally, a statistical t-test for two independent samples is performed on the average weighted density. The density analysis also tracks all contracts that do not meet WSDOT specifications.

$$\text{Total Contract Sample Size (tons)} = \sum_{i=1}^{N} \sum_{j=1}^{M_i} s_{i,j} \tag{37}$$

$$\rho_i = \frac{1}{S_i} \sum_{j=1}^{M_i} (d_{i,j}) * (s_{i,j}) \tag{38}$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

M_i = total distinct number of mix designs included in contract i,

N = total number of contracts,

ρ_i = average weighted density of contract i,

$d_{i,j}$ = field density of mix design j of contract i,

$s_{i,j}$ = sample size of mix design j of contract i, and

S_i = sample size of contract i, summed across all M_i contracts.

5.4.5 ***Asphalt content***

This analysis uses WSDOT's SAM database to investigate field measured asphalt content, comparing the results with published literature on RAP and asphalt content. The analysis integrates the data using contract and mix design numbers for contracts, removing contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). The analysis uses contract age (Eq.(34)), total contract sample size (tons) (Eq.(37)), average weighted asphalt content per contract (Eq.(39)), average weighted JMF difference (Eq.(40)), and average

JMF difference (Eq.(41)). Additionally, a statistical t-test for two independent samples is performed on the average weighted asphalt content. The statistical analysis also performs a linear regression on the average weighted density and the average weighted asphalt content. The JMF difference is also used to determine contracts not within WSDOT asphalt specifications.

$$(AWAC)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (AC)_{i,j} \quad (39)$$

$$(AWJMF)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (JMF)_{i,j} \quad (40)$$

$$(\Delta JMF)_i = (AWAC)_i - (JMF)_i \quad (41)$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$AWAC_i$ = average weighted asphalt content of contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts,

$AC_{i,j}$ = asphalt content of mix design j in contract i,

$JMF_{i,j}$ = Job Mix Formula (JMF) of mix design j in contract i,

$(AWJMF)_i$ = average weighted JMF of contract i, and

$(\Delta JMF)_i$ = Job Mix Formula (JMF) difference for contract i.

5.4.6 ***Voids in mineral aggregate (VMA)***

This analysis uses WSDOT’s SAM database to investigate the field measured VMA, comparing the results with published literature on RAP and VMA. The analysis integrates the data using contract and mix design numbers for contracts, removing contracts with an unusable NMAS (no NMAS, 1-inch NMAS, and 3/4-inch NMAS). The analysis uses contract age (Eq.(34)), total contract sample size (tons) (Eq.(37)), and average weighted VMA per contract (Eq.(42)). Additionally, a statistical t-test for two independent samples is performed on the average weighted asphalt content.

$$(AWVMA)_i = \frac{1}{S_i}\sum_{j=1}^{M_i}\left(s_{i,j}\right) * (VMA)_{i,j} \quad (42)$$

where,

subscript $j \in \{1, \ldots, M_i\}$ denotes mix design j in contract i,

$s_{i,j}$ = sample size of mix design j of contract i,

S_i = sample size of contract i, summed across all M_i contracts,

$VMA_{i,j}$ = voids in mineral aggregate of mix design j in contract i, and

$AWVMA_i$ = average weighted voids in mineral aggregate of contract i.

5.4.7 *Contracts not within specifications*

About 99% of the density and asphalt content conformed to WSDOT specifications demonstrating that the pavements are mostly within specifications. Conversely, about half of the contracts did not conform to the VMA specification likely because it was not subject to bonus or disincentive pay.

- **Density.** Two of the 247 (0.8%) contract averages were below the WSDOT 91% minimum density specification. These two contracts were small, about 247 tons total (0.01%), exhibiting little influence overall. Additionally, the contracts out of specification did not correspond to any noticeable decrease in pavement performance;
- **Asphalt Content.** Two of the 246 (0.8%) contract averages were within the WSDOT asphalt content ±0.5% tolerance. All of these contracts were small, about 2,100 tons total (0.05%), exhibiting little influence overall. The contracts with out of specification asphalt content averages did not correspond to any noticeable decrease in pavement performance;
- **VMA.** Overall, 111 of 234 (47%) of these contracts fall below the minimum WSDOT VMA specification.

5.4.8 *Survey and interviews*

This section describes how the paper uses a survey and interviews to provide additional interpretation and feedback of the data analyses in the preceding sections.

5.4.8.1 WAPA survey

A general survey given to 37 WAPA members from 14 companies (11 asphalt producers, 2 subsidiaries and 1 asphalt testing laboratory) in Washington State provides industry perspective. In partnership with WAPA and WSDOT, the survey asks local participants to offer interpretation, feedback, and common industry reasons in support of the pavement data results. The survey contains 24 questions on a variety of asphalt topics including two relevant RAP related questions (see below). The useful survey response rate, the total number of surveys taken, complete or not, included 18 of 37 individuals (49%).

1. What are the barriers to increasing RAP percentage (over 20%) when producing asphalt mixtures?
2. What is your best estimate of average asphalt binder content (%) and average binder grade of your RAP?

5.4.8.2 WAPA interviews

Interviews with seven WAPA and nine WSDOT people, averaging about one hour per interview, were used to follow up on the survey. These semi-structured interviews capture specific information on a variety of asphalt topics and were meant to uncover, in a conversational manner, industry and owner sentiment not easily expressed in a short survey (e.g. opinions on mix design, construction practices, performance, etc.). The interviewers generated a set of questions for the WAPA members as well as the WSDOT staff and asked all of the interviewees the same questions to maintain consistency. Using a conversational approach, the interviewers asked additional questions depending on the knowledge of the interviewee.

About 5 to 10 minutes of each semi-structured interview questioned the interviewee about density. The interview topics included volumetrics, lift thickness, stockpiling, performance, permeability, cost, placement, 3/8-inch versus 1/2-inch NMAS, and RAP.

5.5 Results

5.5.1 *Construction bid price*

The average weighted low-bid price per ton of high-RAP mixtures is $89.67 per ton and for up-to-20%-RAP mixtures is $84.64 per ton, a difference of $5.03 per ton. The combined bar and line chart (Figure 54) shows the average weighted low-bid average price for each award year in 2017 dollars and planned quantity in tons by RAP category from 2013 to 2017. Contract prices for all high-RAP and up-to-20%-RAP mixtures from 2013 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between contract price means). Cost results fail to reject the null hypothesis at 95% confidence (p-value = 0.226, 95% confidence interval of difference between the means is -73.217, 17.392).

