Effects of Mix Design Parameters on Indirect Tensile Strength and Field Cracking Performance of Asphalt Pavements

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DEDICATION

I would like to dedicate this to my parents, Mary and John. I would not have been able to accomplish this without your unwavering support and encouragement. I would also like to dedicate this to all of the graduate students in the SCIV 121 office for all of the enjoyable times and laughs we shared.

ABSTRACT

Thermal cracking of asphalt concrete pavements is a severe problem in cold climate regions. Thermal cracking occurs due to asphalt pavements contracting when subjected to very cold temperatures. This cold environment also leads to the embrittlement of asphalt materials. This combination of thermal contraction and increased brittle behavior leads to formation of transverse cracks in the pavement surface. These cracks decrease the integrity of the pavement and reduce the ride quality thus increasing the maintenance and rehabilitation expenses.

Presently, no laboratory performance test is required by the Minnesota Department of Transportation (MnDOT) asphalt material specification, as part of acceptance criteria. This significantly increases the risk for poor transverse cracking performance. The objective for this research study is to analyze the effects of mix design parameters on the indirect tensile strength and field cracking performance of asphalt pavements. A comprehensive database of existing mix design information, laboratory test results and pavement performance records was created to perform a statistical analysis. The data obtained from MnDOT was used to create the aforementioned database. The analysis was done to investigate if any mix design parameters (such as, asphalt film thickness, voids in mineral aggregate, asphalt binder grade) had a statistically significant effect on the field cracking performance. It also investigated the suitability of the indirect tensile strength from the modified Lottman test (AASHTO T 283) as a laboratory performance measure to predict pavement cracking.

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CHAPTER 1: INTRODUCTION AND MOTIVATION

1.1 Introduction

One of the main causes of asphalt pavement degradation in cold climate regions, specifically in the northern United States and Canada, is transverse cracking [1]. This is caused by the pavements contracting when they are subjected to low temperatures. The asphalt concrete also becomes brittle as well during the cooling process. The combination of both the thermal contraction and embrittlement of the asphalt mixture lead to transverse cracks forming and propagating within the pavement structure. These cracks lead to decreased serviceability of the pavement to the public. A laboratory performance test to supplement existing asphalt mix design specifications is needed to improve the performance of asphalt pavements throughout their lifetime. This additional mechanical test that will be run in the lab will better predict how an asphalt mix design will perform in the field in terms of transverse cracking. Transverse cracking influences service life and therefore affects the maintenance and rehabilitation costs of the pavement [2]. Better prediction of field performance will lead to decreased rehabilitation and maintenance costs as well as an improved driving surface and higher ride quality for the public.

Analysis of the effect of mix design parameters (such as, asphalt film thickness, voids in mineral aggregate, asphalt binder grade) on field cracking performance is also an important aspect of improving asphalt pavement performance. Creating a comprehensive database that includes both mix design information and pavement performance data will allow for continued analysis of mix design parameter effects on asphalt pavement field performance in the future. This continued improvement will refine the mix design process and result in pavements with decreased transverse cracking.

1.2 Motivation

In current MnDOT 2360 specifications, the asphalt mix design process relies heavily on mix volumetrics for mix acceptance criteria. There are several volumetric requirements the mixes must pass in order to be deemed acceptable for placement in the field, as was see in Figure 1.

A schematic of how this research is aiming to improve current MnDOT 2360 specifications is illustrated in Figure 2. Both an absence of a laboratory performance test and lack of analysis of the effects of mix design parameters on field cracking performance can lead to pavements performing poorly, specifically in low temperature climates.

Table 2360-7 Mixture Requirements				
Traffic Level	**2**	**3**	**4**	**5**
20 year design ESALs	< 1 million	1 – 3 million	3 – 10 million	10 – 30 million
Gyratory mixture requirements:				
Gyrations for N_{design}	40	60	90	100
% Air voids at $N_{design,}$ wear	4.0	4.0	4.0	4.0
% Air voids at N_{design}, Non-wear and all shoulder	3.0	3.0	3.0	3.0
Adjusted Asphalt Film Thickness, minimum μ	8.5	8.5	8.5	8.5
TSR*, *minimum %*	75‖	75‖	80†	80†
Fines/effective asphalt	0.6 – 1.2	0.6 – 1.2	0.6 – 1.2	0.6 – 1.2
Ratio of Added New Asphalt Binder to Total Asphalt Binder,[(1)], min%:				
All Binder Grades	70	70	70	70
Max. Allowable RAP Percentage[2] (shingles are included as part of the allowable RAP percentage)				
PG 58-34, PG 64-34, PG 70-34	20	20	20	20

* Use 6 in [150 mm] specimens in accordance with 2360.2.I, "Field Tensile Strength Ratio (TSR)."
‖ MnDOT minimum = 65
† MnDOT minimum = 70
1 The ratio of added new asphalt binder to total asphalt binder needs to meet the requirements in Table 2360-7 in both mixtures that contain RAP and in mixtures that include shingles as part of the allowable RAP percentage. ((added binder/total binder) x 100 ≥ 70).
2 The Contractor can elect to use a blending chart to verify compliance with the specified binder grade for RAP > 20%. The Department may take production samples to ensure the asphalt binder material meets the requirements. The bleinding chart is on the Bituminous Office Website.

Figure 1: Table 2360-7 Mixture Requirements [3]

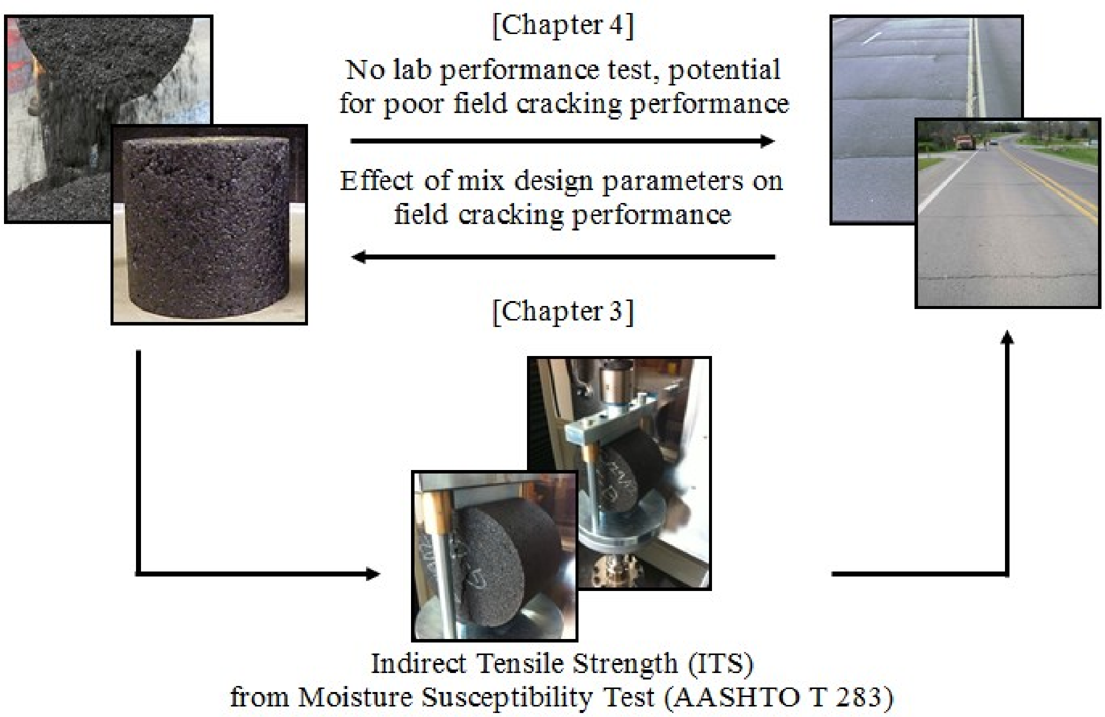


Figure 2: Asphalt mix design process schematic supplemented with laboratory performance test

In Figure 2, the top of the schematic shows the current mix design process of laboratory mix designs being placed in the field without the use of a laboratory performance test as a performance measure against transverse cracking. This leads to poor pavement performance in terms of transverse cracking, which is the distress the pavements shown in Figure 2 are subjected to. Chapter 3 of this thesis analyzes and discusses the effect of mix design parameters, indirect tensile strength (ITS), and tensile strength ratio (TSR) on field cracking performance. This research also analyzes the effect of mix design parameters on field cracking performance and how these parameters can be changed during the laboratory portion of the mix design process to decrease transverse cracking of asphalt pavements. The analysis of effects of mix design parameters on field cracking performance is discussed in Chapter 4 of this thesis.

The bottom of the schematic in Figure 2 shows the addition of the AASHTO T 283 test as a laboratory performance test. Supplementing current specifications with a performance test could also improve the field cracking performance of asphalt pavements. Analysis of the effect of mix design parameters on ITS and Tensile Strength Ratio (TSR) is discussed in Chapter 3. These two modes of improving current MnDOT 2360 specifications will in turn lead to better performing pavements in terms field cracking performance.

The AASHTO T 283 test is already required by MnDOT as part of moisture susceptibility testing. Due to this test already being conducted by MnDOT, it is logical to evaluate if this test is a good indicator of field performance of mix designs. If it is found to be a good indicator of field performance of mixes, implementation into specifications as well as executing the test in the lab can be done with ease. Economic resources can also be saved due to not having to exhaust monetary resources on new equipment. The analysis of mix parameters and their effect on field cracking performance would also be an addition to specifications that could be done with minimal effort.

1.3 Literature Review

One of the main causes of distresses in asphalt pavements in cold climate regions is low-temperature cracking, or as it is more commonly known in the asphalt community as transverse cracking [4] [5]. As the pavement cools and contracts, transverse cracking perpendicular to the pavement centerline occurs [6]. Examples of asphalt pavements subjected to this distress are shown in Figure 3. Cracks in asphalt pavements allow water and other medium to enter, causing degradation of the pavement structure. This loss of pavement integrity leads to increased rehabilitation and maintenance costs and a decreased ride quality to the public. Current asphalt mix design specifications are highly based on mix volumetric measures and require no laboratory performance test as a means to predict field cracking performance of asphalt mix designs [7]. Past research has shown that implementing performance based tests into specifications improves prediction of the field cracking performance [8]. Pavement performance data has also been used as a means to improve ways of predicting field performance of asphalt pavements and refining the mix design process [9] [10]. Improving the mix design process to decrease the amount of low temperature induced transverse cracking will greatly increase the quality of pavements as well as decrease rehabilitation and maintenance costs.

Figure 3: Transverse cracking of asphalt pavements

1.3.1 Current MnDOT 2360 Plant Mixes Asphalt Pavement Specifications

Current practice for design and acceptance of asphalt concrete mix designs to be placed in the field is done per MnDOT Specification 2360 "Plant Mixed Asphalt Pavement". This specification includes information on how the designed mixes are identified and labeled, as well as "Table 2360-7 Mixture Requirements" that include mixture design parameter requirements that the submitted mixes must meet [3]. The mixtures designed are given what is called a mixture designation. This mixture designation is referred to later in the thesis as the "SP#". The SP# is a combination of letters and numbers which describes and differentiates between different asphalt pavement mix designs. The different characters or numbers represent the mix design type, whether it is a wear or non-wear course, the nominal max aggregate size of the mix, traffic level the mix is being designed for, air void requirement of the mix, and the performance grade (PG Grade) of the binder for the mix.

These mixture requirements are based on the traffic level the roadway is being designed for, as can be seen in Figure 1 of the Mixture Requirements table [3]. This traffic level selected is based on 20 year design traffic (expressed as number of Equivalent Single Axle Loads or ESALs) computed for the roadway. (such as, asphalt film thickness, voids in mineral aggregate, asphalt binder grade). This table encompasses the current requirements set forth by MnDOT which a contracted mix design must meet to be deemed satisfactory for placement in the field.

As can be seen in Figure 1, acceptance criteria of designed asphalt mixes depends heavily on mix volumetrics, such as the percentage of air voids at design level of compaction (N_{design}), for both wear and non-wear courses, and also the asphalt film thickness (AFT).

In the Job Mix Formula (JMF) the contractor supplies to MnDOT, the following must also be included: Composite gradation, aggregate component proportions, asphalt binder content of the mixture, design air voids, adjusted asphalt film thickness, and aggregate bulk specific gravity values [3]. This documentation proves the mixes being submitted for approval meet the volumetric requirements set by MnDOT.

Throughout the MnDOT 2360 specification, acceptance criteria relies on the submitted mixes passing requirements based on mix volumetrics. There is one laboratory test however listed among the mix requirements in table 2360-7. This is the AASHTO T 283 moisture sensitivity test. This test consists of six test specimens. Half are tested in dry conditions and the other half are tested after a moisture conditioning and freeze-thaw cycle. The conditioning consists of saturating the specimen to between 70 and 80 percent and then freezing them at -18 °C for 16 hours. After the 16 hours, the specimens are then placed in a water bath at 60 °C for 24 hours. After that time period has elapsed, the specimens are then moved to a water bath of 25 °C for 2 hours, and then tested to determine their indirect tensile strength. The tensile strength ratio (TSR) is determined by dividing the average tensile strength of the condition set by the average tensile strength of the dry set. This ratio is a numerical representation of the negative effect the water conditioning had on the conditioned set of specimens [11]. For traffic levels 2 and 3 a minimum TSR of 75% is required, and for traffic levels of 4 and 5, a TSR or 80% is required.

1.3.2 Laboratory Performance Tests

In the past, research has been done to evaluate and implement a performance test into specifications as a means to decrease the amount and severity of distresses in asphalt pavements. These distresses include rutting, fatigue cracking, thermal cracking, and reflective cracking. A study done to investigate simple performance tests for permanent deformation and fatigue cracking found three tests to have promising results [8]. Other studies have also been done to use performance tests, such as the Texas Overlay Tester, in the laboratory to gain better insight into the field performance of mixes. [9]. This study however focused on fatigue and reflective cracking.

Including a low temperature specification into asphalt mixture design, similar to what is in place for the binder grading system, is needed [10]. Fracture resistance of asphalt mixtures directly influence pavement service life and affect pavement rehabilitation and maintenance costs. Exploring fracture mechanics at low temperatures began in the late 1980's [2]. The Disk Shaped Compact Tension (DCT) and the Semi-Circular Bend (SCB) tests have shown to be a promising to predict transverse cracking. Both are based on the measurement of an asphalt mixture's fracture energy, with DCT fracture energy of 450 J/m^2 as the suggested threshold value. Fracture energy has appeared to be a better indicator of a material to resist fracture than other indirect measures, such as tensile strength [14]. This parameter was developed to better predict an asphalt mixture's tendency to crack in low-temperature climates [13]. This parameter has also been used in a study dealing with reflective cracking, although that is outside the scope of this research [14].

Along with laboratory performance tests, investigation of the dependence of mix design parameters on field cracking performance is also of importance. The ability to identify and make changes to mix parameters that are correlated to field cracking would improve the mix design process. In turn, mixes would have better field cracking performance. Research done in northern Ontario investigated the ability of binder grades to predict field cracking [15]. Air void content was shown to play a role in the fracture toughness in a study done at the University of Minnesota [1]. Although studies have investigated mix parameter effects on field performance, an in-depth statistical analysis of all asphalt mixtures placed in Minnesota over several years and their corresponding field performance has not yet been done.