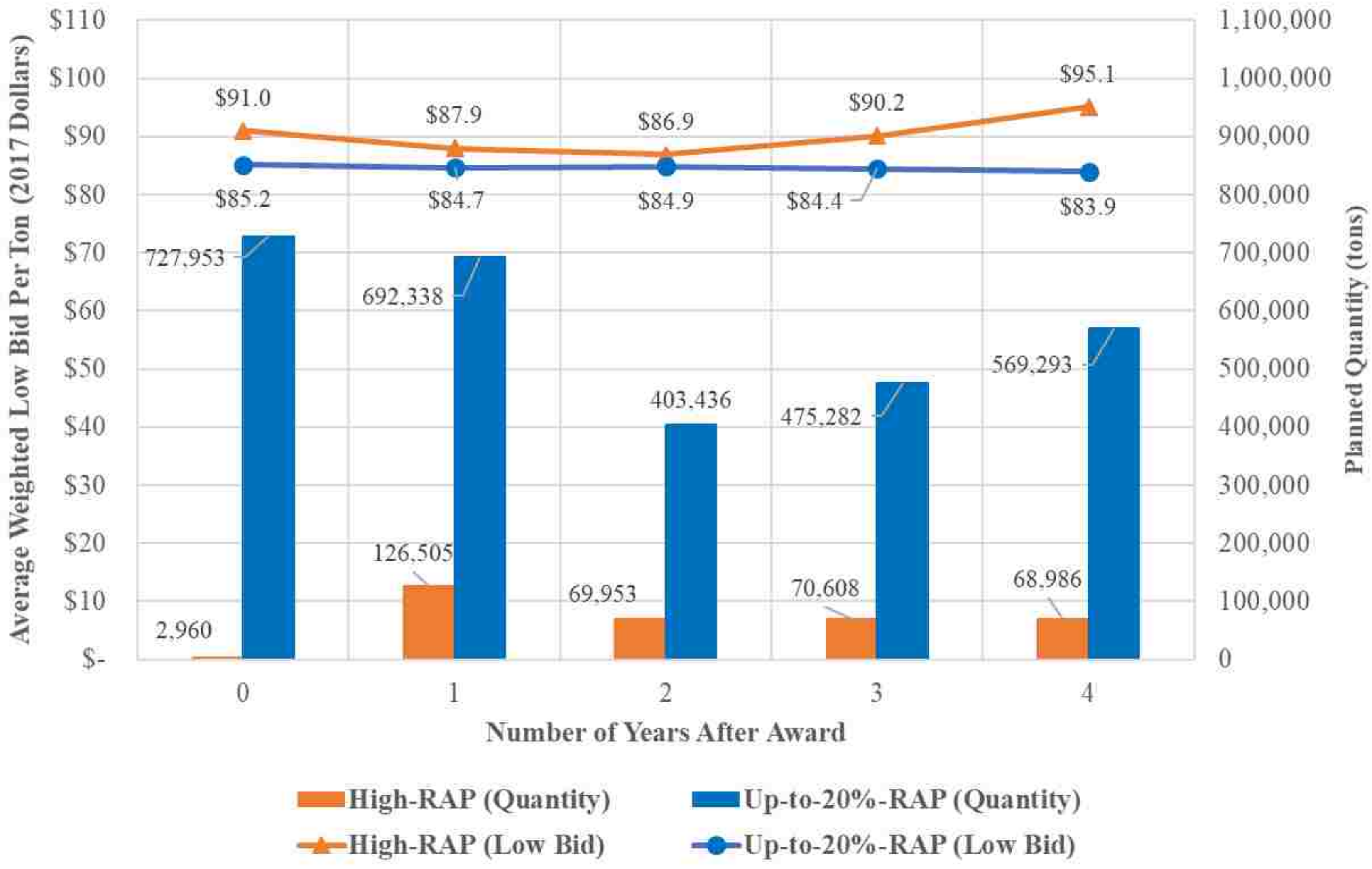


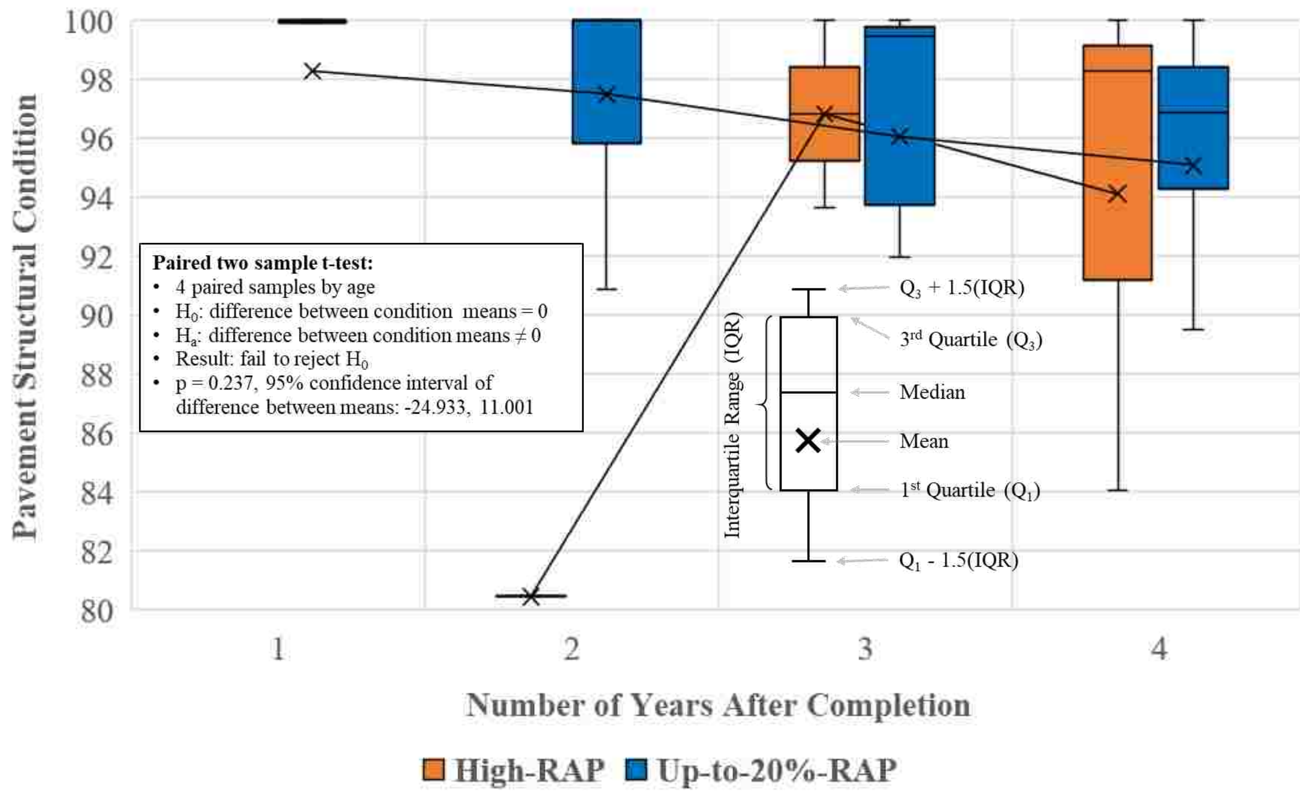
Figure 54. Average Weighted Low Bid Per Ton (2017 Dollars on Line Plots) and Planned Quantity (Tons on Bar Charts) by Number of Years After Award for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2017

5.5.2 *Condition*

5.5.2.1 **Cracking**

The box and whisker plots (Figure 55) show the average weighted PSC, largely a measure of cracking, by contract age for high-RAP and up-to-20%-RAP contracts. Cracking for all high-RAP and up-to-20%-RAP mixtures from 2013 to 2016 were compared using a paired t-test on average weighted cracking values by tons of mix for each age (H_0 = no difference between condition means). Cracking paired t-test results fail to reject the null hypothesis at 95% confidence (p-value = 0.237, 95% confidence interval of difference between the means is -24.933, 11.001). Additionally, cracking for high-RAP and up-to-20%-RAP mixtures were compared using a t-test for two independent samples on the contracts for each age (H_0 = no difference between condition means). At all ages, results for the t-test for two independent samples fail to reject the null hypothesis at 95% confidence. Cracking condition values for each contract by age were compared using a linear regression and results revealed a low R^2 coefficient of 0.038.

Of note, the structural condition for high-RAP contracts with density at two and three years after completion is slightly lower with an average by tons of mix of about 91 (0.31% equivalency cracking in the wheel path) versus about 97 (0.04% equivalency cracking) for up-to-20%-RAP contracts. Additionally, two relatively small high-RAP contracts (two and four years after completion) showed noticeably lower condition values with a PSC of about 80 (1.5% equivalency cracking) and about 84 (1.0% equivalency cracking), respectively (Figure 56).



	Number of Contracts by Years After Completion			
	1	2	3	4
High-RAP	0	1	2	3
Up-to-20%-RAP	5	7	8	29

Figure 55. Average Weighted Pavement Structural Condition and Number of Contracts by Years After Completion for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2016

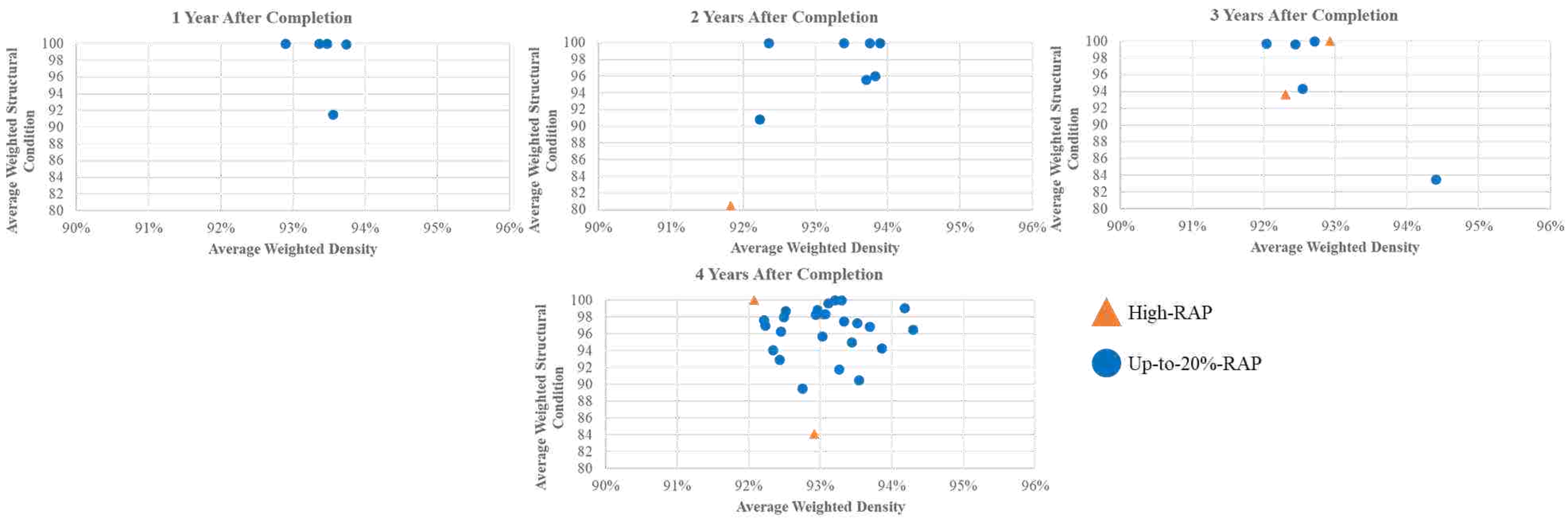
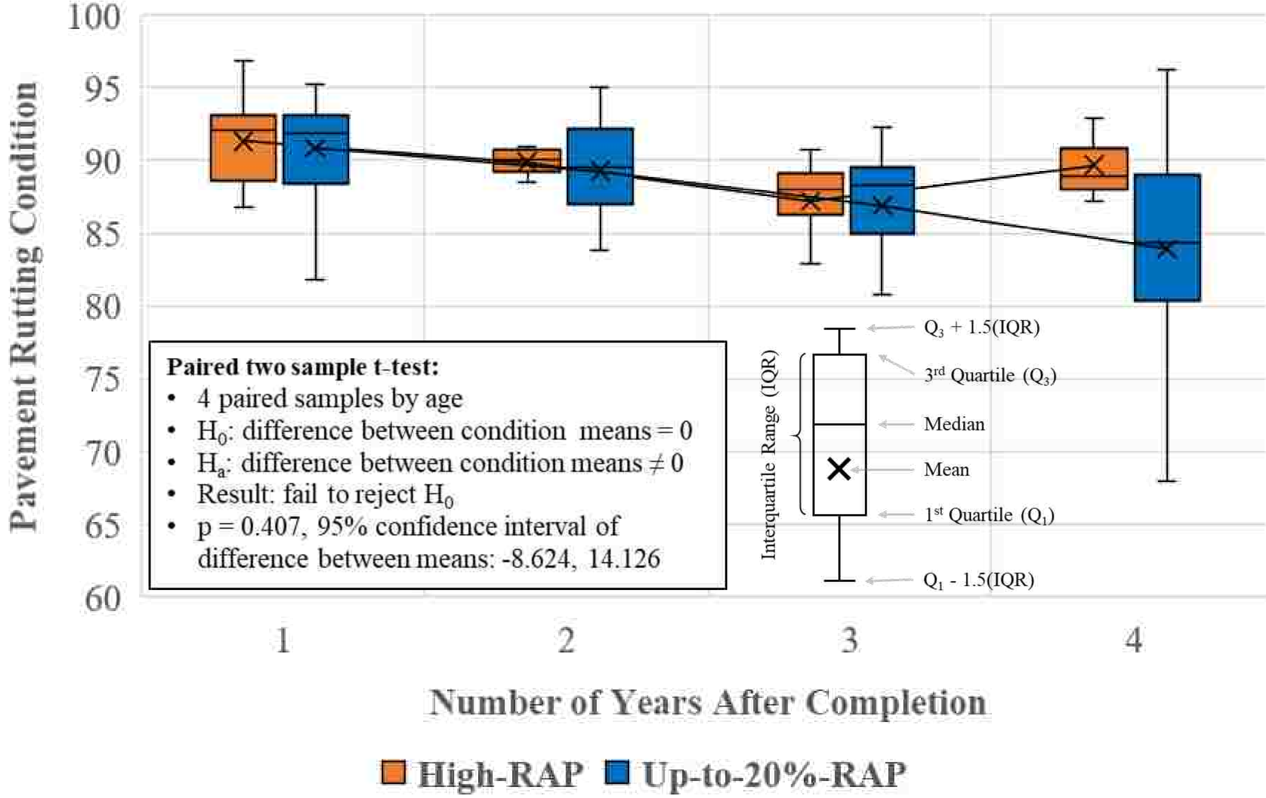