1.3.3 Utilization of Field Performance Data

A key to continued improvement of asphalt pavement performance is analyzing field performance data and using this to improve the mix design process. Field distress surveys as well as well-kept pavement material data are key to this process. Long Term Pavement Performance (LTPP) databases have been used as a means of keeping field performance data of asphalt mixes placed in the field. In several studies, LTPP data has been used as a means to improve models that predict pavement distresses [9] [10] [16]. Other studies that have investigated the impact of pavement parameters on field cracking performance have been conducted in climates that are significantly warmer than Minnesota, such as a study done in California by Zaghloul [17]. A study done by Bonaquist [10] did investigate the sensitivity of input parameters to the Mechanistic-Empirical Pavement Design Guide (MEPDG) predicted performance. This study systematically identified the influence of mix parameters on pavement performance as well as the combined effects of two or more mix parameters, which had not been investigated by previous research studies.

Although studies have been done to analyze the effect of single or combined (multiple) mix parameters, it was done in the context of improving or analyzing the sensitivity of pavement performance prediction models. No previous research was found where one concise and cumulative database exists that contains both the mix design information as well as the pavement performance data. Some databases used as a means to analyze mix parameters with LTPP data either contained limited or missing data [6] [18]. Pavement performance data is only as good as the records that are kept. Without one central source to keep these records organized and up to date, the usefulness of the distress data diminishes. Having a cumulative database of both distress and mix design data would increase the ease of analyzing the effect of mix design parameter on pavement performance. It would also improve the methodology of record keeping by having all needed pavement performance information in one easily accessible format.

1.4 Project Objectives

Based on the literature review, the overall objective of this project was determined as the analysis of the effects of mix parameters on field cracking performance and also to determine the suitability of using the indirect tensile strength (ITS, from AASHTO T 283) into current mix design specifications as a laboratory performance measure. The specific objectives of this study are as listed below.

- Development of a comprehensive database that includes both mix design information as well as field performance data;
- Statistical analysis of field cracking performance against indirect tensile strength from AASHTO T 283 procedure; and,
- Statistical analysis of field cracking performance against asphalt mix design parameters.

1.5 Organization of Thesis

This thesis is organized into five chapters. The chapter 2 begins with a summary of the records that were obtained from MnDOT. These records are referred to as data sources. The method of combining the multiple data sources into one comprehensive database in Microsoft Access is illustrated along with the explanation and method of statistical analysis performed on the data sets pulled from the database. Chapter 3 provides the single and multivariable analysis of mix parameters and their relationship to the indirect tensile strengths (i.e. wet strength and dry strength) of previously tested mixes. The relationship of the ITS and TSR of mixes along with field performance is also discussed. This is then followed by an analysis of the relationship between the mix design parameters and field performance in Chapter 4. Finally, summary, conclusions and future recommendations from this research is presented (Chapter 5). The raw data and the plots are included in the appendix of the thesis.

CHAPTER 2: DATA SOURCES, RESEARCH METHODS, AND RESULTS PRESENTATION

2.1 Introduction

This chapter provides the overview on the various data sources that were used in this study, the methodology that was followed for construction of a comprehensive database and for analysis of various data sets generated using the aforementioned database, and finally description of various schemes used in this dissertation to present the results of the data analysis.

2.2 Data Sources

The data sources that were combined to construct a comprehensive database of asphalt mix design parameters and pavement field cracking performance were obtained from MnDOT's Office of Materials and Road Research (OM&RR). The data was received in the form of Microsoft Excel spreadsheets. Four primary data sources were available. These data sources are comprised of: (1) Mixture Design Reports (MDR); (2) Laboratory Information Management Systems (LIMS); (3) Tensile Strength Ratio (TSR); and, (4) Pavement Management Systems (PMS). It should be noted that the TSR data was previously extracted from the LIMS data source.

As can be seen in Table 1, the data sources are listed along with the number of records that each data set contained. The amount of available data represents a record kept by the MnDOT during the asphalt mix testing or distress survey on the pavement. Different records are located in each data source. For example, cracking amounts are available in the PMS data set while the mix design parameters (asphalt film thickness, voids in mineral aggregate, asphalt binder grade etc.) are located in the LIMS data set. Some data sets contain larger amounts of data based on record keeping conventions. For example, multiple samples were taken from a specific project in the LIMS data set. The PMS data set contains such a large amount of records due to distresses being recorded on the same pavement section over multiple years.

Table 1: Data Sources and Amount of Available Data obtained from MnDOT

Data Source	Amount of Available Data
Material Data Records	12,293
LIMS Database	32,515
TSR Database	2,545
Pavement Management Systems	58,416

Construction of a comprehensive database consisting of all information from all sources was necessary to evaluate the effects of various variables on field performance and on each other as well. Recording the mix design data and having no way to analyze how the mixes are performing in the field gives no feedback as to how to improve the overall mix design process. This database gives MnDOT the ability to extract records from multiple sources and conduct a statistical analysis on the effect of mix parameters on either strength of the mixes or field cracking performance. It can also be utilized in future efforts to analyze and track asphalt mix designs and field performance.

2.2.1 MDR Data

The MDR data consists of asphalt mix designs that were submitted for approval before they were accepted to be used for placement in the field. As can be seen in Table 1, the MDR dataset contains 12,293 records of data. The range of years this data was recorded is 2001 to 2012. Information on mixes containing recycled materials is also found in this data set. A search in the MDR data source for mixes containing recycled materials, such as recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), and Millings, returned 1,039 records. Using both RAP and RAS in asphalt concrete mixes is a relevant means to incorporate materials that would otherwise be waste into an asphalt pavement mix design. Using these waste materials can add a sustainable aspect to the mix design process. While reuse of material might lower the cost of the mix and can add a sustainable aspect, it is important to evaluate the effects of recycled materials on pavement performance to determine if the resulting mixes are truly sustainable in nature or not. A statistical analysis of how these mixes perform in the field, in terms of amount of cracking, was investigated and will be discussed later.

2.2.2 LIMS Data

The LIMS data source consists of mix design information recorded during the pavement construction as part of QA/QC procedure. The LIMS data source is the only source that contains mix design information. This data source is a crucial part of the database due to this reason. Without this information there would be no way to analyze the effect of mix design parameters on mix strength, TSR, or field performance. The data ranges over 2004 to 2012.

The mix design information includes what will be referred to as mix parameters. It is common to use acronyms for these parameters. An explanation of these acronyms and the definitions of various mix parameters used in this study is as follows:

- PG Grade – Superpave Performance Grade of asphalt binder. The high temperature represents an average seven day maximum temperature and the low temperature represents the lowest expected temperature of the pavement surface temperature.
- PG LT- the low temperature of the PG Grade
- PG Spread- The sum of the high temperature and low temperature ratings of the PG Grade. This represents the range of temperature difference for which the binder is graded.
- AFT – Asphalt Film Thickness is an estimate of the thickness of binder coating aggregate.
    - AFT P_{be} – A function of effective binder and surface area of aggregate. The surface area is determined using the gradation anf estimate surface area factors for aggregates in each sieve size range.
    - AFT Adjusted- A function of effective binder and surface area of aggregate in sample as well as specific gravity of aggregates. The surface area of aggregates is based on the gradation. The calculated surface area is adjusted according to the specific gravity of aggregates.
- Air Void Level- Amount of air voids present in an asphalt sample.
    - Design Air Void Level – Percentage of air voids that is selected for design of asphalt mix.
    - Actual Air Void Level – Actual air voids measured from a lab tested sample (typically collected during the mix production or from existing pavement).
- VMA- Voids in Mineral Aggregate represents the volume fraction of air voids and effective asphalt binder in the mix.

- VMA Ignition –Asphalt binder percentage present in a sample obtained by use of an ignition oven. The asphalt binder percentage is then used to calculate the VMA.
- VMA Extraction- Asphalt binder percentage present in a sample obtained by extracting with use of chemicals. The asphalt binder percentage is then used to calculate the VMA.

- VFA – Voids Filled with Asphalt represents the percent of VMA that is occupied by asphalt binder.
- Design Traffic Level- Level assigned to mixes based on the traffic level as expressed by 20 year equivalent single axle loads (ESALs).
- Percent Binder- Percentage of asphalt binder present in asphalt mix.
    - Percent Binder Ignition- Asphalt binder percentage present in a sample obtained by use of an ignition oven.
    - Percent Binder Extraction- Asphalt binder percentage present in a sample obtained by extracting with use of chemicals.

2.2.3 TSR Data

The TSR data source consists of records of the indirect tensile strength (ITS) of different mixes from the AASHTO T 283 (Modified Lottman Test) test [7]. The ITS values are available for mixes with and without moisture conditioning, typically referred to as “dry” and “wet” ITS. From these strengths, the TSR of the mix is then found. This test is typically conducted during the mix design acceptance process as a screening test to ensure that asphalt mix is not susceptible to moisture induced damage. For the mix to be acceptable it must have a minimum TSR of 75% for traffic levels 2 and 3 and 80% for traffic levels 4 and 5. Mix design parameters combined with the wet strength, dry strength, and TSR were statistically analyzed to determine if the AASHTO T 283 test can be used as a laboratory performance test for prediction of field cracking performance [7]. These results will be discussed further in this report. The data contained in the TSR data source range from year 2000 to 2011.

2.2.4 PMS Data

The PMS data source is comprised of both pavement section information as well as distress data. The pavement section information is defined in terms of beginning and ending reference posts as well as beginning and ending total mileage, or GIS coordinates. A Log Point Listing form is used by the MnDOT district office to convert GIS points to reference posts. These conversions were done prior to obtaining the records.

The PMS data source contains all of the field performance (distress) data, specifically cracking performance of different pavement sections. Information pertaining to route types (Interstates, State highways, and US highways) and route numbers are included in this data source which contains 188 unique routes. The distress information includes transverse cracking, longitudinal cracking, rutting, raveling, patching, and longitudinal joint deterioration. Due to the main focus of this study pertaining to cracking of asphalt pavements, only transverse and longitudinal cracking were included in the statistical analysis phase. Inclusion of this data source into the database allows for the ability to track the effect of different mix design parameters on field performance of the pavement over several years. This data contains information recorded between year 2004 and 2011.

The transverse and longitudinal cracking data in the PMS data is collected based on the severity of the cracks, namely low, medium and high. For each severity level the data is reported in terms of percent cracking (% cracking) which is calculated as 2 times the number of cracks per 500 feet length of the survey section. For purposes of conducting a statistical analysis between amount of cracking and laboratory tests as well as asphalt mix parameters, a number of measures of field cracking performances can be calculated. In this study, the researchers looked at transverse and longitudinal cracking amounts in two primary ways: (1) total cracking; and, (2) total weighted cracking. Total cracking is sum total of low, medium and high severity cracks, whereas weighted cracking amount is arbitrary cracking amount with weight factors of 1, 2 and 4 applied to low, medium and high severity crack amounts.

The total cracking and total weighted cracking amounts for a given PMS section for each year of distress survey can be used to calculate additional cracking measures that are representative of field cracking performance. These measures for transverse cracking are described in Table 2.

Table 2: Field Cracking Measures

Measure	Description	Unit
Maximum Total Transverse Cracking Amount (MTCTotal)	Maximum transverse cracking amount (low + medium + high) of all survey years for a pavement section normalized against number of years for which pavement section has been in service.	% cracking/year
Maximum Total Weighted Transverse Cracking Amount (MTCWeighted)	Maximum weighted transverse cracking amount (low + 2*medium + 4*high)/6 of all survey years for a pavement section normalized against number of years for which pavement section has been in service.	% cracking/year
Maximum Total Transverse Cracking Rate (MTCRTotal)	Maximum increase in total transverse cracking amounts (low + medium + high) between any two consecutive years of service.	% cracking/year
Maximum Total Weighted Transverse Cracking Rate (MTCRWeighted)	Maximum increase in total weighted transverse cracking amounts (low + 2*medium + 4*high)/6 between any two consecutive years of service.	% cracking/year
Average Total Transverse Cracking Rate (ATCTotal)	Difference between maximum and minimum total transverse cracking amounts (low + medium + high) divided by number of years that pavement section has been in service.	% cracking/year
Average Weighted Total Transverse Cracking Rate (ATCWeighted)	Difference between maximum and minimum total weighted transverse cracking amounts (low + 2*medium + 4*high)/6 divided by number of years that pavement section has been in service.	% cracking/year

2.2.5 GIS Data

It should also be noted that Geographic Information Systems (GIS) records obtained from MnDOT were also used in constructing the comprehensive database. This data source was needed due to it containing the State Project (SP) number for each pavement section, which is a key piece of information that was instrumental in linking the field performance data back to the mix parameter data sources. A total of 1,321 records from 1999-2012 were included in this data source.

2.3 Data Mapping

The computer software program used in this study to compile and build the comprehensive database of both mix design parameters and field performance data was Microsoft Access. This software program allows for importing different sets of data, such as Microsoft Excel Spreadsheets, and combining or "linking" the multiple data sets together into one comprehensive database. The five data sources described previously are imported as "Tables" into Access. The combination of these tables into one Access file creates a comprehensive database. This newly formed database allows for vital information from different sources to be combined together in one list. This list of data can then be used for analysis. For this study, asphalt mix design parameters from the LIMS data source were combined with ITS, TSR, and field performance data for conducting statistical analysis.

The "linking" of data sources will be referred to as "data mapping" throughout the rest of the report. The records that are common across various data sets are used for "linking" them. These common records are referred to as "mapping parameters". These are the means by which multiple data sources are combined together to allow for specific information to be extracted from each source. They also allow for traversing throughout multiple data sets when looking for specific mix parameters or field performance quantities. Searches conducted within Access for certain parameters are referred to as queries.

2.3.1 Data Mapping Parameters

For the multiple data sets that are imported into Access, it is crucial to have as many defining mapping parameters in common as possible. Having multiple ways to link the data sets together refines the results when a query is conducted in Access. When mapping parameters are linked within Access, only information that both tables have in common will be returned upon running the query. The mapping parameters used from each data source are listed in Table 3. Without these mapping parameters there would be no way to link all of the data sources together, and no database could be built.

Table 3: Mapping parameters related to different data sources

Data Source	Mapping Parameter
Material Data Records	MDR, Mix Design
LIMS Database	Project Number (SP), MDR , Mix Design
TSR Database	Project Number (SP), Mix Design
Pavement Management Systems	Route Type, Route Number, Year, Pavement Section Reference Points
Geographic Information Systems	Route Type, Route Number, Year, Pavement Section Reference Points, Project Number (SP)

The PMS as well as the GIS data sources have multiple mapping parameters in common. These include route type, route number, and pavement section reference points. These two data sources were combined into one source that contained both field performance cracking distress information as well as the Project Number, which was from the GIS data source. It was crucial to combine these two sources due to the project number being needed to link the distress information back to the mix parameter data sources. An explanation of how this combination of PMS and GIS data into one source is explained in Section 2.3.3.