Figure 56. Average Weighted Pavement Structural Condition Versus Average Weighted Density by Number of Years After Completion for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2016

5.5.2.2 **Rutting**

The box and whisker plots (Figure 57) show the average weighted PRC by contract age for high-RAP and up-to-20%-RAP contracts. Rutting for all high-RAP and up-to-20%-RAP mixtures from 2013 to 2016 were compared using a paired t-test on average weighted rutting values by tons of mix for each age (H_0 = no difference between condition means). Rutting paired t-test results fail to reject the null hypothesis at 95% confidence (p-value = 0.407, 95% confidence interval of difference between the means is -8.624, 14.126). Additionally, rutting for high-RAP and up-to-20%-RAP mixtures were compared using a t-test for two independent samples on the contracts for each age (H_0 = no difference between condition means). At all ages, results for the t-test for two independent samples fail to reject the null hypothesis at 95% confidence. Rutting condition values for each contract by age were compared using a linear regression and results revealed an R^2 coefficient of 0.239.

Of note, the rutting condition for high-RAP contracts four years after completion is slightly higher with an average by tons of mix of about 90 (0.08 inches) versus about 82 (0.14 inches) for up-to-20%-RAP contracts. Figure 58 shows that poor rutting performance is not likely to occur with high-RAP contracts.



	Number of Contracts by Years After Completion			
	1	**2**	**3**	**4**
High-RAP	7	4	8	3
Up-to-20%-RAP	30	28	25	29

Figure 57. Average Weighted Pavement Rutting Condition and Number of Contracts by Years After Completion for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2016

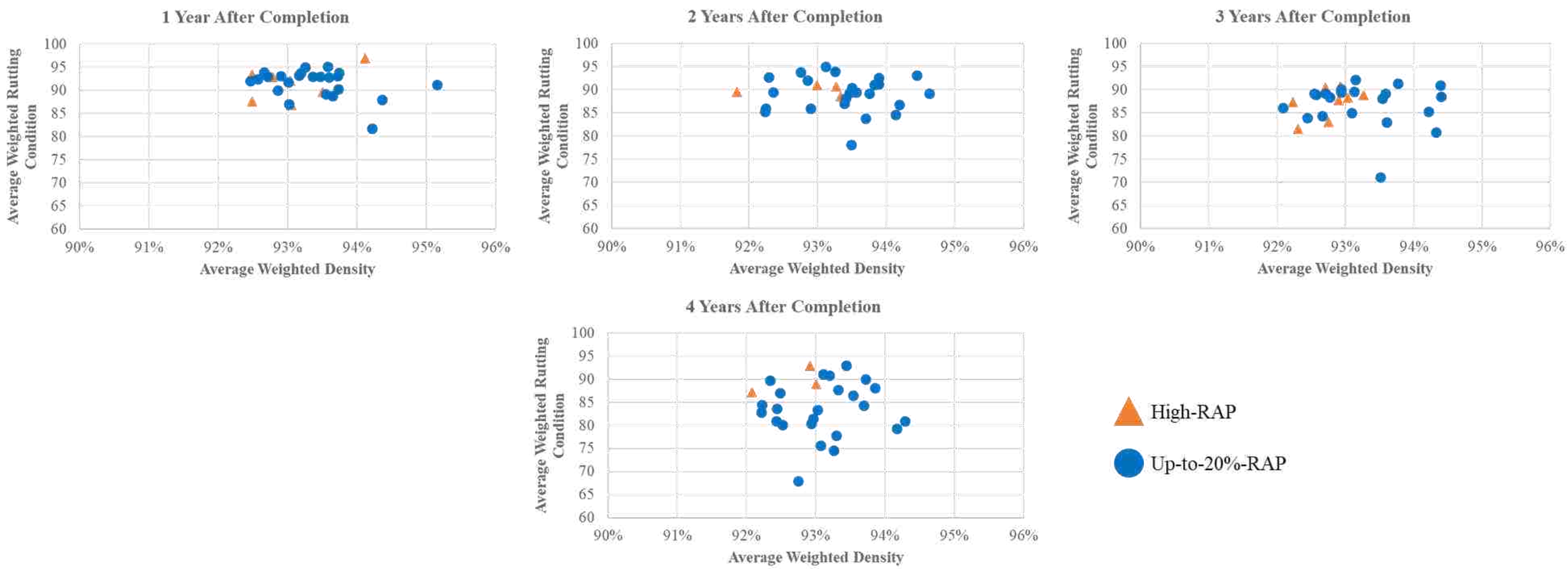


Figure 58. Average Weighted Pavement Rutting Condition Versus Average Weighted Density by Number of Years After Completion for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2016

5.5.2.3 **Older contracts**

Because HMA pavements typically fail or show signs of distress with age, this section explores the data's two oldest years (ages three and four) to identify any apparent trends between the overall condition, the condition of the individual sections, and other field data (e.g. density, asphalt, VMA). Figure 59 and Figure 60 analyze the older high-RAP contracts (three to four years after completion) with density values by showing a histogram of the number of pavement sections versus condition value along with NMAS, gradation, density, VMA, asphalt content, and condition. The data show a lower contract condition is typically driven by an inconsistency in condition values across the contract. The contract data show no apparent trend between condition and density, asphalt content, or VMA.

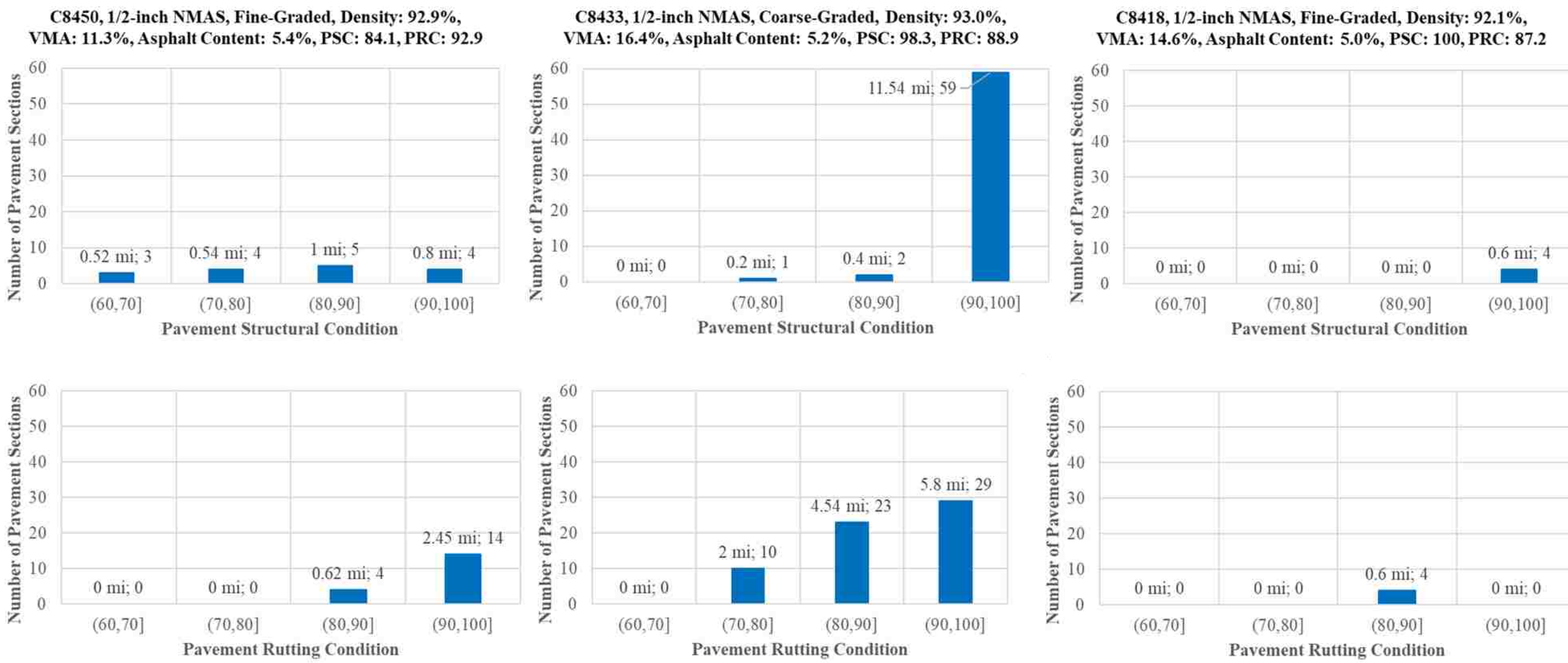


Figure 59. Number of Pavement Sections Versus Pavement Structural Condition and Pavement Rutting Condition for High-RAP Contracts Completed in 2013