2.3.2 Data Mapping within Microsoft Access

The method of using mapping parameters to join data sources in Microsoft Access is visualized in Figure 4. This screen shot illustrates how a query is conducted in Microsoft Access. The two tables selected in this example are the LIMS and TSR data sources. These tables are joined by mapping parameters in order to link the two sources together. This linking will allow for only information that is common between the two tables to be returned upon running the query. Mapping parameters of project number and mix designator (indicated as SP# in the figure) are shown in this example as the links between the two data sources. Connecting the two data sources by these mapping parameters allows for a query to be run that returns specific information from each source. For example, a search can be done that returns mix parameters (PG Grade, Percent Binder, etc.) from the LIMS data source that are paired with their corresponding ITS based on using project numbers and mix designators as mapping parameters between the two sources.

The linking of LIMS and TSR data sources is shown in Figure 5. This schematic again shows that the two tables are linked together by use of Project Number and Mix Designator as mapping parameters. The final outcome from this linking and combining is also shown in Figure 5. From this combined data set, lists of specific mix design information and corresponding ITS or TSR of that mix can be returned.

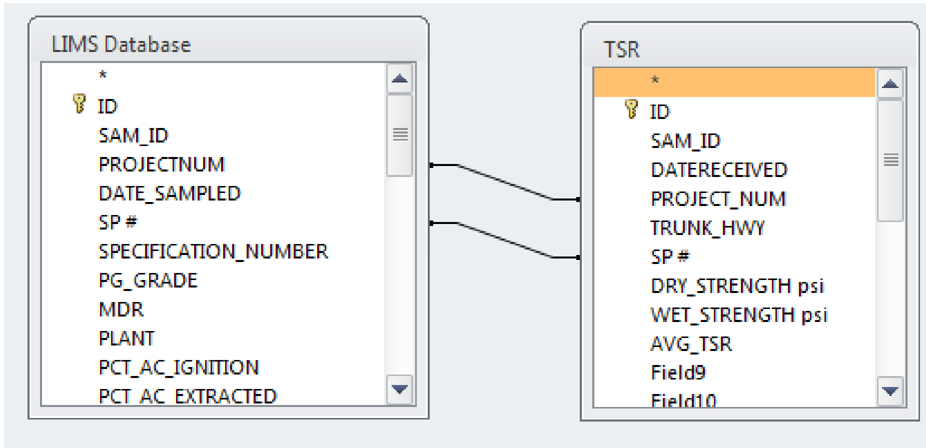


Figure 4 : Joining of Mapping Parameters between Data Sources in Microsoft Access

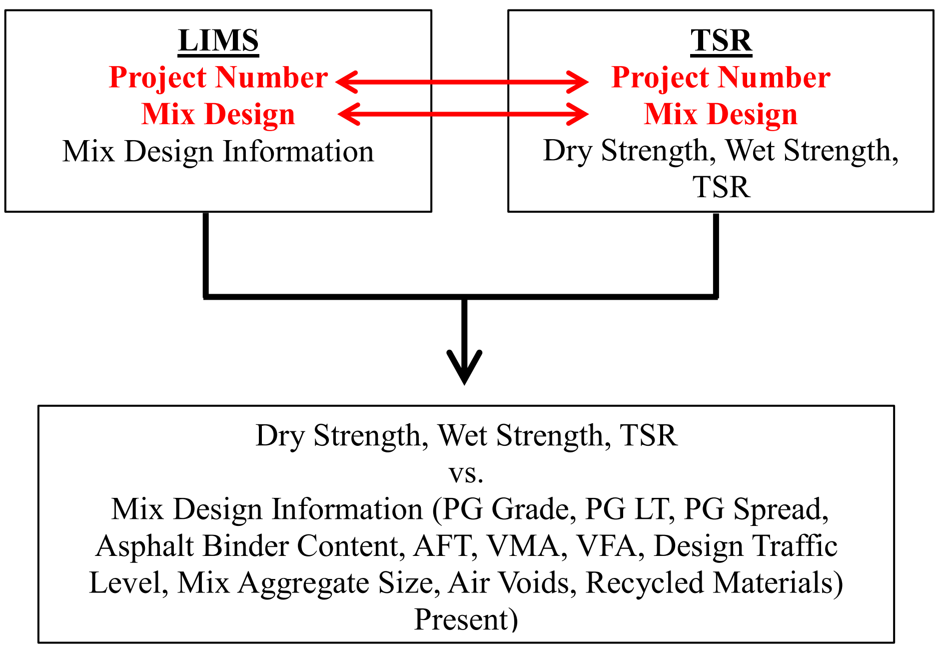


Figure 5: Linking and combining of LIMS and TSR data sets in Microsoft Access

2.3.3 Data Mapping using Custom Algorithm

For cracking distress data that was combined and analyzed with mix design information, the PMS data source needed to contain a mapping parameter that is common with both the LIMS and TSR data sources. The PMS data source contains distress information, as can be seen in Figure 6, is the only source of field cracking data in the comprehensive database. Without a common mapping parameter between the TSR, LIMS, and PMS data sources, no analysis of cracking data with mix parameters could be conducted.

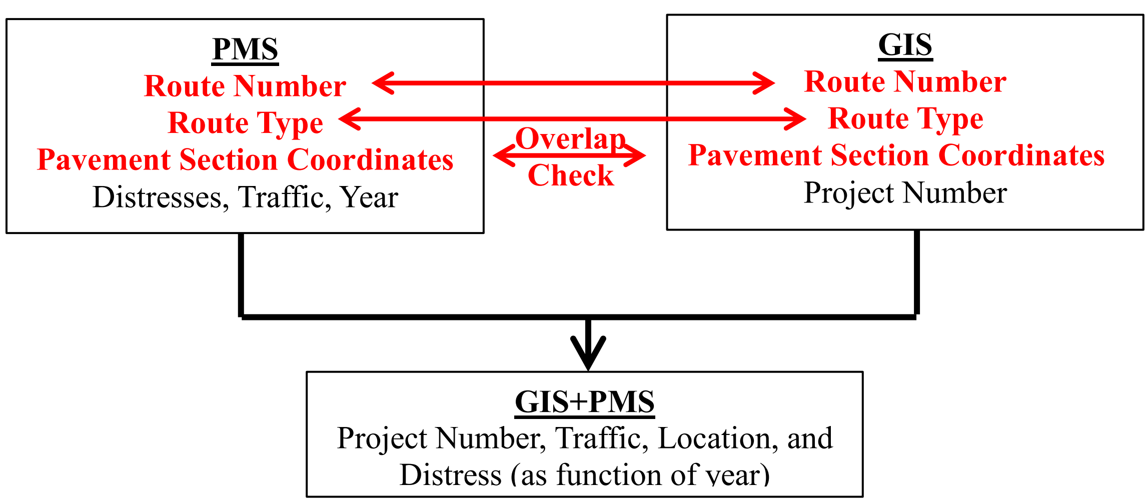


Figure 6: Linking and combining of PMS and GIS data sets in Microsoft Access

The GIS data source does however have a mapping parameter in common with the LIMS and TSR data sources. The Project Number (SP) of various mixes was included in GIS information. Both TSR and LIMS also contain the Project Number (SP) as a mapping parameter, as seen in Table 3.

There was a need to combine the PMS and GIS data in order for the Project Number of various mix designs to be joined with cracking distress information. Use of Microsoft Access for such combination was not possible as the PMS evaluation sections are often evenly spread across highway and do not directly overlap with scope of a pavement construction project, which is the case with GIS and in-turn LIMS and TSR databases.

Both PMS and GIS data sources contained common mapping parameters such as route number, route type, and pavement section coordinates. These pavement section coordinates however did not match up perfectly from one data source to another. This is due to the scope of pavement construction and rehabilitation projects to be independent from the PMS distress survey sections. An algorithm was created in Visual Basic within Microsoft Excel in order to combine the GIS and PMS data. The combined data was generated using the GIS coordinates of pavement sections.

The algorithm convention was to traverse through each record in the GIS dataset and for that record identify all the overlapping pavement sections in the PMS database. Once the exact match in GIS and PMS records had checked for the same route number, route type, and pavement section coordinate within the PMS source, the program then went to the next GIS record and continually looped through the program until every record was checked. Four different scenarios were possible while checking if the pavement section coordinates overlapped between the PMS and GIS data sources. These scenarios are shown schematically in Figure 7. The highlighted areas denote areas of overlap between pavement sections from the GIS and PMS data sources. Scenarios 3 and 4 also contained an additional check to ensure the overlap length of the pavement was at least 10% of total length of the GIS or PMS pavement section. If after the program was run and it was determined the pavement sections did match, the GIS records along with cracking information was combined on a table. This allowed for the cracking distress data to contain the Project Number mapping parameter.

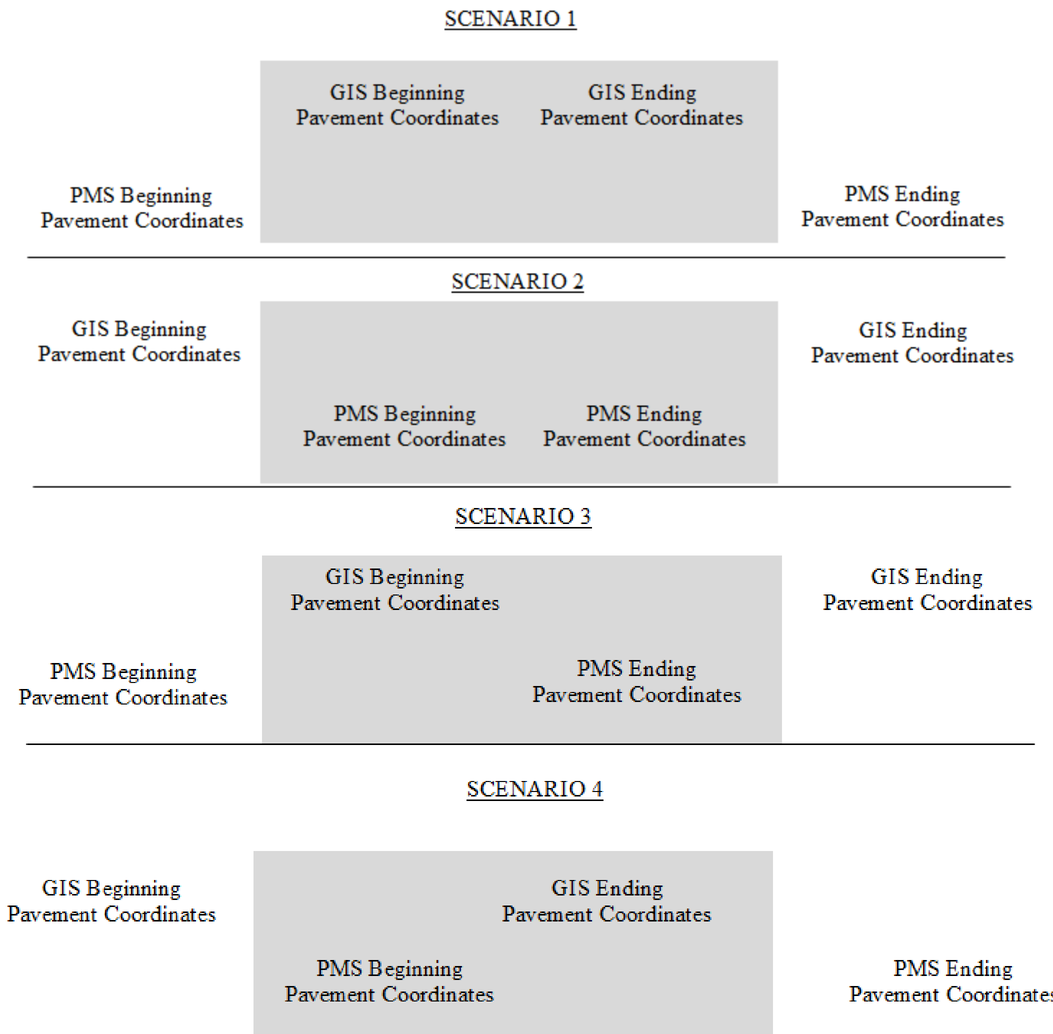


Figure 7: Pavement section coordinate overlap scenarios

Before the combination of GIS and cracking records could be done, a check of both distress survey years and years of newest rehabilitation or maintenance efforts on the corresponding pavement sections needed to be completed. The PMS data source contained information on years during which distress surveys were conducted. A large number of records exist in this data source due to distress surveys being conducted and recorded for multiple years for the same pavement section. The GIS data source contains the project let date, or most recent date of maintenance or rehabilitation construction.

Within the Visual Basic program, logic was implemented to screen out only records from the distress surveys that were conducted during the year of roadway construction or after the year of roadway construction. Distress data recorded before the latest construction year was screened out due to the cracking data not accurately corresponding to the asphalt material properties available in the database. The range of years of construction let dates within the GIS data source is 1999-2012. The ranges of years for which distress surveys are available in PMS data source range from 2004-2011. This results in records from 1999-2003 from the GIS data source to be screened out of the cracking analysis. Overall, the cracking analysis was conducted on pavements from the years 2004-2012.

Both transverse and longitudinal cracking data is recorded in the combined GIS and PMS data source. Within the Visual Basic code, six different cracking measures were calculated and recorded. These are same as those described in Table 2, that is, Maximum Total Transverse Cracking Amount (MTCTotal), Maximum Total Weighted Transverse Cracking Amount (MTCWeighted), Maximum Total Transverse Cracking Rate (MTCRTotal), Maximum Total Weighted Transverse Cracking Rate (MTCRWeighted), Average Total Transverse Cracking Rate (ATCTotal), and Average Weighted Total Transverse Cracking Rate (ATCWeighted) for transverse cracking. Similar measures are recorded for the longitudinal cracking. All of these amounts were recorded and included on a new data sheet with both GIS and field cracking data. The total amount of GIS and cracking records returned after running the macro was 2,128.

The cracking amounts in the PMS data source were recorded based on their severity of low, medium, or high. Both the total amount of cracking for each cracking measure along with a weighted cracking column were calculated after all of the data had been joined. The weighted column was calculated based on an arbitrary numerical value being placed on the different severity of cracking. Low severity was multiplied by an arbitrary weight of 1, medium severity was multiplied by 2, and high severity cracking was multiplied by 4. These values were then summed to represent a weighted cracking amount.

The maximum cracking for both transverse and longitudinal cracking was reported as the largest amount of cracking that occurred between distress survey years. This was done by checking the amount of cracking occurring each year, and returning the largest value. This value was then divided by the number of survey years conducted to represent the maximum cracking that occurred per year.

The maximum cracking rate for both transverse and longitudinal cracking was calculated by finding the absolute difference between cracking amounts from year to year. The absolute difference was used to negate if the amount was positive or negative. The largest difference of cracking rates between years was returned as the maximum longitudinal or transverse cracking rate. The low, medium, and high maximum cracking rates were also summed to create a total column as well as a weighted column. The weighted column used the same arbitrary numbering convention as the maximum cracking columns.

The average cracking for both transverse and longitudinal cracking was calculated based on the minimum cracking value subtracted from the maximum cracking value. This value was then divided by the number of years the pavement had been in service since the latest date of rehabilitation or maintenance, as per the GIS records. Total and weighted columns were also calculated for the average cracking values.