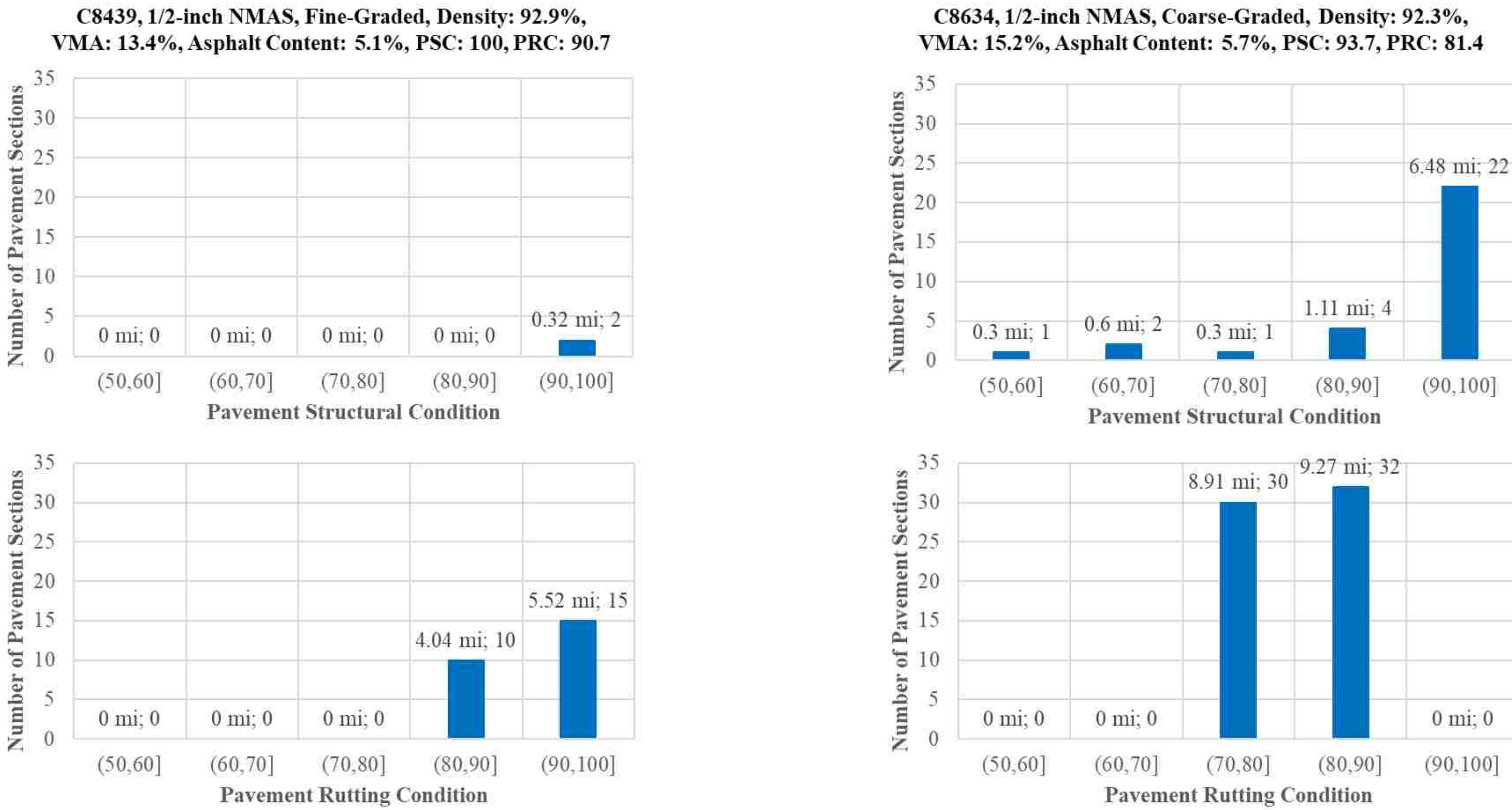


Figure 60. Number of Pavement Sections Versus Pavement Structural Condition and Pavement Rutting Condition for High-RAP Contracts Completed in 2014

5.5.3 *Density*

The overall average weighted density for all mixtures from 2013 to 2017 is 93.23%. The overall average density of high-RAP mixtures is 93.06% and for up-to-20% mixtures is 93.25%, a difference of 0.19%. Density for all high-RAP and up-to-20%-RAP contracts from 2013 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between density means). Density results reject the null hypothesis at 95% confidence (p-value = 0.045, 95% confidence interval of difference between the means is -0.60%, -0.006%). Of note, the high-RAP average density by contract from ages one to three (23 of 37, or 62%, high-RAP contracts) is slightly less than 93% in each of these years. During this time, 15 of 23 contracts (65%) of the high-RAP contracts yield a density less than 93% on average.

5.5.4 *Asphalt content*

The overall average weighted asphalt content for all mixtures from 2013 to 2017 is 5.37%. The overall average weighted asphalt content of high-RAP mixtures is 5.23% and for up-to-20%-RAP mixtures is 5.39%, a difference of 0.16%. Asphalt content for all high-RAP and up-to-20%-RAP contracts from 2013 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between density means). Asphalt content results reject the null hypothesis at 95% confidence (p-value = 0.005, 95% confidence interval of difference between the means is -0.3%, -0.06%). The number of asphalt content sublots below the JMF for the three high-RAP contracts at age four with density and condition data are 3 of 33 (9.1%), 6 of 9 (66.7%), and 6 of 8 (75%). The condition data for the latter two contracts with a high number of sublots below the JMF are 100 (cracking)/87.2 (rutting) and 84.1 (cracking)/92.9 (rutting), respectively.

5.5.5 *VMA*

The overall average weighted VMA for all mixtures from 2013 to 2017 is 14.1%. The overall average weighted VMA of high-RAP mixtures is 13.88% and for up-to-20%-RAP mixtures is 14.11%, a difference of 0.23%. VMA for all high-RAP and up-to-20%-RAP contracts from 2013 to 2017 were compared using a t-test for two independent samples (H_0 = no difference between density means). VMA results fail to reject the null hypothesis at 95% confidence (p-value = 0.321, 95% confidence interval of difference between the means is -0.766%, 0.252%). Of note, 20 of 35 (57%) of the high-RAP contracts and 91 of 199 (46%) of the up-to-20%-RAP contracts fall below the minimum.

5.5.6 *WAPA Survey and WAPA/WSDOT Interviews*

5.5.6.1 **The average estimated asphalt content of WAPA respondents' RAP is about 5.0%**

5.5.6.2 **Meeting mix design requirements is the top barrier to use of high-RAP mixtures**

The top three barriers to WAPA respondents use of high-RAP mixtures include meeting mix design volumetric requirements (25% of respondents), stockpile management (19%) and other (19%). The other barriers identified include inclement weather (e.g. high moisture content of RAP stockpiles after heavy rain), inconsistencies between contractor and WSDOT testing procedures, and WSDOT stockpile management and testing frequency requirements.

5.5.6.3 **About 90% of WAPA respondents do not complete high-RAP projects**

Only 13% of the survey respondents and one of seven WAPA interviewees indicated that high-RAP mixtures were used on WSDOT projects. Some WAPA interviewees indicated that they complete high-RAP mixtures for other agencies (e.g. cities, counties).

5.5.6.4 **High-RAP mixtures incur additional costs**

The only WAPA interviewee with high-RAP mixture experience stated that they incur additional costs because of WSDOT's additional mixture testing and stockpile management requirements. According to the survey, these additional WSDOT requirements represent the top two barriers to using high-RAP mixtures.

5.5.6.5 **High-RAP mixtures present performance concerns**

During the interviews, the WSDOT staff expressed concerns about the potential for high-RAP mixtures to cause an increase in the severity and extent of pavement distresses. Premature cracking is the predominant failure type for high-RAP mixtures due to rigidity and stiffer asphalt binder.

5.6 Discussion

5.6.1 *Limitations*

The purpose of the paper is to use WSDOT field and performance data to characterize the influence of high-RAP mixtures on performance. This method uses actual field data and its usefulness relies on quality data. Also, there are many unmeasured variables (e.g. construction quality, underlying pavement/soil conditions, etc.) that could influence dependent performance variables beyond condition (e.g. asphalt content, density) data. Although industry perspectives can assist in results interpretation, this method is likely to only identify very broad, strong trends and sometimes expected trends are not seen above the noise of unmeasured variables. This paper uses and compares findings from the literature, field data, and industry perspectives. At times, the findings from these sources do not all agree. Additionally, almost all of the high-RAP mixtures came from one contractor and were constructed in Western Washington where mixture prices have been historically higher and pavement life has been historically longer (Wen et al. 2016).