Once this combined sheet of cracking data was recorded, it was then imported back into Microsoft Access to be included in the database. This allowed for the cracking data to be linked with the LIMS, TSR, and MDR data sources by the Project Number mapping parameter. This is schematically shown in Figure 8. From this combined data source, queries were conducted to combine cracking amounts and cracking rates with various mix parameters. These lists of data were then statistically analyzed, which are discussed later in this report.

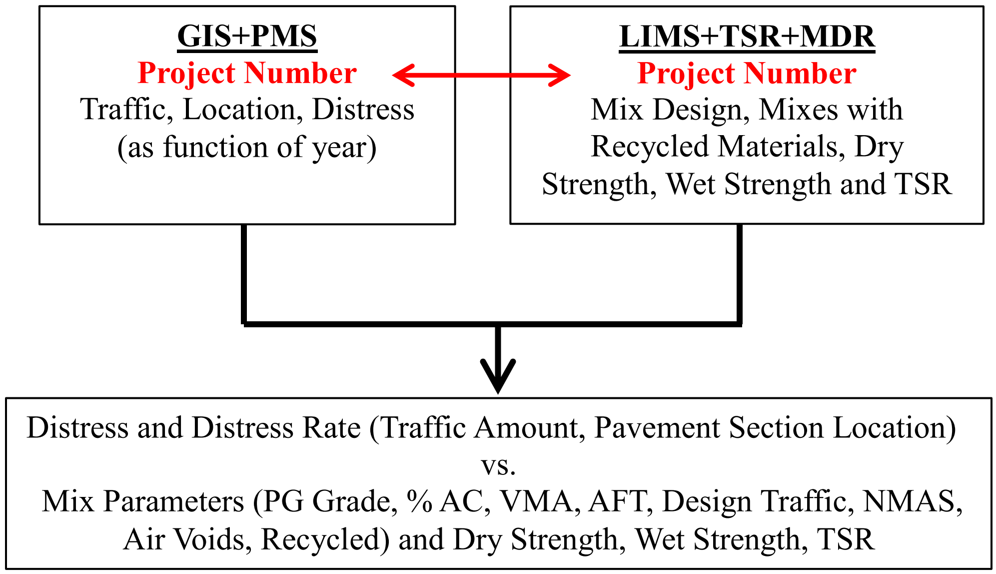


Figure 8: Linking and combining of PMS and GIS data sets to LIMS, TSR, and MDR data

2.4 Data Analysis Methodology

As described in the previous section, a comprehensive database of both mix design parameters and field performance cracking information was built in order to analyze if a statistically significant relationship existed between these measures. A statistically significant relationship would illustrate that certain mix design parameters have an effect on field cracking performance. Whether mix parameters and field cracking performance were related to ITS (dry or wet), or TSR of various mixes was also investigated. Significant relationships between mix design parameters and field cracking performance and the ITS or TSR is of interest when analyzing the effectiveness of using the AASHTO T-283 test as a field performance measure. Similarly, the effect of mix design parameters on cracking performance can provide information that can help modify mix design requirements and policy decisions, such as recommended asphalt binder grades or allowance for use of recycled materials. Figure 9 provides the schematic of data analysis. Data was exported from the comprehensive database and imported into statistical software titled SAS. A least-square mean and regression analysis was conducted on the data sets. The statistical analysis procedure used in this research is described in this section as analyzing mix design parameters with ITS data, as an example. Similar analyses were conducted for other measures, such as field cracking performance and mix design parameters.

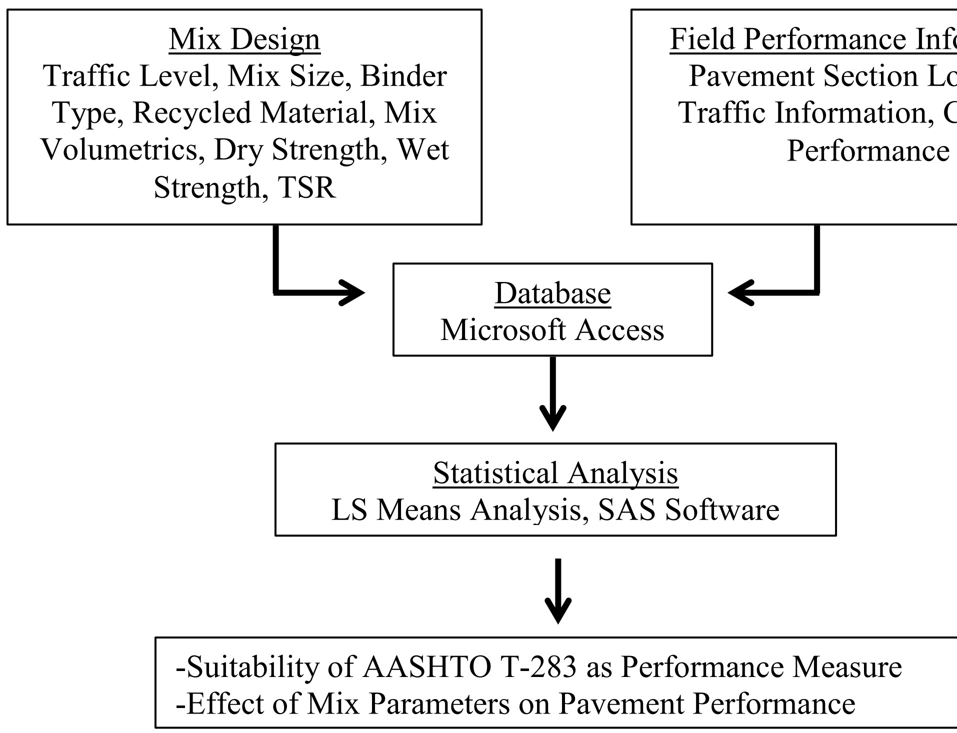


Figure 9: Schematic of database and data analysis organization

The statistical analysis dealing with mix parameters, ITS (dry and wet) and TSR was done in two phases. The first phase of statistical analysis includes single variable correlation. This consisted of only one mix parameter being paired with the ITS (dry and wet) and TSR, and then analyzed to investigate if a statistically significant relationship existed between them. The second phase of the analysis was a multiple variable correlation. Based on findings in phase one, groupings of two mix parameters were extracted from database records and returned with their ITS and TSR values. Mix parameters used in both the single and multiple variable analyses will be discussed in Chapter 3 in more depth.

Once the data was exported from the database, it was input to the SAS software. The data was analyzed using the least square means (LS Means) procedure. This type of analysis allows for investigating effects of multiple variables on a parameter of interest. For example, combined effects of asphalt mix design traffic level and asphalt binder grade on the dry ITS of mix.

2.5 Statistical Analysis of Mix Parameters and ITS and TSR

In statistics, inferences are made as to the confidence of predicting different unknown parameters. For example, a numerical estimate of a parameter can be done by a single point estimate or confidence interval, which represents a range of values the predicated parameter is likely included in.

Another form of predicting values of parameters is by using a non-numerical system of hypothesis testing. This form of statistical inference uses a choice between "two conflicting theories, or hypotheses" [17]. It clearly defines two possible outcomes from an experiment and uses probability to choose one outcome over the other. These two choices are called the null hypothesis and the alternative hypothesis. The null hypothesis is the choice that is trying to be disproved by hypothesis testing. This is to say, we are accepting the null hypothesis unless through probability we can prove that the alternative hypothesis is the better choice [17].

The statistical analysis conducted dealing with mix parameters and dry strength, wet strength, and TSR was done in two phases. The first phase was a single variable analysis. This consisted of only one mix parameter being paired with the dry strength, wet strength, and TSR and then analyzed to investigate if a statistically significant relationship existed. The second phase of the analysis was a multiple variable analysis. Based up on findings in phase one, groupings of two mix parameters were pulled from database records and returned with their dry strength, wet strength, and TSR values. Mix parameters used in both the single and multiple variable analysis will be discussed in Chapter 3 more in depth.

Once the data was exported from the database it was able to be input to the SAS software. The analysis that was run on the data was an LS Means analysis. This type of analysis allows for investigating effects of multiple variables. Due to a multiple variable analysis being conducted in this thesis, the LS Means analysis was chosen as the proper analysis to run on the selected data. The null hypothesis in the LS Means analysis is that the mix design parameters have no effect what it is being analyzed with (ex. ITS (dry), ITS (wet), or TSR). A p-value of > 0.05 indicates it can be said with 95% confidence that the null hypothesis is correct and no statistically significant relationship exists between the mix parameter and either ITS (dry), ITS (wet), or TSR. A p-value of < 0.05 indicates that it can be said with 95% confidence that the null hypothesis is not true, and it can be rejected. This means that the mix parameter does have a statistically significant relationship with either ITS (dry), ITS (wet), or TSR and it does indeed effect these values.

A screenshot of an output from the SAS software is shown in Figure 10. This table contains a variety of statistical and regression outputs based on input data. The value that is of most interest in this study was the p-value from the TYPE III SS results. It is labeled in the lower right hand of the output table in Figure 10. The TYPE III SS results were used versus the TYPE I SS due to TYPE III being a partial sum of squares. This means that the variables are being analyzed with all other variables present in the statistical model. With TYPE I, the variables are being added one at a time to the model based on how they were input into the program. This is referred to as a sequential sum of squares. Due to observing how the parameters affect the model as a whole with all other parameters also included, specifically during the multiple variable analysis, the TYPE III output is most relevant

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	39	2012247.125	51596.080	59.63	<.0001
Error	7919	6852193.158	865.285		
Corrected Total	7958	8864440.283			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.227002	29.23860	29.41573	100.6058

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	8	1842434.403	230304.300	266.16	<.0001
AsphaltContent	6	71981.532	11996.922	13.86	<.0001
PGGrade*AsphaltConte	25	97831.190	3913.248	4.52	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	8	125732.9492	15716.6187	18.16	<.0001
AsphaltContent	6	13602.0369	2267.0061	2.62	0.0154
PGGrade*AsphaltConte	25	97831.1899	3913.2476	4.52	<.0001

P<0.05
reject null
hypothesis

Figure 10: Output from LS Means Analysis in SAS of a multiple variable analysis

In statistics, a null hypothesis is used to determine if there exists a relationship between certain variables. The p-value represents if the null hypothesis is rejected or accepted, meaning it is either true or false. It is common practice to utilize a relatively low p-value (< 0.05) for rejecting the null hypothesis. This can also be stated as "there exists a mathematical relationship between variable 1 and variable 2, such that a linear function of variable 1 can predict variable 2 within a 95% confidence interval spread of variable 2 data". For the analysis conducted in this research, the null hypothesis was that no significant relationship occurred between mix parameters and ITS, TSR, or cracking measures. Thus, a p-value of < 0.05 represents a significant relationship occurring between the mix parameters being tested and either the ITS, TSR, or field cracking measures.

In the example shown in Figure 10, the multiple variable analyses containing mix parameters of PG Grade and Asphalt Content were analyzed against ITS (dry) to determine if a statistically significant relationship existed. The p-values for all mix parameters were < 0.05. Both PG Grade and the combined effect of PG Grade and Asphalt Content have p-values of < 0.0001, while Asphalt Content has a p-value of 0.0154. The smaller p-value represents that the significance between the variables is strong. The null hypothesis was rejected and it can be stated that PG Grade, Asphalt Content, and combined effects of PG Grade and Asphalt Content are related to the ITS (dry) of the asphalt mixes in database. It can also be inferred that the PG Grade and combined effects of PG Graded and Asphalt Content are strongly related to ITS (dry), whereas asphalt content is weakly related.

The initial analysis of ITS and TSR data with mix design parameters was conducted using the least squares mean regression analysis (LS Mean). This analysis was sufficient for most mix parameters due to the refinement of the data sets that was done through the use of bounds on the mix parameter values. These bounds allowed the LS Mean procedure to analyze the mix parameters with ITS or TSR. However, when conducting analysis to determine the statistical significance between ITS or TSR and the field cracking performance, it is not possible to put bounds on either set of variables due to the extent of spread. Thus, linear regression was sought as the alternative way to conduct a statistical analysis. Linear regression is based on inputting variables and analyzing if a linear relationship exists between them. An output from a linear regression analysis from the SAS software can be seen in Figure 11. The null hypothesis in a linear regression procedure is that the parameter estimate of the variable is 0. The parameter estimate column is outlined in Figure 11. This means that a p-value < 0.05 represents accepting the null hypothesis, and the parameter estimate is significantly different from zero. Thus, concluding that the variable contributes to the linear model of parameter that is being tested. In the example shown in Figure 11, ITS (wet) has a p-value < 0.0001. This represents that the parameter (transverse cracking amount) can be expressed as function of ITS (wet). The linear regression output also provides the coefficient of determination (or R^2) which is measure of the quality of fit for the aforementioned linear model. This parameter is important as it provides the measure of reliability with which the parameter (such as field cracking amount) can be predicted using the variable (such as ITS (wet)). For brevity only concise tables showing the p-values will be included in the rest of the report, however the detailed analysis results are included in the appendix.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	3703.95146	3703.95146	20.17	<.0001
Error	358	65736	183.61954		
Corrected Total	359	69440			

Root MSE	13.55063	R-Square	0.0533
Dependent Mean	16.68097	Adj R-Sq	0.0507
Coeff Var	81.23405		

← Very low R-square
Poor quality of fit

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	6.59044	2.35746	2.80	0.0055
WetStrength	1	0.12242	0.02726	4.49	<.0001

← p-value < 0.05
Accept null hypothesis

Figure 11: SAS linear regression output table

2.6 Presentation of Results

The data obtained after the statistical analysis will be presented in both graphical and tabular formats that contain information on the statistical inference gained from the SAS analysis as well as from the linear regression. Graphing of the data is shown to illustrate any concentration of data points that occurred as well as the spread of data points. Graphical interpretation is also important as the statistical analysis can often times indicate that one variable (such as, percent binder content) has significant effect on a quantity of interest (such as ITS), but may not point out as to how much change in that variable leads to a significant change in the quantity of interest. Furthermore, the quality of fit in linear regression also provides insight on reliability of using the variable to predict the quantity of interest as well as the general direction of trend.

Data vital to describing statistical relationships and significance will be included in the main body of the report. All other tables and graphs can be found in the electronic dataset that is accompanying this report. More concise tables have been generated for each set of data analyses. An example of such summary table is shown in Table 4. The table is showing the parameters that are being compared to ITS. These could be air void level, percent binder content, PG grade, ITS etc. Also notice that the last row of table shows results from grouped or paired analysis (herein referred to as "multiple variable analysis"), whereby combined effect of two parameters on the ITS was evaluated. The table shows three scenarios, the first scenario is for correlation between Parameter 1 and field cracking amount, where a relatively high p-value (> 0.05) indicates that field cracking amount is independent of Parameter 1. The second scenario shows that there exists a weak correlation between field cracking amount and Parameter 2, as evident by p-value that is smaller than 0.05 but not close to zero. Finally, the third scenario is in the last row which indicates that in a combined manner Parameter 1 and Parameter 2 has statistically significant effect on the ITS.

Table 4: Example of statistical analysis data table

Mix Parameter	p-value	Related to Mix Strength?
Parameter 1	0.231	No
Parameter 2	0.00235	Yes
Parameter 1 and Parameter 2	< 0.0001	Yes

An example of graphical presentation of the data is presented in Figure 12. This graphical data provides information that is supplemental to the information from Table 4. The statistical test informed that Parameter 2 has an effect on amount of cracking however did not provide us with additional information such as, how significantly does amount of field cracking change with change in Parameter 2, how reliably the field cracking can be predicted using Parameter 2, and finally whether the data agrees with general engineering knowledge. The plot shown in Figure 12 provides this information. It can be observed that the change in field cracking amount is relatively small over a large change in Parameter 2, which in case of this plot is ITS (dry). For change in ITS (dry) of 40 to 200 psi, the field cracking amount increased from 9 to 35 %/500 ft./year. The plot also indicates that the trend is counter-intuitive to general engineering knowledge that greater tensile strength is preferred. Finally, the quality of fit is very poor with coefficient of determination (R^2) to be 0.0474. Thus, this graphical representation was helpful in determining that Parameter 2 should not be used as a pavement performance indicator since: (a) The reliability of predicting performance is low (because of low R^2); (b) The effect of Parameter 2 on amount of cracking is small (small change in amount of field cracking for large change in Parameter 2); and (c) The data trend is reverse of what is expected based on engineering knowledge.

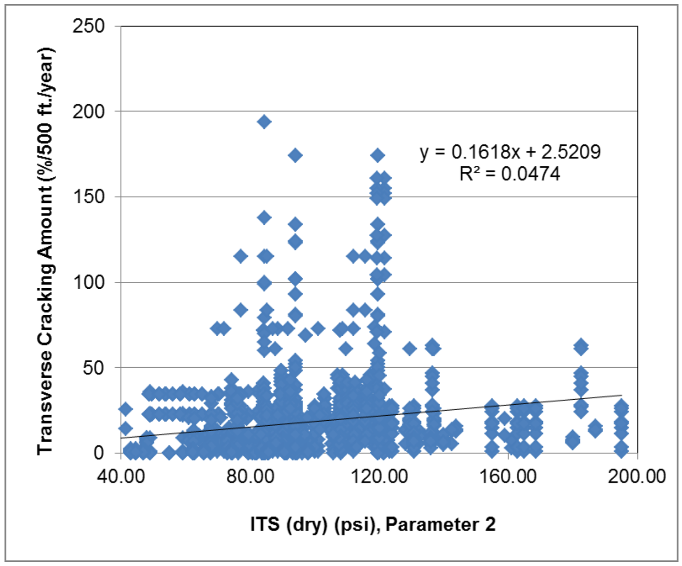


Figure 12: Example of graphical presentation

CHAPTER 3: EFFECT OF MIX DESIGN PARAMETERS ON INDIRECT TENSILE STRENGTH AND TENSILE STRENGTH RATIO

3.1 Introduction

This chapter describes the analysis that was conducted to determine suitability of the properties obtained from the AASHTO T-283 test procedure in the form of dry and wet indirect tensile strength (ITS) and/or tensile strength ratio (TSR) as mix performance parameter(s). Since the AASHTO T-283 testing is already part of the current MnDOT 2360 specifications for plant produced asphalt mix, if the material properties from this test can be used as pavement performance measure, minimal additional implementation and testing infrastructure development would be necessary.

As described in Chapter 2, the analysis was conducted in two phases. The first phase evaluated whether various mix design parameters had significant effects on lab measured ITS and TSR. The second phase evaluated the correlation between ITS and TSR with field cracking measures. The evaluation of effects of mix design parameters on ITS and TSR was necessary to determine if ITS and TSR are sensitive to commonly used asphalt mix design controls, such as asphalt film thickness (AFT) or asphalt binder grade.

3.2 Effects of Mix Design Parameters on ITS and TSR

This section describes the statistical analysis and the corresponding results for determination of effects of mix design parameters on the ITS and TSR of asphalt mixes. The initial analysis was conducted by evaluating statistical significance of one mix design parameter at a time on ITS and TSR, which is herein referred to as “single variable analysis". This was followed by a "multiple variable analysis" where combined effects of parameters were evaluated.

3.2.1 Single Variable Analysis

The first phase of the statistical analysis dealt with looking into the relationship between single mix parameters (single variable) and ITS (dry), ITS (wet), and TSR of various mixes. The mix parameters extracted by using queries run within the established database are listed in Table 5. The definitions of various mix design parameters are provided in section 2.2.2 LIMS Data.

Table 5: Single variable analysis mix parameters

Mix Parameters	AASHTO T 283 Measurements
AFT (AFT P_{be} and Adjusted AFT)	Dry Indirect Tensile Strength (Dry ITS), Wet Indirect Tensile Strength (Wet ITS), Tensile Strength Ratio (TSR).
Air Voids (Actual and Design)	
NMAS (Aggregate Mix Size)	
Percent Binder (Ignition and Extraction)	
PG Grade	
PG Spread	
PG LT	
Design Traffic Level	
VMA	
VFA	

The data is presented as the scatter plot for purpose of visualizing the breadth of the data and also to show if any visually observable trends were present (or absent). The data was thereafter processed to evaluate normalized frequencies of the ITS and TSR as function of mix design parameter and also to determine the mean, medium and standard deviations. Finally the data was processed through statistical analysis software SAS to determine if there was a statistically significant relationship between the mix parameters and ITS or TSR. The analysis and results are presented for one mix parameter at a time in subsequent subsections. Please note that for brevity only select results are presented herein.

3.2.2 Asphalt Film Thickness

The asphalt film thickness of mixes was compared against ITS (dry and wet) and TSR. The range of values for adjusted AFT was between 4 and 12 microns, and for those only based on P_{be} between 2 and 7 microns. A plot of the data points for AFT Adjusted and ITS (wet) is shown in Figure 13. The plot and the statistical analysis showed that no clear relationship exists between adjusted AFT and wet ITS. This poor relationship between the AFT mix parameter (both P_{be} and adjusted) was also evident in the analysis against dry ITS and TSR. This poor relationship corresponds to AFT not having significance on the ITS or TSR.

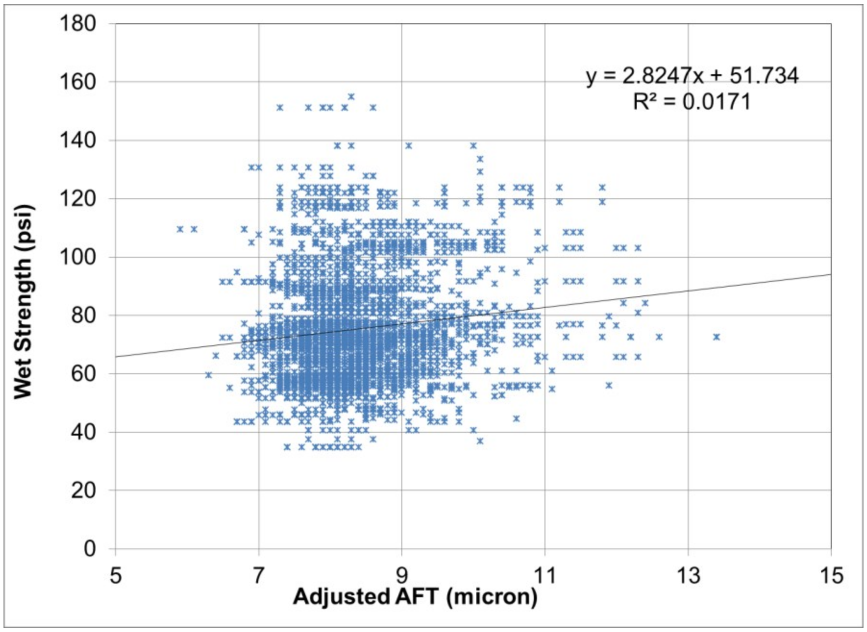


Figure 13: Asphalt Film Thickness versus Wet Strength

3.2.3 Designed Air Voids

Design air void levels that were extracted from the database represented three distinct values of 3.0%, 3.5%, and 4.0%. Initial graphing of the design air void level against ITS (dry) showed that a better representation of these results needed to be conducted, as seen in Figure 14.

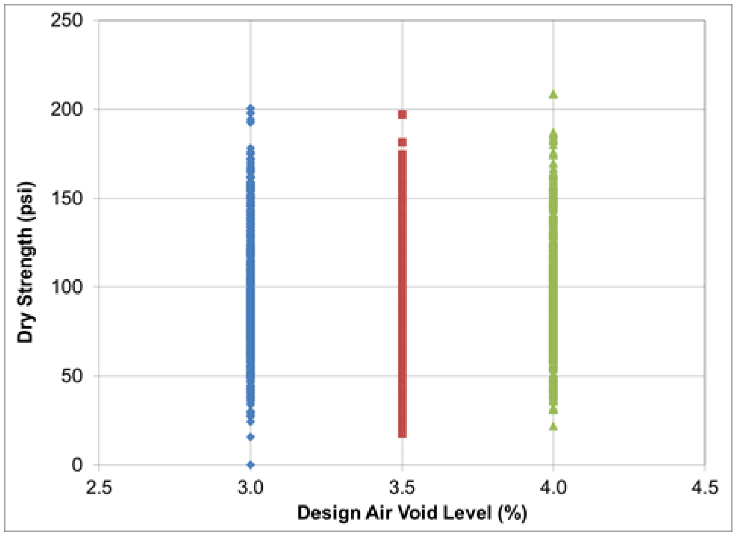


Figure 14: Initial plotting of ITS (dry) versus design air void level

A better representation was done by calculating the normalized frequencies of ITS and TSR intervals at 10 psi and 10% increments for each design air void level. Each frequency level represents the percent of mixes that were present for the given interval at the air void level. The normalized frequency plot for ITS (dry) and design air voids is present is Figure 15.

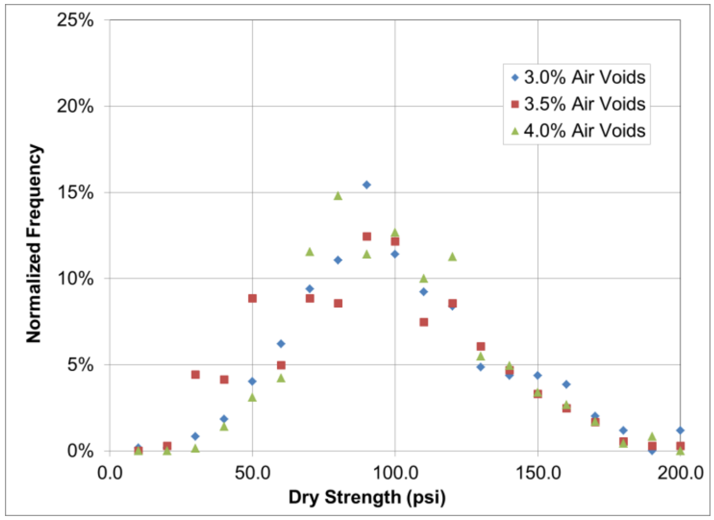


Figure 15: Normalized frequency plot of ITS (dry) for each design air void level

Table 6: ITS (dry) and design air void level statistics

ITS (dry) (psi)			
	3.0% Air Voids	3.5% Air Voids	4.0 % Air Voids
Median	90.6	88.0	92.7
Average	95.8	88.6	96.2
Standard Deviation	34.4	35.6	30.8

These normalized frequency plots allowed a visual representation of the average ITS or TSR value for each air void level. They also show if the spread in data and the mean values of ITS or TSR varied with the design air void levels. The median, average and standard deviation of each data set was also calculated and shown in Table 6. No noticeable trend is seen in the plot (Figure 15) and the statistical information (Table 6) also reaffirms this claim. This indicates that the correlation between design air void level and ITS (dry) is poor. Similar results were also seen during analysis of design air level against ITS (wet) and TSR.

3.2.4 Measured Air Voids

Actual air void level measurements were compared against ITS and TSR. The measured air void content of mixes ranged from values of 1-6 %. A plot of measured air voids and ITS (dry) is presented in Figure 16. Little correlation can be seen with a minor trend of increasing strength values with increasing air void level. The air void level and TSR show a very weak correlation between the two as well (c.f. Figure 17), with a trend of decreasing TSR with increasing air voids. This trend is expected as asphalt mixes with higher air voids tend to show decrease in strength after undergoing moisture conditioning. A similar relationship was also seen between the measured air voids and ITS (wet).

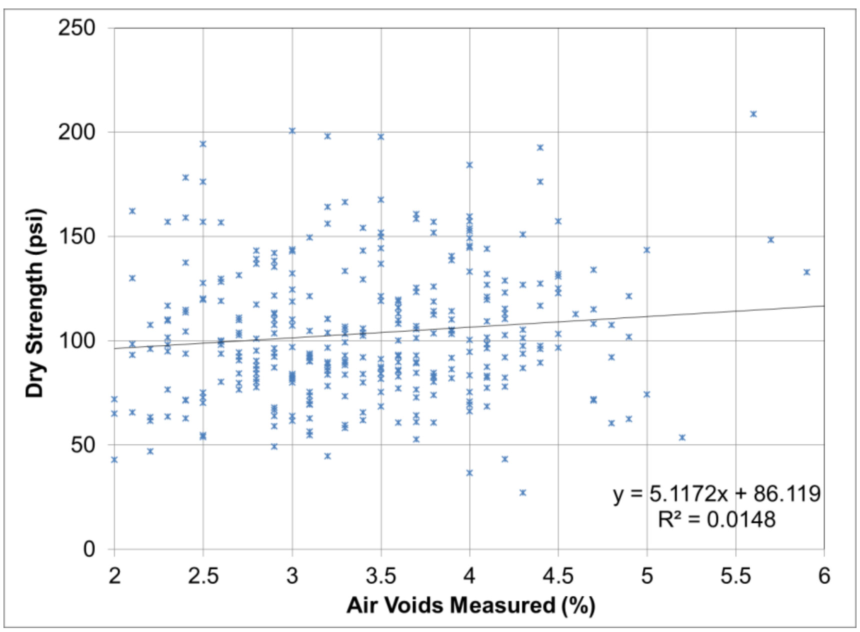


Figure 16: Measured air void level versus ITS (dry)

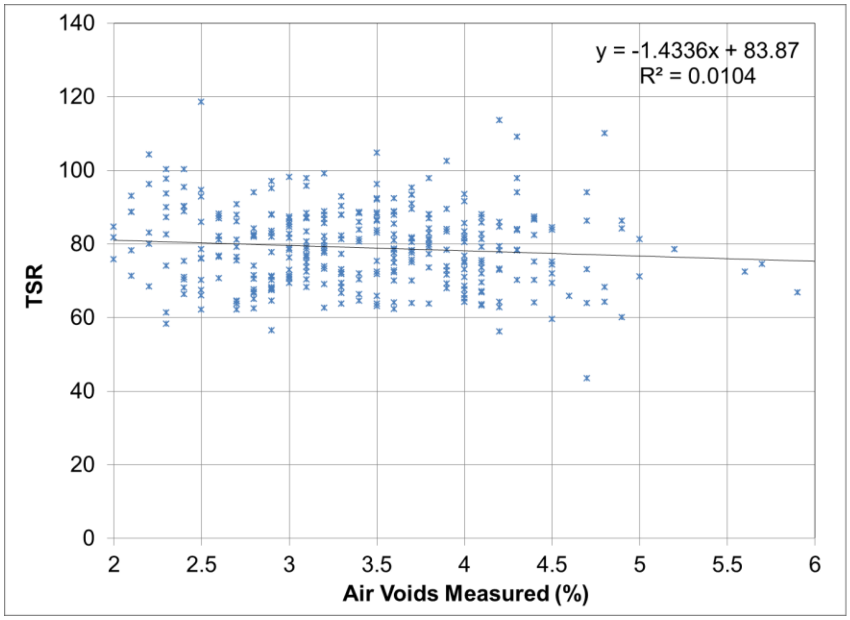


Figure 17: Measured air void level versus TSR

3.2.5 Mix Size (Nominal Maximum Aggregate Size)

The Nominal Maximum Aggregate Size (NMAS) represents the largest sieve size that retains less than 10% aggregate by weight. The NMAS of asphalt mixes were compared against ITS and TSR. The comparisons were conducted for 3/4 in., 1/2 in., 3/8 in., and 0.187 in. (#4) sized mixes. The data was analyzed using a normalized frequency, as it was discretized in four mix sizes. The normalized plots ITS (dry) for each of the four NMAS are presented in Figure 18.