5.6.2 *Limited high-RAP data is available*

Because this paper only includes five years of high-RAP field and performance data, trends that take longer to develop (notably, cracking) may not have had enough time to express themselves fully. The discussion points that follow may change as the high-RAP sections continue to age.

5.6.3 *High-RAP construction costs are about $5 per ton more*

The construction cost analysis weighted by quantity reveals that high-RAP mixtures cost about $89 per ton and the up-to-20%-RAP mixtures cost about $84 per ton, a difference of about $5 per ton. The statistical analysis of the construction bid price by contract of the high-RAP versus the up-to-20%-RAP contracts fails to reject that the difference between the means is zero. The statistical evidence suggests that there is insufficient evidence to conclude that high-RAP contracts produce a different construction bid price than up-to-20%-RAP contracts (Figure 54). This finding conflicts with the literature that high-RAP mixtures are cheaper. A likely explanation for this finding is location. About 64% of all contracts (about 55% of tonnage) and about 88% of high-RAP contracts (about 80% of tonnage) are in Western Washington where the average weighted cost is about $11 per ton higher than Eastern Washington.

5.6.4 *High-RAP mixtures perform similarly to up-to-20%-RAP mixtures*

There is insufficient statistical evidence to conclude that high-RAP contracts produce a different overall average weighted structural and rutting condition than up-to-20%-RAP contracts. However, the cracking data show a couple of the high-RAP with good condition values but are slightly lower than the up-to-20%-RAP contracts at the same age (Figure 55-Figure 56). These contracts are worth monitoring for future analysis. Conversely, the rutting data show that high-RAP contract rutting performance may be trending higher than up-to-20%-RAP contracts for the oldest contracts, age four (Figure 57-Figure 58). During this time, the average weighted rutting for high-RAP mixtures (0.08 inches) is about half of up-to-20%-RAP mixtures (0.14 inches). Given the literature findings, a possible interpretation is that high RAP mixtures perform similarly to or better than virgin RAP mixtures, particularly in terms of rutting resistance. However, because the high-RAP data is limited at this age (three contracts), it is difficult to conclude anything other than the two mixtures are no different.

5.6.5 *Field density is about 0.2% lower for high-RAP mixtures*

The high-RAP mixtures exhibit a slightly higher average weighted field density of 93.06% versus 93.25% for up-to-20%-RAP mixtures, a difference of about 0.2%. The statistical analysis suggests that the difference between these means is statistically significant. Of note, 20 of 37 (55%) high-RAP contracts exhibit a field density of less than 93% versus 78 of 210 (37%) up-to-20%-RAP contracts. This is consistent with the literature that the desired density is sometimes challenging to achieve with high-RAP mixtures, particularly with joint density (Stroup-Gardiner 2016).

5.6.6 *High-RAP asphalt content is about 0.2% higher*

The high-RAP mixtures exhibit a lower average weighted field measured asphalt content of 5.2% versus 5.4% for up-to-20%-RAP mixtures, a difference of about 0.2%. The statistical analysis suggests that the difference between these means is statistically significant. A possible interpretation is that the asphalt content is low for high-RAP mixtures due to a lower than expected contribution from the RAP. A lower asphalt content may lead to increased "raveling and surface cracking" (Christensen and Bonaquist 2006).

5.6.7 *High-RAP VMA is about 0.2% lower*

The high-RAP mixtures exhibit a lower average weighted VMA of about 13.9% versus 14.1% for up-to-20%-RAP mixtures, a difference of about 0.2%. There is insufficient statistical evidence to conclude that high-RAP contracts produce a different overall average weighted VMA than up-to-20%-RAP contracts. Because the literature is unclear on RAP's impact on VMA, it is difficult to determine the lower VMA for high-RAP mixtures. Given the slightly lower density (i.e. higher air voids) of high-RAP mixtures, a possible interpretation of the lower VMA may be due to a lower effective asphalt content potentially caused by a higher amount of fines in the mix. At age four, the data show that the high-RAP contract structural performance may be trending higher with a higher VMA ($R^2 = 0.801$). However, because the high-RAP data is limited at this age (three contracts), it is difficult to conclude anything other than the two mixtures are no different.

5.6.8 *No clear trends link elevated field density and increased performance*

The condition data analysis does not reveal a clear trend between density and cracking/rutting performance; however, the data show increased cracking and rutting with age for all densities (Figure 55-Figure 60). This finding does not align with literature and some survey/interview comments that elevated field density produces increased performance. This does not imply that the literature and survey/interviews are incorrect, but rather there is not available field evidence to support them.

5.7 Conclusion

This paper investigates the impacts of high-RAP mixtures on performance in Washington State by synthesizing WSDOT mix design, QA, and performance data for mixtures completed between 2013 and 2017 as well as relevant industry perspectives. The high-RAP mixtures cost more likely because of location and have not shown significant performance benefits or issues on a statewide level over the last five years. The conclusions are:

- **The construction bid price of high-RAP mixtures slightly exceeds up-to-20%-RAP mixtures by about $5 per ton**;
- **There is no evidence that there is a difference between the cracking and rutting condition means for all mixtures**;
- **High-RAP mixtures have a slightly lower in-place density than up-to-20%-RAP mixtures by about 0.2% on average** (93.06% for high-RAP mixtures, 93.25% for up-to-20%-RAP mixtures);
- **High-RAP mixtures have less asphalt than up-to-20%-RAP mixtures by about 0.2% on average** (5.23% for high-RAP mixtures, 5.39% for up-to-20%-RAP mixtures);
- **High-RAP mixtures have a slightly lower VMA than up-to-20%-RAP mixtures by about 0.2% on average** (13.88% for high-RAP mixtures, 14.11% for up-to-20%-RAP mixtures).

The limited high-RAP data available (only data from the first five years of pavement life) reduces the ability to identify a compelling case that high-RAP mixtures are better or worse than mixtures with less RAP. It may be that performance differences will emerge in later years. The utility of the cost, mix design, field, and performance data method presented in this paper (1) analyzes data over a five-year period of time and (2) uses the data to compare with literature findings and industry perspectives. The numerous variables not analyzed (e.g. paving conditions) necessarily make the standard of proof quite high to show significant differences between high-RAP mixtures and HMA performance. As a result, some analyses (e.g. cracking/rutting performance) showed no significant differences. This does not imply that there are not differences, but rather there is not enough evidence to identify them. Notably, performance reasons for high-RAP mixtures were not universally confirmed nor were they rejected. This could be because of the coarse nature of the comparison or because it is too early in the pavement life to identify significant performance differences.

5.8 Acknowledgments

The authors would like to thank WSDOT and WAPA for their support and contributions to this effort. The views in this paper are those of the authors and do not reflect the official views and policies of WSDOT.

5.9 Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request. The data includes Unit Bid Analysis, SAM, and WSPMS.

5.10 Additional considerations

The preceding narrative, figures, and tables in this chapter approximately meet ASCE journal submission length requirements. This section covers additional in-service pavement data considerations that do not fit the paper length requirements but deserve analysis.

5.10.1 *Traffic load*

Another consideration for high-RAP, up-to-20%-RAP, and performance is the amount of pavement traffic experienced over the pavement life. This section analyzes the number of traffic loading (i.e. equivalent single axle loads, ESALs) in the context of cracking and rutting condition to determine if a higher amount of traffic loading decreases performance. The analysis uses total lane miles (Eq.(35)), number of ESALs after the last major rehabilitation effort, and number of average weighted ESALs per contract (Eq.(43)). The data source for ESALs per lane mile section is the 2017 WSPMS and Table 8 breaks down the number of contracts.

$$(AWESAL)_i = \frac{1}{L_i}\sum_{k=1}^{Q_i}\left(\lambda_{i,k}\right)*(ESAL)_{i,k} \tag{43}$$

where,

subscript $k \in \{1, \ldots, Q_i\}$ denotes segment k in contract i,

Q_i = total number of segments in contract i,

L_i = total lane miles in contract i,

$\lambda_{i,k}$ = total lane miles in segment k of contract i,

$(ESAL)_{i,k}$ = number of ESALs after major rehab of segment j in contract i, and

$(AWESAL)_i$ = average weighted ESAL value of contract i.

5.10.1.1 Cracking condition

The average of ESALs since the last major rehabilitation per lane mile for high-RAP mixtures is about 1.1 million and for up-to-20%-RAP mixtures is about 2.0 million. The R^2 coefficient is low for all contracts, 0.21 for high-RAP contracts and 0.001 for up-to-20%-RAP contracts. It is worth noting that none of the high-RAP contracts are poorly performing (≤ 50 cracking condition value).

5.10.1.2 **Rutting condition**

The average number of ESALs since the last major rehabilitation per lane mile for high-RAP mixtures is about 0.8 million and for up-to-20%-RAP mixtures is about 1.3 million. The R^2 coefficient is low for all contracts, 0.0076 for high-RAP contracts and 0.0075 for up-to-20%-RAP contracts. It is worth noting that none of the high-RAP contracts are poorly performing (≤ 50 rutting condition value).

For both cracking and rutting contracts, the results do not show any apparent trends between RAP mixture, number of ESALs since the last major rehabilitation, and condition (Figure 61-Figure 62).