The basic data statistics are shown in Table 7. The shaded columns of results represent NMAS values that contained very few data points. Due to a small representation of data for these NMAS values, the focus of results is on NMAS values of 1/2 in. and 3/8 in. The 1/2 in. NMAS did show a slightly higher value for average and median dry strength as compared to the 3/8 in. This very slight correlation of mix size to strength was also evident with wet strength. The TSR analysis showed no relationship between mix size and TSR value. The wet strength and TSR normalized plots are shown in Figure 19 and Figure 20 respectively.

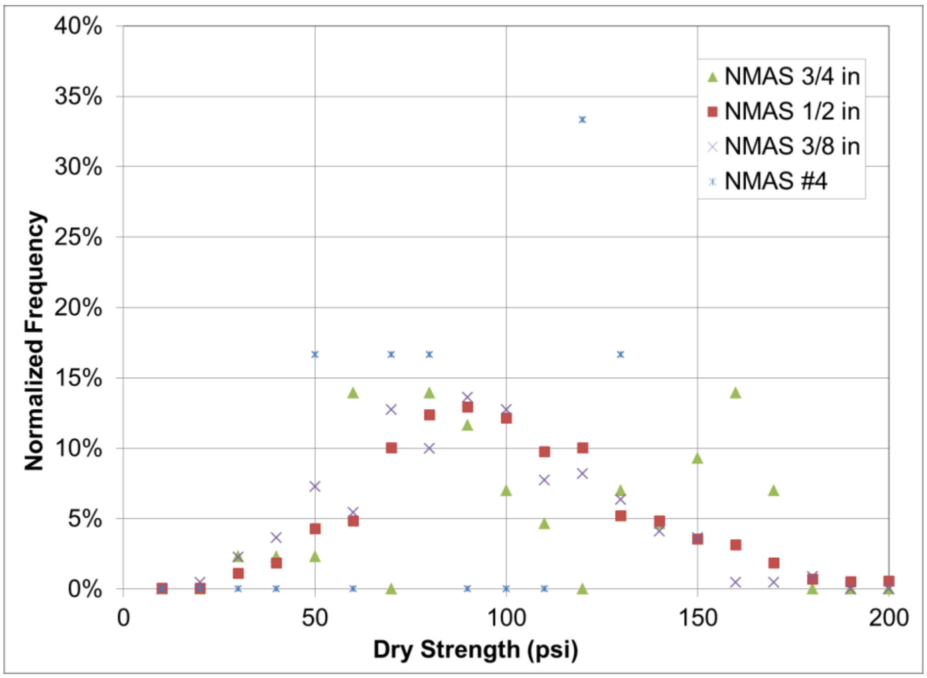


Figure 18: NMAS and Dry Strength normalized plot

Table 7: ITS and TSR statistics for various mix sizes (NMAS)

ITS (dry) (psi)				
Mix Size	3/4 in.	1/2 in.	3/8 in.	#4
Median	93.6	91.9	84.3	93.7
Average	103.5	95.4	87.0	91.3
Standard Deviation	42.4	33.1	31.2	26.1
ITS (wet) (psi)				
Mix Size	3/4 in.	1/2 in.	3/8 in.	#4
Median	74.9	72.2	66.9	73.5
Average	76.9	74.8	67.9	76.2
Standard Deviation	25.7	24.5	22.7	23.1
TSR (%)				
Mix Size	3/4 in.	1/2 in.	3/8 in.	#4
Median	77.8	79.2	79.8	84.8
Average	77.9	79.6	79.5	85.1
Standard Deviation	12.1	10.4	11.1	10.9

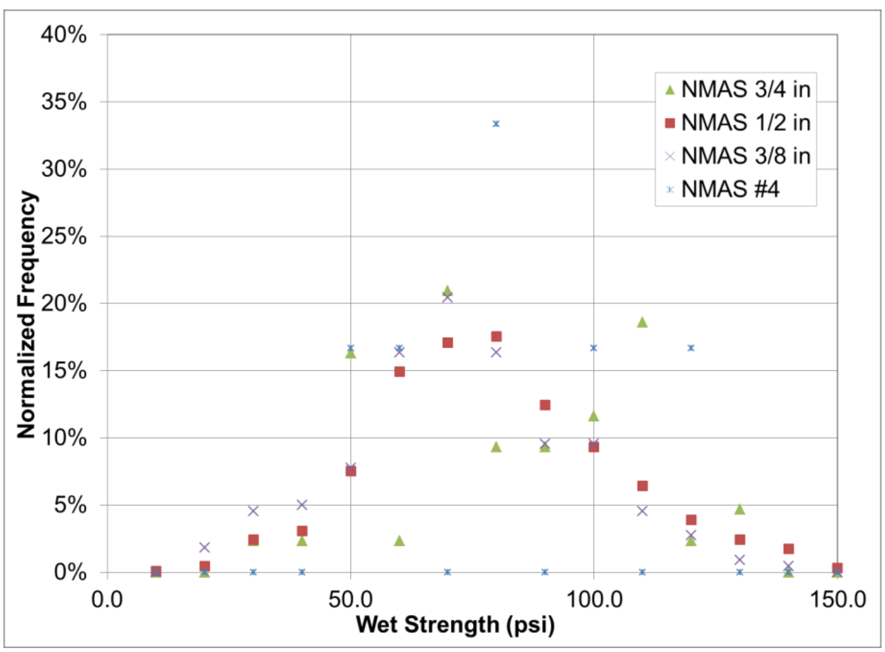


Figure 19: NMAS and Wet Strength normalized plot

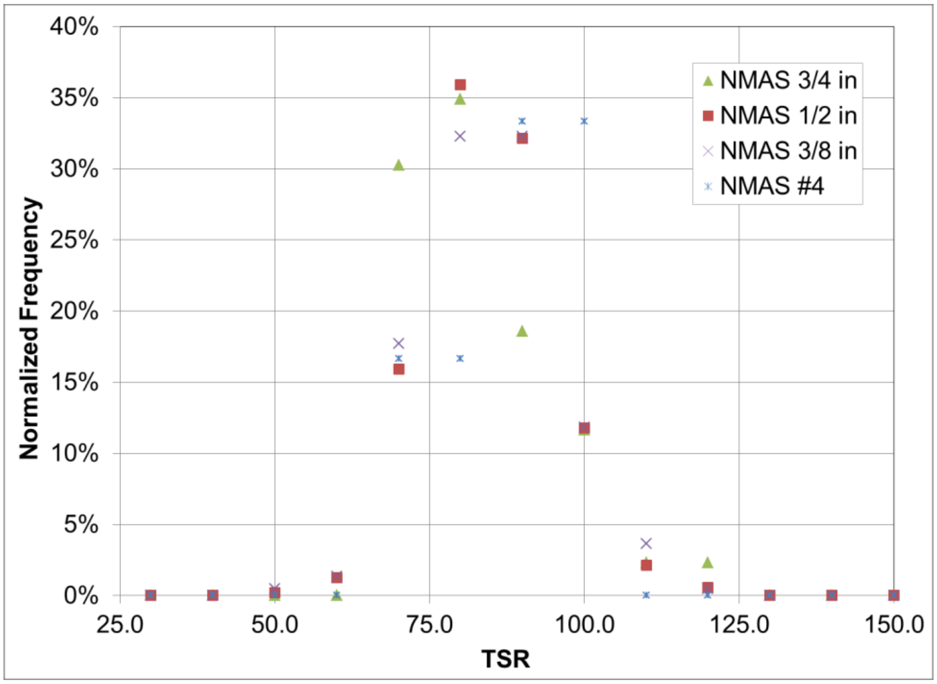


Figure 20: NMAS and TSR normalized plot

3.2.6 Asphalt Binder Content (Percent Binder)

The amount of asphalt binder present in mixes, measured using both ignition and extraction methods, was statistically evaluated. As stated previously, ignition and extraction refer to different laboratory methods used to determine the asphalt content of mixes. When percent binder content was compared to ITS (wet) and TSR, the trend of minimal to no correlation was seen. For TSR, the values stayed fairly constant between the different binder percentages. The strengths slightly increased with increasing percent binder amounts, but this effect was minimal. The analysis showed the same results for percent binder content determined using chemical extraction. When percent binder content was compared to ITS (wet) and TSR, the trend of minimal to no correlation was seen. For TSR, the values stayed fairly constant between the different binder percentages. The strengths slightly increased with increasing percent binder amounts, but this effect was minimal. The analysis showed the same results for percent binder content determined using chemical extraction.

Figure 21 shows the spread of data for asphalt binder content versus ITS (dry). No discernible correlation between asphalt binder content and ITS was observed A very slight increase of ITS can be seen from a linear fit.

When percent binder content was compared to ITS (wet) and TSR, the trend of minimal to no correlation was seen. For TSR, the values stayed fairly constant between the different binder percentages. The strengths slightly increased with increasing percent binder amounts, but this effect was minimal. The analysis showed the same results for percent binder content determined using chemical extraction.

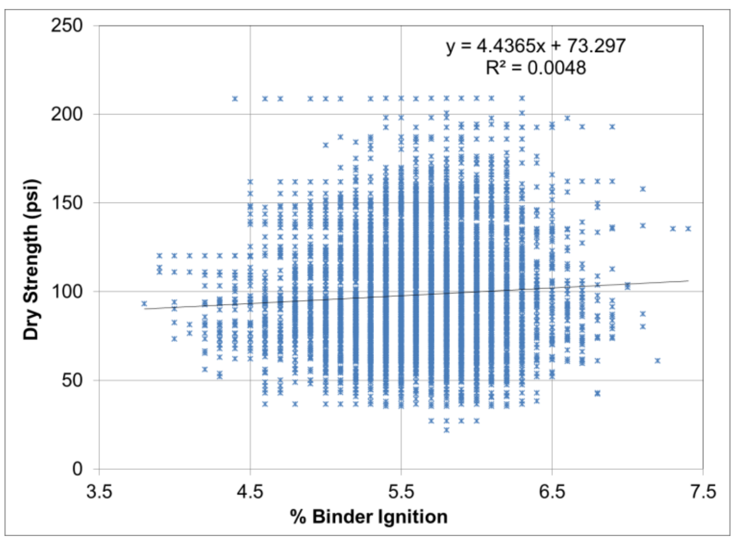


Figure 21: Percent asphalt binder content (ignition) versus ITS (dry)

3.2.7 Asphalt Binder Grade (PG Grade)

The PG Grade of mixes found within the database included eight different grades. These eight grades are shown along with the percent of mixes that used a given type of grade in Table 8. For the entire amount of PG grade data in the database, a significant amount exists for PG 58-34 and PG 58-28. This can be attributed to these being the most widely used asphalt binder grades in Minnesota. Binder grades of PG 58-40, PG 64-22, and PG 70-34 represented less than 1% of total data extracted from the database.

PG Grade	Percentage of Data
PG 58-28	63.40%
PG 58-34	20.50%
PG 58-40	0.20%
PG 64-22	0.50%
PG 64-28	9.80%
PG 64-34	4.40%
PG 70-28	1.00%
PG 70-34	0.20%

Table 8**:** Distribution of data of each binder grade

The normalized frequencies of ITS (dry) for each binder grade is plotted in Figure 22. The basic statistical data for the ITS (dry and wet) and TSR for each binder grade is presented in Table 9 .The grayed out columns represent binder grades with limited amount of data and thus it may not have a representative number of mixes to draw a reliable conclusion. The comparison of average ITS values constantly show that softer binder grades yield lower strength. This is expected as the ITS in AASHTO T 283 test is measured at 25 °C, where the mechanical behavior of mix is driven significantly by the binder behavior. The TSR showed little dependence on binder grade. Binders with greater spread in high and low temperature grades showed slightly higher values.

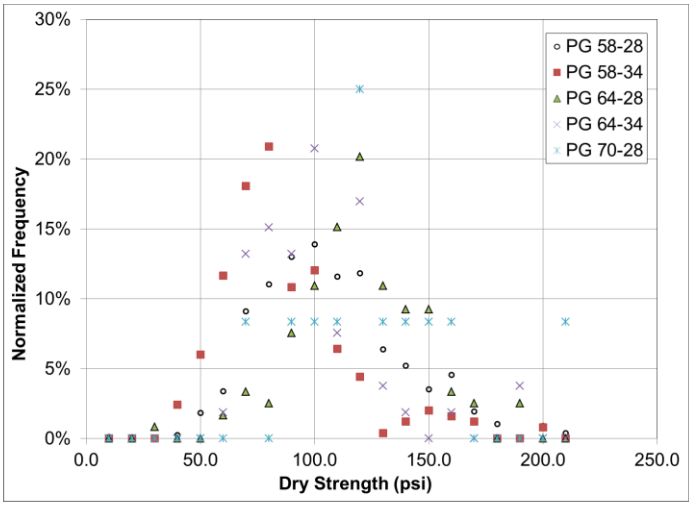


Figure 22: Normalized frequency plot of ITS (dry) for various asphalt binder grades (PG)

Table 9: ITS and TSR statistics for various asphalt binder grades (PG)

ITS (dry) (psi)								
Grade	PG 58-28	PG 58-34	PG 58-40	PG 64-22	PG 64-28	PG 64-34	PG 70-28	PG 70-34
Median	97.20	75.90	85.90	117.10	114.50	92.00	116.05	103.70
Average	101.84	81.08	85.90	119.18	115.16	96.50	122.23	103.70
Standard Deviation	31.08	28.00	---	---	27.38	26.82	36.30	---
ITS (wet) (psi)								
Grade	PG 58-28	PG 58-34	PG 58-40	PG 64-22	PG 64-28	PG 64-34	PG 70-28	PG 70-34
Median	76.00	62.60	66.75	103.80	91.60	78.00	101.40	91.35
Average	78.58	65.42	66.75	104.48	94.03	79.17	101.08	91.35
Standard Deviation	22.26	18.32	---	---	23.05	19.87	23.26	---
TSR (%)								
Grade	PG 58-28	PG 58-34	PG 58-40	PG 64-22	PG 64-28	PG 64-34	PG 70-28	PG 70-34
Median	78.00	81.90	77.90	85.25	82.00	83.50	83.70	87.85

Average	78.23	82.68	77.90	87.48	82.19	82.89	84.17	87.85
Standard Deviation	9.57	10.58	---	---	9.56	8.88	8.12	---

The asphalt binder grade data can be further analyzed with focus only on the low temperature grade of the binder, referred to as "PGLT". The main reason for evaluating binder grade data in context of PGLT is to focus on the thermal cracking behavior, which is the focus of this research. The distribution of the PGLT amongst the mixes present in database is tabulated in Table 10.

Table 10: Amount of data Distributed between PG LT

PG LT (°C)	Percentage of Mixes in Database
-22	0.5%
-28	73.1%
-34	26.2%
-40	0.2%

The ITS and TSR data corresponding to each PGLT was converted to normalized frequencies and plotted (Figure 23). A significant increase in strength for mixes with PGLT of -34 °C to -28 °C was observed, this is evident from the frequency plot as well as the average ITS values shown in Table 11. As stated previously, this decrease in strength for mixes with PGLT -34 °C binders over -28 °C binders is partially due to testing temperature associated with AASHTO T 283 specification [18].

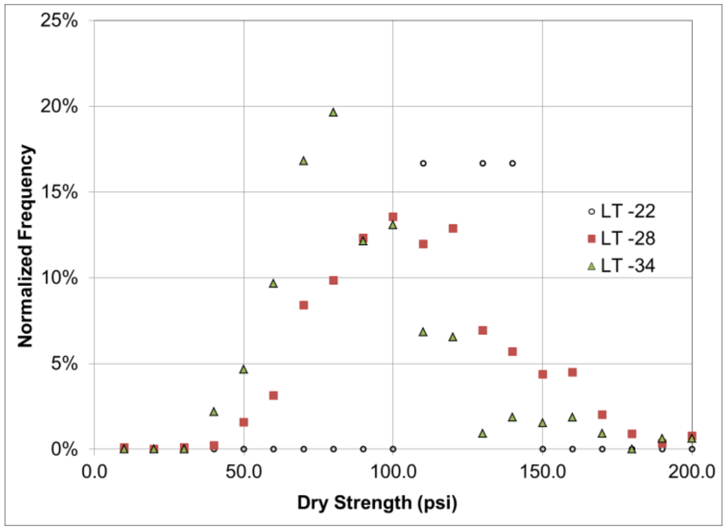


Figure 23: Normalized frequency plot of ITS (dry) for various temperature binder grades (PGLT)

Table 11: ITS (dry) for various low temperature asphalt binder grades (PGLT)

ITS (dry) (psi)				
PGLT	-22 °C	-28 °C	-34 °C	-40 °C
Median	117.1	100.8	79.2	85.9
Average	119.2	103.8	84.2	85.9
Standard Deviation	9.2	31.1	28.5	28.1

An alternative for evaluation of dependence of ITS and TSR on the type of asphalt binder is to look at data from the perspective of the spread in the binder grade. The PG spread of binder is essentially the difference between the high and low temperature grade of the binder. For the mixes present in the database the spreads of 86, 92, 98 and 104 °C were found. The distribution of the data falling under these spreads as well as the asphalt binders that provide these spreads are listed in Table 12. Due to use of PG 58-28 and PG 58-34 being primary asphalt grades for large amount of asphalt mixes in Minnesota, significant amount of data fell in 86 and 92 °C spread category.

Table 12: Distribution of data for PG Spread

PG Spread (°C)	PG Grades with listed Spread	Percentage of Data
86	PG 58-28, PG 64-22	64.2%
92	PG 58-34, PG 64-28	30.0%
98	PG 58-40, PG 64-34, PG 70-28	5.6%
104	PG 70-34	0.2%

The normalized frequency plots for the ITS (dry) and PG spreads of 86, 92 and 98 °C are presented in Figure 24. The statistics for the ITS (dry) for mixes in each PG spread category is tabulated (Table 13). The data shows that higher ITS values are present for mixes with PG spread of 86 and 98 °C as compared to 92 °C. The primary amount of mixes with PG spread of 98 °C represent binders with PG 64-34 and PG 70-28 grades, thus higher ITS values are expected. The PG spread did not show any discernible trends with TSR.

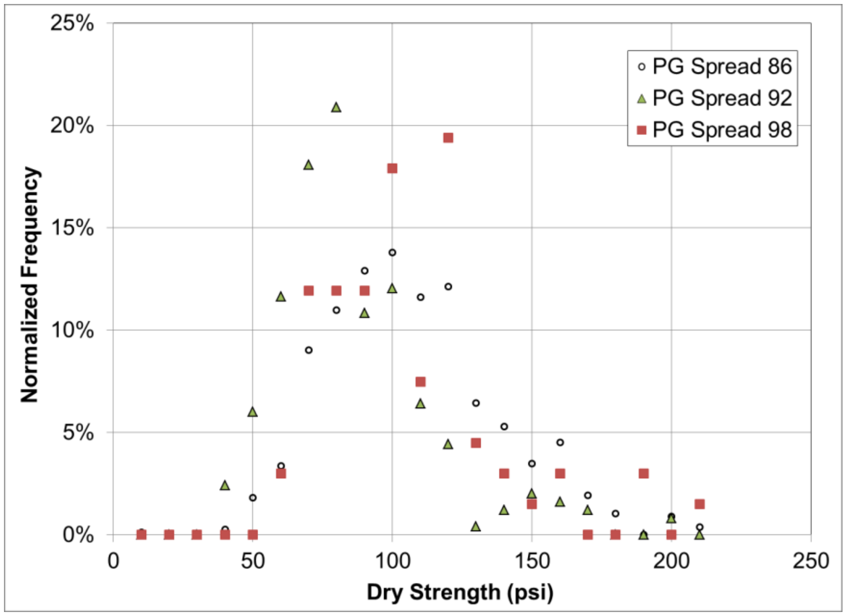


Figure 24: Normalized frequency plots of ITS (dry) for various spreads in binder grade (PG Spread)

Table 13: ITS (dry) for various spreads in asphalt binder grades (PG Spread)

ITS (dry) (psi)				
PG Spread	86 ºC	92 ºC	98 ºC	104 ºC
Median	97.90	86.95	97.40	103.70
Average	101.98	91.65	100.79	103.70
Standard Deviation	31.01	32.04	30.03	---

From analyzing PG Grade, PGLT, and PG Spread data, it can be concluded that there was a relationship between the binder type and ITS. This trend was especially evident binders with low temperature PG of -28 and -34 °C. This dependence is reflection of the test temperature of the AASHTO T 283 procedure [18]. This test is run at 25 °C, and it is run at this temperature regardless of what PG Grade is used in the specimen. This temperature does not accurately reflect the low temperatures pavements in Minnesota and other cold regions are subjected to during the winter months. The test temperature needs to be much lower in order to replicate what the mix will be subjected to when placed in the field. To replicate how the specimens will act and behave in environments for which they are rated for, they should be tested at temperatures for which they are designed. A mix using a PG Grade with a low temp of -34 °C should be tested around that temperature range rather than at 25 °C to model in place conditions.

3.2.8 Design Traffic Level

The database included mixes designed at traffic levels of 2, 3, 4, and 5. These traffic levels correspond to 20 year design ESALs as described in MnDOT 2360 specifications. The distribution of data extracted from the database pertaining to traffic level can be seen in Table 14. A large portion of the data corresponds to traffic levels of 2 and 3. The normal frequency plots of ITS (dry) for various traffic levels are presented in Figure 25. It can be seen that as the design traffic level increases the data generally shifts towards greater ITS. The basic statistical information for ITS (dry) data at each traffic level, shown in Table 15, also indicates the same.

Table 14: Distribution of data for design traffic levels

Traffic Level	Percentage of Data
2	37.2%

3	45.0%
4	16.3%
5	1.6%

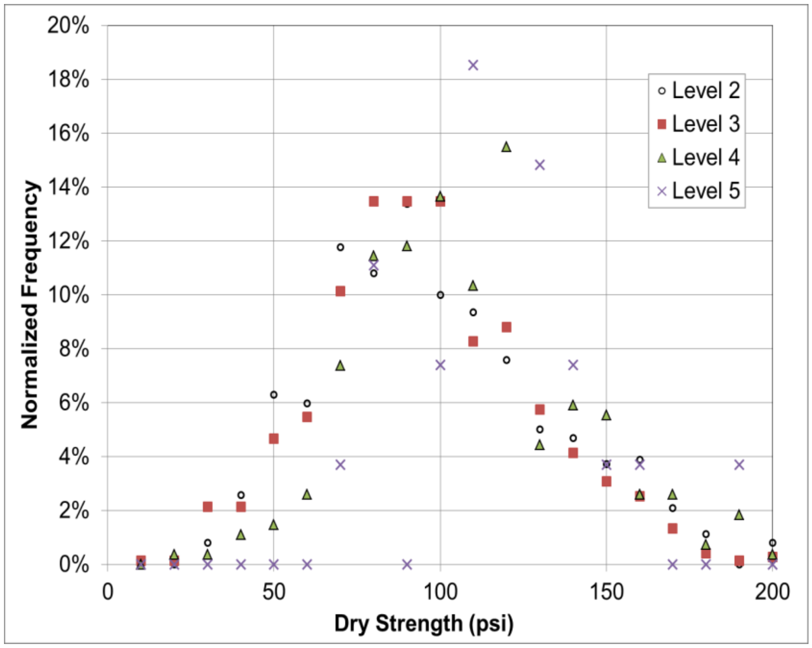


Figure 25: Normalized frequency plot of ITS (dry) for various traffic levels

Table 15: ITS (dry) for various design traffic levels

ITS (dry) (psi)				
Design Traffic Level	2 (< 1 million ESAL)	3 (1-3million ESAL)	4 (3-10 million ESAL)	5 (10–30 million ESAL)
Median	88.6	88.75	99.8	112.7
Average	93.5	91.2	103.1	117.8
Standard Deviation	34.7	31.9	31.8	31.4

The increase in ITS with increasing design traffic levels can be attributed to the greater amounts of crushed aggregate requirement at high traffic levels. For example, the MnDOT 3139 specifications require that mixes produced for traffic level 4 have 85% coarse aggregate with at least one crushed face and 8% with two or more versus a level 3 mix only requires 55% coarse aggregates to have at least one crushed face. With the ITS testing conducted at 25 °C, the aggregate shape plays an important role in the measured strength. Mixes with greater amount of crushed aggregates have capability to carry higher loads prior to failure.

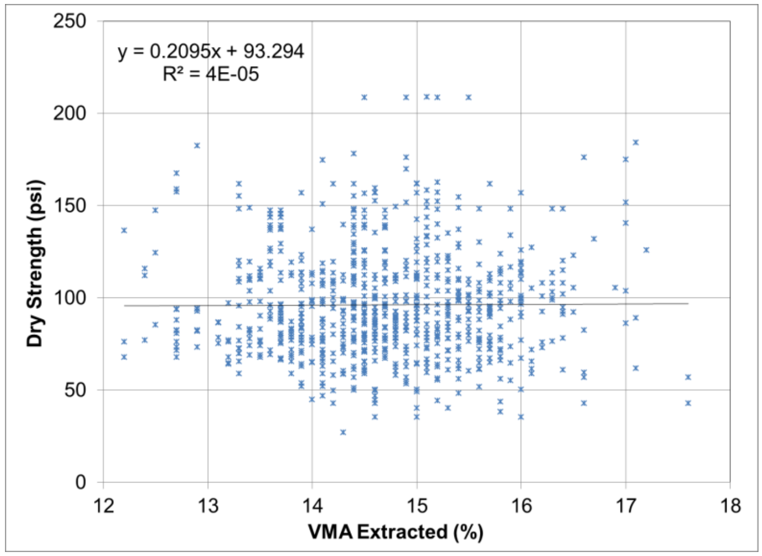
The statistical measures for the TSR data at various design traffic levels is tabulated in Table 16. The average TSR values for level 2 and 3 mixes are very close to each other. The increase in TSR values for level 4 and 5 is evident form the data and follows the higher requirement for TSR as per the MnDOT 2360 specifications.

Table 16: TSR for various design traffic levels

TSR (%)				
Design Traffic Level	2 (< 1 million ESAL)	3 (1-3million ESAL)	4 (3-10 million ESAL)	5 (10–30 million ESAL)
Median	78.4	78.9	81.5	83.8
Average	78.9	79.28	81.5	85.3
Standard Deviation	11.1	10.48	9.0	9.3

3.2.9 Voids in Mineral Aggregates (VMA)

The VMA calculated using the chemical extraction and ignition oven procedures were used for analysis. The data scatter for ITS (dry) and VMA (extraction) is presented in Figure 26. The data analysis demonstrated that for VMA calculated using either methods of chemical extraction or ignition oven, the ITS (dry and wet) and TSR showed



minimal to no correlation.

Figure 26: Voids in mineral aggregate (VMA chemical extraction method) versus ITS (dry)

3.2.10 Voids Filled with Asphalt (VFA)

The VFA values were compared with ITS (dry and wet) and TSR. Like VMA, the VFA values determined using chemical extraction and ignition oven methods were available in the database. The data scatter for ITS (dry) against VFA (ignition method) is plotted in Figure 27. The data analysis showed that ITS and TSR did not correlated with the VFA from either methods (extraction and ignition).

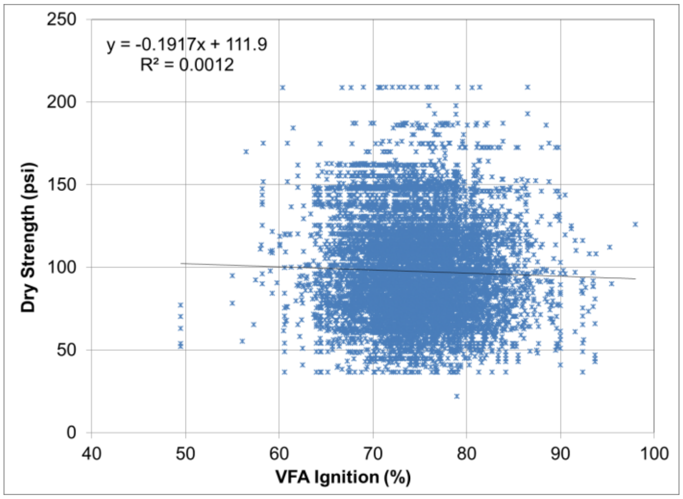


Figure 27: Voids filled with asphalt (VFA ignition oven method) versus ITS (dry)

3.2.11 Summary of Single Variable Analysis

The results from statistical testing of the ITS (dry) dependence on mix design parameters is summarized in Table 17. The only mix design parameters that caused ITS (dry) to have statistically significant dependence are the asphalt binder grade, air void level, mix size and design traffic level. Analysis showed that a change in PG Grade, in terms of low temperature of -34 to -28 °C, resulted in an increase in ITS. This may be attributed to the temperature at which the strength testing is conducted for the AASHTO T 283 procedure [18]. The traffic level correlating to mix strength can be attributed to the amount of fractured or crushed aggregate required in mixes depending on design traffic level. The increasing air void level showed very slight increase in the ITS (dry) and the increasing mix size showed minor increase in ITS (dry) as well. The ITS (wet) values were also compared against the mix design parameters to determine if it depended on them in a statistically significant manner. The results are presented in Table

18. In general, the results follow similar trends as discussed for ITS (dry), the only difference is that ITS (wet) did not demonstrate dependence on the actual air void level.