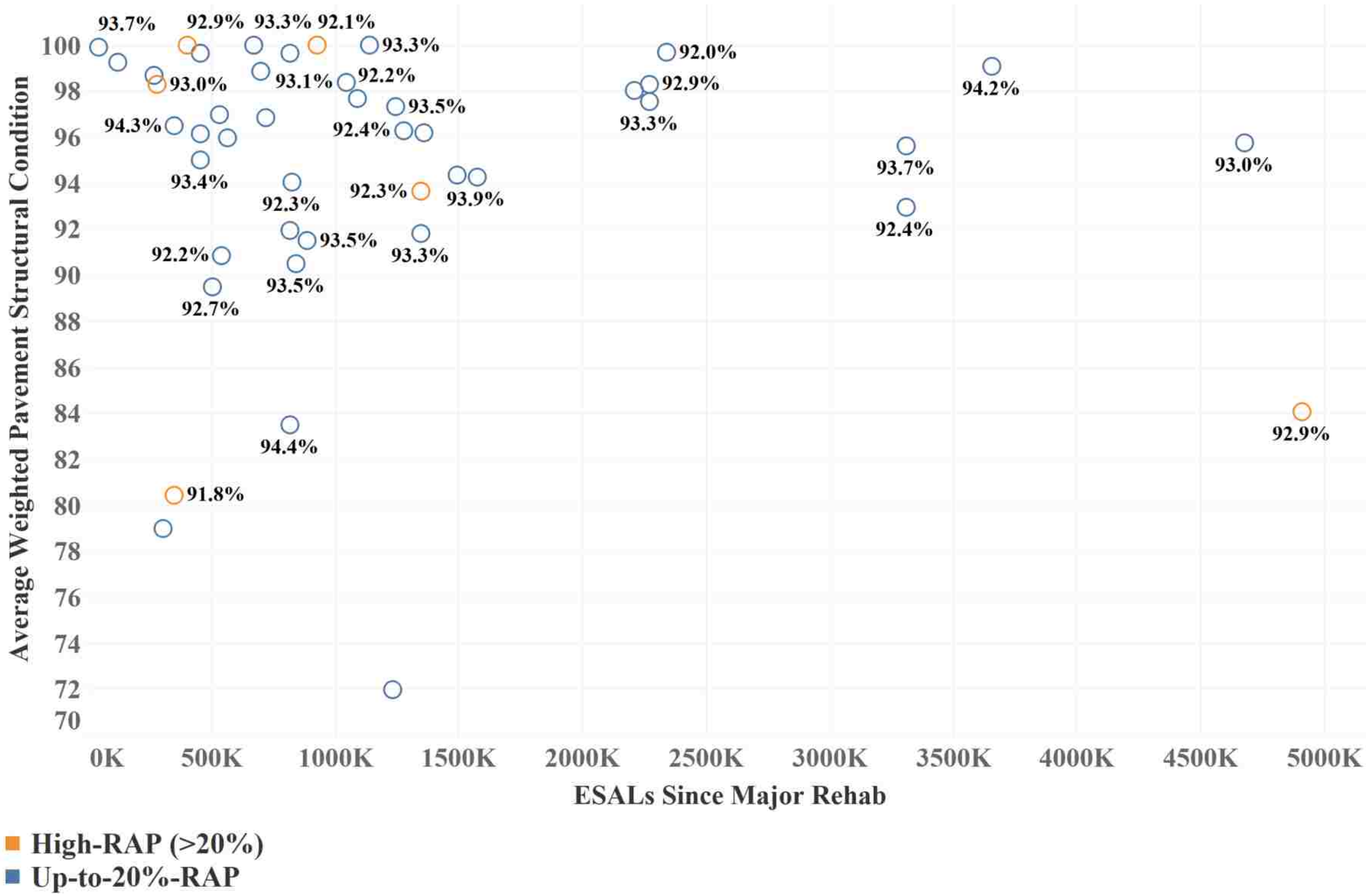


Figure 61. Average Weighted Pavement Structural Condition and Average Weighted Density Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2016

Figure 62. Average Weighted Pavement Rutting Condition and Average Weighted Density Versus Number of Equivalent Single Axle Loads (ESALs) Since the Last Major Rehabilitation for High-RAP and Up-to-20%-RAP WSDOT Asphalt Pavement Mixtures, 2013 to 2016

Chapter 6. Conclusions and Recommendations

6.1 Conclusions

This dissertation formulates, tests, and evaluates an in-service pavement approach of using large amounts of integrated cost, mix design, construction, and performance data over a long period of time (10+ years) to inform policy and specifications development. Using this approach, Washington State Department of Transportation (WSDOT) pavement performance regarding (1) 3/8-inch versus 1/2-inch nominal maximum aggregate size (NMAS) hot mix asphalt (HMA) mixtures, (2) the influence of elevated in-place density and other mixture characteristics on HMA mixtures, and (3) the influence of high-reclaimed asphalt pavement (RAP) HMA mixtures (> 20%) are analyzed by integrating cost, mix design, construction, and performance data for mixtures completed between 2007 and 2017. The subsections below summarize the dissertation's in-service pavement data approach and case study findings, conclusions, contributions, and recommendations. This chapter also includes how the in-service pavement data approach may be applicable to U.S. Air Force (USAF) airfield and road pavements and how the high-level findings of the WSDOT case studies may be useful to the USAF pavement program.

6.1.1 *In-service pavement data approach conclusions*

This dissertation defines and tests an in-service pavement data approach to leverage large amounts of linked cost, mix design, construction, and performance data to inform mix design and construction processes as well as pavement policy and specification development. The approach uses shared fields (e.g. contract, mix design, and lot number) to link the pavement data. This approach captures pavement data from different stages of pavement projects (e.g. mix design, construction, performance after completion) to better understand the relationship between actual in-service performance and mix design, structural design, and construction variables. To analyze the data, the approach uses weighted calculations by tons of mix/lane miles, statistical analyses (e.g. t-tests, linear regression, etc.), tables (e.g. high-level data summaries), and plots (e.g. visualizations by location, box and whisker by age, lot-level histograms, etc.).

The overall conclusions of this approach are:

- **The in-service pavement data approach is a repeatable framework that can be used to better understand the relationship between actual in-service performance and mix**

design, structural design, and construction variables. This approach can be used again for future research given the following criteria for success: (1) availability of credible and/or sufficient data (see definitions below) and (2) a means of linking the data (e.g. contract number).

  - **Credible.** The data is available and there are reasons to believe its accuracy.
  - **Sufficient.** While it is difficult to say exactly how much data are sufficient to make this effort fruitful, smaller data sets than the high-RAP set (e.g. 6 of 55 contracts, ~11%, over a four year period contain cracking performance data) make it difficult to identify any meaningful differences between compared data sets that go beyond statistically unsupported speculation.

- **The in-service pavement data approach is generalizable to any field with large data sets on in-service pavements (e.g. airfields, state highway agencies, city/county roads, etc.).** The literature indicates that state highway agencies are currently the main focus of this approach; however, with available and reliable pavement data the approach is appropriate in other pavement contexts. For example, airfields typically track this kind of pavement cost, mix design, construction, and performance data and the use of this approach would be appropriate to inform airfield design and construction policies/specifications. Other uses include city, county, and federal (e.g. Department of Defense) pavement programs. However, it is likely that most local owners will not have the required data (e.g., a city usually does not collect and/or retain the necessary data).
- **The data framework offers a method to examine asphalt pavement performance at high- and low-levels.** Because the data includes the complete population, the analysis can easily shift from high-level findings (e.g. completion year) to more detailed, low-level findings (e.g. lot, sublot). As a result of this flexibility, the data analysis can investigate apparent high-level trends at a deeper level or determine if trends at the lot or contract level are manifested at a higher level.
- **The resource commitment to perform the in-service pavement data approach is significant.** Until the process is automated, or a homegrown data architecture is built, the resource commitment (e.g. time, personnel hours, system education, etc.) required to assemble the data is quite high. For example, the estimated database build time for this

dissertation is conservatively about 1,500 person-hours (includes data collection, processing, and synthesis for all three WSDOT case studies).

- **There are many uncontrolled and/or unmeasured variables that affect pavement performance.** Therefore, it can be difficult to determine the effects of just one dependent variable. It is likely that even if an effect exists (e.g. higher asphalt content leads to greater field density) other unmeasured variables can be adjusted in the field to compensate (e.g. higher asphalt mixtures are compacted less). In one sense, this can be frustrating from a data analysis standpoint, but in another it can be reassuring because a shortcoming in one area of mix design or construction can be adequately compensated for by efforts in another area so long as there is a clear goal. This may be most evident in density. While many variables can affect density (e.g. asphalt content, gradation, compaction type and effort, mix temperature, particle shape/size, VMA, etc.) the end goal of field compaction (which, for WSDOT pavements appears to be about 93% of theoretical maximum density, TMD) drives a contractor to manipulate the variables which it can control to meet that goal. Conversely, if no end goal exists (e.g. during the 2007-2017 time frame of the data in this dissertation WSDOT did not pay a bonus/penalty related to voids in mineral aggregate, VMA) then the mix design and construction process may not be managed to control that parameter causing that parameter to fall short of its desired value (e.g. ~45% of VMA tests in the 2007-2017 time frame were out of specification).

  Ultimately, this may mean that choosing the priorities of asphalt pavement mix design and construction has a large influence over long-term performance. It is realistic to assume that not all specifications can be established as equal priority goals in the process, therefore some must be favored over others with bonus/penalty pay playing a large role in establishing this priority. Over time the traditional statistical specification bonus/penalty pay items of in-place density, asphalt content, and gradation seem to provide contractors the incentive and latitude to produce quality pavements. This may be because they are the ideal parameters, but, more likely, they have been in effect long enough that the paving industry has been able to adapt its practices to meet these requirements and produce quality pavements. Changing them, especially drastically, may result in an adjustment period.

- **The pavement data disconnect across different systems (WSPMS, SAM, Unit Bid Analysis) limits the usefulness of the data.** The WSDOT pavement data architectures were built as standalone, disconnected systems. Because of this, sublot and lot SAM data is not traceable (mostly) to an identifiable lane mile section in WSPMS nor is condition data of a lane mile section in WSPMS traceable (mostly) to sublot and lot data in SAM. For example, given a selected 0.2 lane mile section in WSPMS, it may be possible in rare instances to determine the field density; however, it is not possible to determine field asphalt content, VMA, etc. of that section using just the available data. Consequently, a connected WSPMS and SAM data analysis at the lane mile section and/or lot level is not achievable as currently constructed. Further, SAM sublot and lot identification numbers are not aligned across parameters. For example, the lot identification numbers for VMA do not align with the lot identification numbers for asphalt content, density, gradation, etc. Similarly, a connected SAM analysis across lot and sublots is not achievable; however, such a traceable system is possible, but it will likely require the creation of a new system.

- **Disparate data tonnage and lane mile section sizes requires data normalization.** Pavement specification requirements drive different field measurement tonnages for different parameters (e.g. asphalt content, density, VMA, etc.) and different project sizes. For example, the density lots mostly use 400 tons of mix (about 40% or 6,000 lots) to evaluate the density. The remaining number of lots (about 55% or 9,000 lots) range from 4 to 4,000 tons of mix. Similarly, the pavement cracking and rutting condition analysis mostly uses a 0.2 lane mile section (about 70% of 36,000 lane mile sections). The remaining number of lane mile sections (about 30% or 10,000 lane mile section) range from 0.01 lane miles to 0.6 lane miles. As a result of these data differences, a normalized approach is required to ensure mixtures with small/large tonnages or lane mile sections do not overly influence the analysis.

6.1.2 *Case study conclusions*

The NMAS, density, and high RAP findings of this analysis contribute field performance and cost insights to inform asphalt pavement planning, design, construction, and specification/policy development.

6.1.2.1 **Chapter 3 (Nominal Maximum Aggregate Size, NMAS)**

This paper compares WSDOT 3/8-inch and 1/2-inch NMAS mixtures using cost, mix design, field quality assurance, and field pavement management system data for contracts completed between 2007 and 2017. Performance of 3/8-inch NMAS mixtures is of particular interest to WSDOT because it recently increased the number of 3/8-inch NMAS contracts and tonnage to address asphalt pavement durability concerns. The primary findings are:

- **The construction bid price of 3/8-inch NMAS mixtures exceeds 1/2-inch NMAS mixtures by about $8 per ton**;
- **The overall weighted average for field measured asphalt content of 3/8-inch NMAS mixtures exceeds 1/2-inch NMAS mixtures by about 0.7%**;
- **The overall average weighted field density for both 3/8-inch and 1/2-inch NMAS mixtures is about 93%**;
- **There is no statistical evidence that there is a difference between the weighted cracking and rutting performance means.**

6.1.2.2 Chapter 4 (Density and mixture characteristics)

This paper investigates the relationship between in-place field density and key mix design, quality assurance, and pavement condition data for WSDOT pavements from 2007 through 2017. Current national and WSDOT efforts to raise in-place density are intended to improve pavement life based on laboratory, field, and theoretical relationships that show higher density is likely to result in longer pavement life. The primary findings are:

- **The overall average weighted field density for all WSDOT HMA mixtures is about 93%**;
- **The 92% density LSL produces a financial incentive for contractors to change practices of about $26,200 per contract or about $2 per ton on average;**
- **There are no clear trends between increased field density and asphalt content;**
- **The overall weighted average for field measured asphalt content for all WSDOT HMA mixtures is 5.43%;**
- **There are no clear trends that link field density and performance;**
- **There is no statistical evidence that there is a difference between cracking and rutting performance means for all mixtures.** The data do show that cracking performance of fine-graded mixtures may be trending higher (less cracking) than coarse-graded mixtures for older contracts, ages 8-10. Additionally, data show that cracking performance of older 3/8-inch NMAS mixtures may be trending higher (less cracking) than 1/2-inch NMAS mixtures for older contracts, at ages eight to nine (cracking data with density is not available for 3/8-inch NMAS mixtures at age 10).

6.1.2.3 **Chapter 5 (High-Reclaimed Asphalt Pavement)**

This paper investigates the performance of WSDOT asphalt mixtures that contain over 20% RAP completed between 2013 and 2017 using cost, mix design, field quality assurance, and field pavement management system data. Mixtures containing more than 20% RAP by weight are termed "high-RAP" mixtures because 20% is the WSDOT threshold for adding testing and specification for RAP-containing mixtures. The conclusions are:

- **The construction bid price of high-RAP mixtures slightly exceeds up-to-20%-RAP mixtures by about $5 per ton**;
- **There is no evidence that there is a difference between the cracking and rutting condition means for all mixtures**;
- **High-RAP mixtures have a slightly lower in-place density than up-to-20%-RAP mixtures by about 0.2% on average** (93.06% for high-RAP mixtures, 93.25% for up-to-20%-RAP mixtures);
- **High-RAP mixtures have less asphalt than up-to-20%-RAP mixtures by about 0.2% on average** (5.23% for high-RAP mixtures, 5.39% for up-to-20%-RAP mixtures);
- **High-RAP mixtures have a slightly lower VMA than up-to-20%-RAP mixtures by about 0.2% on average** (13.88% for high-RAP mixtures, 14.11% for up-to-20%-RAP mixtures).

6.1.2.4 **Overall Conclusions**

The overall case study conclusions of this dissertation are:

- **3/8-inch NMAS mixtures are more expensive and perform similarly to 1/2-inch NMAS mixtures but may be trending higher than 1/2-inch NMAS mixtures in terms of cracking and rutting condition for older contracts.** The construction cost analysis reveals that 3/8-inch NMAS contracts cost about $8 more per ton than 1/2-inch NMAS contracts. Performance of 3/8-inch NMAS contracts is similar to 1/2-inch NMAS contracts; however, the cracking and rutting mixture performance data for some of the older contracts (ages 9-10) may be trending slightly higher.
- **Fine-graded mixtures perform similarly to coarse-graded mixtures and the data do not show any poorly performing fine-graded mixtures.** For contracts with just density values (some contracts do not have density data in SAM), performance of fine-graded contracts is similar to coarse-graded contracts; however, the cracking performance mixture data for older

fine-graded contracts (ages 8-10) may be trending higher. During this time, the equivalency cracking in the wheel path for coarse-graded mixtures is about three times higher than fine-graded mixtures. However, the WSDOT system of contractor mix design may be discouraging fine-graded mixtures since they are likely to require more asphalt and therefore be more expensive to produce.

- **The 92% density specification produces a financial incentive for contractors to change practices of about $26,200 per contract or about $2 per ton on average.** On average, the 91% density specification yields a bonus of about $11,400 per contract ($0.75 per ton) and the new 92% density specification (without any operational changes) yields a bonus loss of about -$14,800 per contract (-$0.98 per ton), a difference of about $26,200 ($1.72 per ton).
- **The data do not show any clear trends that link elevated field density and increased performance.** The condition data analysis does not reveal a clear trend between density and cracking/rutting performance. Although the data show increased cracking and rutting with age for all densities, it is difficult to identify any evidence of a strong linkage between density and performance. What can be seen is that for the contracts with an average weighted density of 94% or higher, none of the contracts are performing poorly (≤ 50 cracking/rutting condition value) for both cracking and rutting. It may be that as the analyzed pavements age beyond 10 years (the oldest pavement surface analyzed in this paper), the trend may continue and provide better evidence of differences between fine- and coarse-graded mixtures and 3/8-inch and 1/2-inch NMAS mixtures.
- **High-RAP mixtures are slightly more expensive because of location and perform similarly than up-to-20%-RAP mixtures but may be trending higher in terms of rutting for the oldest contracts.** The construction cost analysis reveals that high RAP mixtures cost about $5 per ton more than up-to-20%-RAP mixtures. About 64% of all contracts (about 55% of tonnage) and about 88% of high-RAP contracts (about 80% of tonnage) are in Western Washington where the average weighted cost is about $11 per ton higher than Eastern Washington. Performance of high RAP contracts is similar to up-to-20%-RAP contracts; however, the oldest contracts (age four) may be trending higher in terms of rutting performance. However, because the high-RAP data is limited at this age (three contracts), it is difficult to conclude anything other than the two mixtures are no different.

- **There may be insufficient data for 3/8-inch NMAS and high-RAP mixtures to draw ultimate conclusions.** Because the life of WSDOT surface courses is about 15 years, most of the pavement data do not show any significant performance degradation until after four to five years. As a result, the 3/8-inch NMAS mixtures (began around 2007) have not had time to fully express themselves. The limited high-RAP data available (only data from first five years of pavement life) reduces the ability to identify a compelling case that high-RAP mixtures are better or worse than mixtures with less RAP. It may be that performance differences will emerge in later years.

6.2 Using the In-Service Pavement Data Approach to Inform U.S. Air Force Airfield and Road Policies and Standards

This section describes how the in-service pavement data approach may be applicable to U.S. Air Force (USAF) airfield and road pavements and how the high-level findings of the WSDOT case studies may be useful to the USAF pavement program.

6.2.1 *Application of the in-service pavement approach in the U.S. Air Force*

Currently, the U.S. Air Force (USAF) owns and operates about 200 million square yards of asphalt and concrete pavements at over a hundred installations worldwide (U.S. Air Force 2018). These installations also likely contain hundreds of millions of square yards of asphalt and concrete road pavements. Use of the in-service pavement data approach with USAF airfield and road data can inform mix design and construction processes as well as pavement policy and specification development. Unlike the WSDOT data described in Chapter 2, the only pavement data available at an enterprise level is the cost and performance data. The USAF typically houses mix design and construction data at the local installation; however, a historical mix design and construction database for all installations at an enterprise level is not available. In the last few years, the Air Force Civil Engineer Center (AFCEC) has begun to store this type of data for future use.

6.2.1.1 Potential USAF data sources

This section describes the potential USAF data sources available to complete the in-service pavement data approach. It is important to note that it is difficult to precisely identify the USAF pavement data available beyond a high-level estimate, particularly at an enterprise level.

- **Cost.** The USAF Civil Engineer information technology system (TRIRIGA), AFCEC, and the local installations house Air Force-wide cost data for all pavement projects. This data is available mostly in electronic form; however, in some cases the data is available in paper form.

- **Mix design/construction.** If available, the local installations typically house pavement mix design and construction field result data (e.g. NMAS, lift thickness, gradation, density, etc.). In some cases, AFCEC, the U.S. Army Corps of Engineers, and/or the Naval Facilities Engineering Command store this data. These organizations are only required to store the data temporarily (e.g. three years) so some of the installations may have limited available pavement data. Because of this, it may be difficult to uncover mix design and construction HMA pavement data over three years old. This data is available in electronic and paper form.
- **Performance (PAVER).** PAVER is the USAF's Pavement Management System (PMS). For both airfield and roads, PAVER uses the Pavement Condition Index (PCI) to describe pavement performance. The PCI scale ranges from 0 (failed) to 100 (good) (U.S. Air Force 2017). This data is available in electronic form.

6.2.1.2 Initial in-service pavement data research efforts

Once identified and linked together, these data sources provide a unique opportunity to investigate how a large amount of historical cost, mix design, field, and performance data (ideally greater than three years) can be linked and used to provide insight on mix design, construction, policy, and specification development in the USAF as well as the Department of Defense (DoD). Since this type of pavement data is subject to numerous unmeasured variables, information and perceptions from USAF engineers, the U.S. Army Corps of Engineers, the Naval Facilities Engineering Command, and industry should be used to provide expert interpretation, feedback, and common industry perspectives. These perspectives can be captured through the use of a survey and interviews. Because it is not feasible to analyze all USAF installations with one study, an initial, representative selection of USAF installation airfield and road data is appropriate for the first use of the in-service pavement data approach. Initially, the data linkage will occur manually. This initial small research effort will help determine the effort necessary to link and use the data for future research efforts.

6.2.2 *Application of WSDOT case study findings to the U.S. Air Force*

Although the WSDOT case studies are specific to Washington State, some of the high-level findings are universally applicable and could help inform the USAF and DoD road HMA pavement mix design, construction, policy, and specification development.

6.2.2.1 **Relevant U.S. Air Force pavement specifications**

The DoD's Unified Facilities Criteria (UFC) 3-250-01 provides design guidance on roads and parking areas (Department of Defense 2016). The UFC guidance instructs readers to use the local state highway agency and/or the Pavement-Transportation Computer Assisted Structural Engineering (PCASE) software to design the installation's road pavements (Department of Defense 2016). Because of this, the chapter on flexible pavement design does not prescribe a minimum in-place density, it does not give specific guidance on NMAS or gradation, nor does it provide guidance on the use of recycled materials.

6.2.2.2 **In-Place Density**

Because of the evidence in published literature and the data in this dissertation, the addition of an in-place density requirement for all USAF installations may be a consideration in the next update to the road design UFC. One of the issues with the current UFC construct's use of the local state highway agency's design specification is that about half (29 of 51) of state highway agencies use statistical evaluation procedures (i.e. percent within limits, PWL, for pay factor and bonus) (Aschenbrener et al. 2017).

Contractors typically target an average in-place density higher than the minimum specification limit to make it easier to achieve the bonus (Willoughby and Mahoney 2007). However, enforcement of statistical evaluation procedures at USAF installations is unlikely because of resource availability limitations. An absence of a pay factor and bonus could decrease contractor motivation and impact decisions during construction on DoD installations. For example, a recent road project at Joint Base Lewis McChord used a WSDOT mix design but the statistical evaluation procedures were not used even though WSDOT uses statistical evaluation for in-place density. If the statistical evaluation procedures are not enforced, the in-place density may be lower, potentially decreasing HMA pavement service life and increasing USAF pavement rehabilitation costs. One possible solution is to use simple averages for the lots with a prescribed minimum lot average (e.g. 93%) and an accompanying minimum density for each sublot (e.g. 91%) (Aschenbrener et al. 2017). Of the 22 state highway agencies that use the minimum lot average procedure, 17 of 21 uses a minimum lot average of 92% in-place density or higher (Aschenbrener et al. 2017). This method simplifies the calculations and reduces the oversight required. Another possible solution is to use the local state acceptance procedures and figure out a better way to enforce those on the base.

6.2.2.3 **Smaller NMAS and Fine-Graded Mixtures**

Because of the evidence in published literature and the data in this dissertation, the use of HMA mixtures with smaller NMASs and/or fine-graded mixtures for all USAF installations may be a consideration in the next update to the road design UFC. The UFC road design criteria for HMA pavements does not currently prescribe mix design characteristics for NMAS (smaller versus larger NMASs) or gradation (fine- versus coarse-graded). Instead, the road design UFC broadly leans on the local state highway agencies and/or the PCASE software to dictate mix design properties. However, the use of smaller NMAS or fine-graded mixtures may provide pavement performance value (e.g. decreased permeability, decreased compactive effort, etc.) at a similar cost to other mixtures across all USAF installations.

6.2.2.4 **High-RAP Mixtures**

Because of the evidence in published literature and the data in this dissertation, guidance on the use of HMA mixtures with recycled materials may be a consideration in the next update to the road design UFC. The UFC road design criteria for HMA pavements does not currently prescribe guidance on recycled materials. Instead, the road design UFC broadly leans on the local state highway agencies and/or the PCASE software to dictate mix design properties. According to the 2017 National Asphalt Pavement Association Asphalt Pavement Industry Survey on Recycled Materials (National Asphalt Pavement Association 2018), the average estimated RAP by state ranged from 10% to 35% with a nationwide state highway agency average of about 20%. This demonstrates that the state highway agencies mostly use up-to-20%-RAP mixtures. However, several published findings show that the higher RAP mixtures (> 25% RAP) mostly perform similarly for cracking and rutting. Use of pavements with higher RAP mixtures at USAF installations may have the potential to decrease construction costs at a similar cracking and rutting performance. One possible way forward is to update the UFC to more directly address RAP as evidence around the U.S. is accumulating as to its performance.

6.3 Recommendations

6.3.1 ***In-service pavement data approach recommendations***

- **Increase connectivity and precision of asphalt pavement data sources.** Recommend reworking the standalone cost, mix design, construction, and performance databases to create a unified database that connects all of the relevant parameters in the construction life cycle.

This interconnected database should clearly link the mix designs, sublots, lots, and lane mile sections across the measured data parameters (e.g. asphalt content, density, VMA, condition, etc.) by date. This kind of database framework will provide more precise, traceable indicators of pavement performance.

- **Expand the WSDOT data to reduce unmeasured variables.** Because the data provided did not include all variables such as soil/underlying pavement conditions, compactive effort, etc., an effort should be made to expand the available data used in this approach. If the data is already available and is determined to provide value to the analysis, it should be included in the data approach. Additionally, if the data is not already available but is determined to provide value, WSDOT should consider adding it to the data architecture. Conversely, WSDOT should not add data unless it is convinced that the data provides value.

6.3.2 *Case study recommendations*

- **Monitor 3/8-inch NMAS mixture long term performance.** In the next 5 to 10 years, the first generation of 3/8-inch NMAS pavements will have completed their first life cycle, making available a larger data set of 3/8-inch NMAS pavement measurements. Another similar study, using 15-20 years of 3/8-inch NMAS data will offer details about updated cost, mix design, construction, and performance (e.g. cracking, rutting, and service life) data.
- **Investigate greater use of fine-graded mixtures and consider tightening the No. 8 sieve tolerance bands.** A relatively large amount of pavement data over a long period of time show that there is no evidence of poor performing fine-graded (versus coarse-graded) mixtures. As a result, WSDOT should investigate using more fine-graded mixtures across the Washington State pavement road network particularly in areas with a history of decreased service life (e.g. Eastern Washington, mountainous terrain). Pursuit of more fine-graded mixtures would also require a tightening of the No. 8 sieve tolerance bands. Currently, the percent passing for 3/8-inch NMAS mixtures is 32% to 67% and for 1/2-inch NMAS mixtures is 28% to 58% (WSDOT 2018d).
- **Investigate elevated in-place density in the field and with a larger data set.** As WSDOT transitions to a lower specification limit of 92% of theoretical maximum density, WSDOT should investigate and track how contractors adjust their construction operations to achieve the new density. Additionally, WSDOT can explore 1/2-inch NMAS volumetric designed mixtures using a larger pavement dataset over a longer period (e.g. 2004-2020) to investigate

how higher in-place densities (e.g. 93% of TMD and above) impact asphalt pavement service life. A subset of this larger data set will exhibit high in-place density (93.5% to 94.0% of TMD and above), providing service life insights that may predict how pavements will perform at the new density specification. To achieve a bonus at the new density specification, contractors will likely begin to construct pavements at a higher in-place density (possibly 94% of TMD on average).

- **Monitor high RAP mixture long term performance.** In the next 10 to 15 years, the first generation of high RAP pavements will have completed their first life cycle, making available a larger data set of high RAP pavement measurements. Another similar study, using 10-20 years of high RAP data will offer details about updated cost, mix design, construction, and performance (e.g. cracking, rutting, and service life) data.

6.4 Disclaimer

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