Table 17: Significance of mix design parameters on ITS (dry)

Mix Parameters	p-value	ITS (dry) is related to mix parameters?
AFT Adjusted	0.2121	no
AFT Pbe	0.8865	no
Percent Binder (Chemical extraction)	0.2559	no
Percent Binder (Ignition oven)	0.2453	no
VMA (Chemical extraction)	0.1633	no
VMA (Ignition oven)	0.0313	yes (weak)
PG Grade	< 0.0001	yes
VFA (Chemical extraction)	0.0669	no
VFA (Ignition oven)	0.7937	no
Design Air Void Level	0.0009	yes
Actual Air Void Level	0.0081	yes
Mix Size (NMAS)	0.0014	yes
Design Traffic Level	< 0.0001	yes

Table 18: Significance of mix design parameters on ITS (wet)

Mix Parameters	p-value	ITS (wet) is related to mix parameters?
AFT Adjusted	0.0969	no
AFT Pbe	0.8953	no
Percent Binder (Chemical extraction)	0.0536	no
Percent Binder (Ignition oven)	0.2188	no
VMA (Chemical extraction)	0.6859	no
VMA (Ignition oven)	0.0709	no
PG Grade	< 0.0001	yes
VFA (Chemical extraction)	0.1395	no
VFA (Ignition oven)	0.5256	no
Design Air Void Level	< 0.0001	yes
Actual Air Void Level	0.1716	no
Mix Size (NMAS)	0.0013	yes
Design Traffic Level	< 0.0001	yes

The TSR measurements in the database were also analyzed to determine if there was statistically significant dependence of TSR on various mix design parameters. The summary of this analysis is presented in Table 19. The results show that only asphalt binder grade (PG), design air void level, and design traffic level were significant variables affecting the TSR of mixes. The results from the single variable analysis were used to decide on groupings of mix parameters to be analyzed during the multiple variable analyses, which are discussed in the next section.

Table 19: Significance of mix design parameters on TSR

Mix Parameters	p-value	TSR is related to mix parameters?
AFT Adjusted	0.1822	no
AFT Pbe	0.5294	no
Percent Binder (Chemical extraction)	0.2549	no
Percent Binder (Ignition oven)	0.0522	no
VMA (Chemical extraction)	0.8959	no
VMA (Ignition oven)	0.4088	no
PG Grade	< 0.0001	yes
VFA (Chemical extraction)	0.5668	no
VFA (Ignition oven)	0.1529	no
Design Air Void Level	0.0007	yes
Actual Air Void Level	0.3137	no
Mix Size (NMAS)	0.4261	no
Design Traffic Level	0.0002	yes

3.3 Multiple Variable Analysis

The multiple variable analysis was the next step in evaluating the effects of mix design parameters on ITS and TSR. In the single variable analysis, only one mix parameter was compared to the ITS and TSR values. The multiple variable analysis grouped mix parameters together to quantify their combined effect on strength and TSR. It is important to conduct this type of analysis, since while independently two parameters may not show significant effect on ITS in a combined manner they might be significant. For example, the VMA of the mix may not be significantly affecting the ITS when looked independently, but combined effects of VMA and asphalt content may be significant.

The groupings of mix parameters were done based on the results obtained from the single variable analysis. These groupings are illustrated in Figure 28. The mix parameter that was found to have dependence to mix strength in the single variable analysis was the PG Grade. Due to these parameters already being known to influence the mix strength, they were paired with other mix parameters. The PG Grade of different mixes was combined with VMA, Asphalt Content, and AFT for multiple variable analyses. AFT (AFT P_{be} and AFT Adjusted) and VMA (Ignition and Extraction) were also paired with asphalt content to quantify their combined effects on mix strength and TSR.

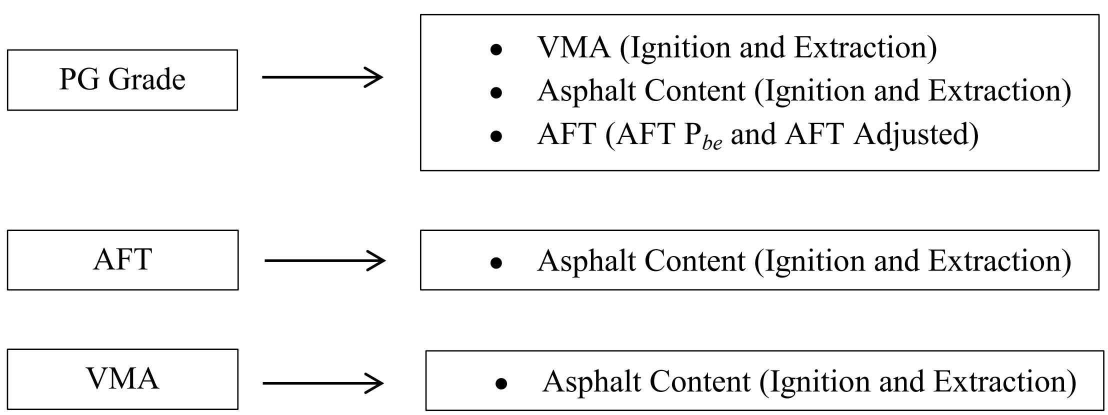


Figure 28 : Multiple Variable Analysis Mix Parameter Groupings

The combined effects of the pairings on ITS (dry and wet) and TSR was determined using the least-squares mean analysis using the statistical analysis software SAS. The lists of paired parameters were first obtained from the comprehensive database. To refine the results from the statistical analysis, bounds were put on the different mix parameter values. Character values were given to define these bounds. The bounds put on the mix parameter values as well as the characters assigned to each bound can be seen in Figure 29.

The results of the least-square means analysis are presented in concise summary tables. The dependence of ITS (dry) on grouped mix parameters are shown in Table 20. The results for similar set of analyses with the ITS (wet) is presented in Table 21. The results are very similar to those obtained for ITS (dry).

VMA (%)	Character
< 11	A
11-12	B
12-13	C
13-14	D
14-15	E
> 15	F

% Binder	Character
< 3.5	A
3.5-4.0	B
4.0-4.5	C
4.5-5.0	D
5.0-5.5	E
5.5-6.0	F
> 6.0	G

AFT (microns)	Character
< 6.0	A
6.0-7.0	B
7.0-7.5	C
7.5-8.0	D
8.0-8.5	E
8.5-9.0	F
9.0-10	G
> 10	H

PG Grade	Character
52-34	A
58-28	B
58-34	C
64-28	E
64-34	F
70-28	H
70-34	I
64-22	L

PG LT	PG Grade	Character
-28	58-28, 64-28, 70-28,	A
-34	52-34, 58-34, 64-34, 70-34	B
-22	64-22	C

PG Spread	PG Grade	Character
86	52-34, 58-28, 64-22	A
92	58-34, 64-28	B
98	64-34, 70-28	C
104	70-34	D

Figure 29: Character Keys for the bounds of various asphalt mix parameters

Table 20: Dependence of ITS (dry) on grouping of mix parameters

Mix Parameters	p-value	ITS (dry) is related to mix parameters?
PG Grade and VMA Extracted	0.0977	no
PG Grade and VMA Ignition	0.0535	no
PG Grade and Percent Binder Extracted	0.1292	no
PG Grade and Percent Binder Ignition	<0.0001	yes
PG Grade and AFT Adjusted	<0.0001	yes
AFT Adjusted and Percent Binder Ignition	<0.0001	yes
AFT Adjusted and Percent Binder Extracted	0.4029	no
AFT Pbe and Percent Binder Extracted	-	no
AFT Pbe and Percent Binder Ignition	-	no
VMA Extracted and Percent Binder Extracted	0.0024	yes
VMA Extracted and Percent Binder Ignition	0.4082	no
VMA Ignition and Percent Binder Extracted	0.0678	no
VMA Ignition and Percent Binder Ignition	<0.0001	yes

Table 21: Dependence of ITS (wet) on grouping of mix parameters

Mix Parameters	p-value	ITS (wet) is related to mix parameters?
PG Grade and VMA Extracted	0.1721	no
PG Grade and VMA Ignition	0.3070	no
PG Grade and Percent Binder Extracted	0.2474	no
PG Grade and Percent Binder Ignition	<0.0001	yes
PG Grade and AFT Adjusted	0.0040	yes
AFT Adjusted and Percent Binder Ignition	<0.0001	yes
AFT Adjusted and Percent Binder Extracted	0.0731	no
AFT Pbe and Percent Binder Extracted	-	no
AFT Pbe and Percent Binder Ignition	-	no
VMA Extracted and Percent Binder Extracted	0.0286	yes
VMA Extracted and Percent Binder Ignition	0.7975	no
VMA Ignition and Percent Binder Extracted	0.1139	no
VMA Ignition and Percent Binder Ignition	0.0020	yes

The analysis shows that the ITS on the mix is strongly dependent on pairings of PG grade and asphalt binder content (ignition method), PG grade and AFT adjusted, AFT adjusted and percent binder content (ignition method), and VMA (ignition method) and percent binder content (ignition method). The ITS also showed dependence on the pairing of VMA (extraction method) and percent binder content (extraction method), but this dependence is weaker than the ones listed before.

The mix parameter pairings involving percent binder content using chemical extraction yielded results of no correlation to ITS, with exception to the pairing with VMA (extraction method). In contrast, pairings including percent binder content determined using ignition oven, with exception to being paired with VMA (extraction method), yielded correlation to ITS. This suggests that the method of determining the percent binder content in asphalt mixes can bias the ITS of mix and require further investigation.

Since the asphalt mix design procedures rely heavily on use of volumetric quantities such as AFT or VMA, it was expected that through groupings with either binder content or PG grade the ITS will show dependence on these. However the results indicate a non-consistent dependence of ITS on either AFT or VMA. This result indicates that if the ITS was to be used as performance measure, the presence of either AFT or VMA requirements in specification cannot substitute the need for measuring ITS through laboratory testing.

The TSR data was also analyzed to determine its dependence on grouping of mix variables. The results are presented in Table 22. The analysis resulted in only one strong dependence, which is for the grouped pairing of PG grade and percent binder content (ignition method). Other dependencies varied from intermediate to weak. Once again, no clear dependence for the volumetric measures (AFT and VMA) were seen when they were grouped with PG grade or asphalt content.

Table 22: Dependence of TSR on grouping of mix parameters

Mix Parameters	p-value	TSR is related to mix parameters?
PG Grade and VMA Extracted	0.1705	no
PG Grade and VMA Ignition	0.0145	yes
PG Grade and Percent Binder Extracted	0.7439	no
PG Grade and Percent Binder Ignition	<0.0001	yes
PG Grade and AFT Adjusted	0.6000	no
AFT Adjusted and Percent Binder Ignition	0.0020	yes
AFT Adjusted and Percent Binder Extracted	0.0099	yes
AFT Pbe and Percent Binder Extracted	-	no
AFT Pbe and Percent Binder Ignition	-	no
VMA Extracted and Percent Binder Extracted	0.0042	yes
VMA Extracted and Percent Binder Ignition	0.0551	no
VMA Ignition and Percent Binder Extracted	0.0118	yes
VMA Ignition and Percent Binder Ignition	0.0020	yes

3.3.1 Summary of Analysis to Evaluate Effects of Mix Design Parameters on ITS and TSR

The analysis of the ITS and TSR data with respect to various asphalt mix design parameters provided insight into dependence of these mechanical properties on the mix design. The analysis yielded following findings:

- Most asphalt mix volumetric parameters (such as, AFT, VMA, VFA and air void level) show minimal to no influence on the ITS. The TSR of mix deteriorates slightly with increase in air void level.
- Increase in the asphalt binder content (% AC) leads to reduction in ITS of the mix. This indicates that the ITS, as determined using AASHTO T-283 procedure which is at 25 °C, may be decreasing as the mixes become more ductile in nature.
- The ITS of mix decreases with use of softer asphalt binder grade such as, PG 58-34 as compared to PG 58-28. The low temperature binder grade (PGLT) has a significant effect on ITS. The drop in ITS with use of softer binder also supports the hypothesis that ductile mixes will have lower ITS.
- The ITS values for traffic level 4 and 5 mixes are significantly higher than level 2 and 3 mixes. The increase in ITS is anticipated due to increase amount of crushed aggregates in high traffic level mixes.

The minimal dependence of ITS on mix volumetrics and the decreasing trend in ITS values with use of softer binder grades and higher binder amounts reduce the confidence for its use as a pavement cracking performance indicator. However, it is important to directly evaluate the correlation between actual field cracking performance of asphalt pavements in Minnesota against the corresponding ITS values of the mixes before drawing the final conclusion on the topic. The next section presents the analysis between field cracking measures and ITS (and TSR) to determine if these lab measured parameters can be used to predict the field performance and in-turn can be used as laboratory performance test.

3.4 Correlation between Field Cracking Measures and ITS

The contents of this section include description of statistical analysis that was conducted for investigating the relationship between ITS (dry and wet) and TSR against field cracking performance. The field cracking performance was expressed in the form of twelve different measures of transverse and longitudinal cracking. For transverse cracking these measures are: Maximum Total Transverse Cracking Amount (MTCTotal), Maximum Total Weighted Transverse Cracking Amount (MTCWeighted), Maximum Total Transverse Cracking Rate (MTCRTotal), Maximum Total Weighted Transverse Cracking Rate (MTCRWeighted), Average Total Transverse Cracking Rate (ATCTotal), and Average Weighted Total Transverse Cracking Rate (ATCWeighted). Similar measures were also used for longitudinal cracking. The detailed description of these measures and their calculation are discussed in Chapter 2 of this report (refer to Table 2).

The analysis and results presentation for this section is divided in two potions. The first subsection discusses the maximum total and weighted cracking amounts and rates whereas the second subsection focuses on the average cracking rates.

3.4.1 Effects of ITS and TSR on Maximum Cracking Amounts and Rates

3.4.1.1 ITS (dry)

The linear regression analysis of the maximum transverse and longitudinal cracking amounts and rates provided insight into relationships between the ITS (dry) of asphalt mixes and the field cracking performance. The results from this analysis are presented in the form of summary table as well as the scatter plots showing the linear fitting lines and quality of fit (R^2). The summary of analysis is provided as Table 23. The results show that ITS (dry) of the mix has an effect on all maximum transverse and longitudinal cracking amounts and rates except the maximum total longitudinal cracking rate. It should be noted that the primary cracking parameter of interest in this study is the maximum weighted transverse cracking amount (MTCWeighted), as it is expected to be the most encompassing measure that is closely related to the pavement durability and ride quality.

Table 23: Effects of ITS (dry) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to ITS (dry)?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	0.0012	yes
MLCRTotal	0.4671	no
MLCRWeighted	0.0023	yes

In order to further analyze the effects of ITS (dry) on the pavement transverse cracking, the complete dataset for ITS (dry) is plotted against the MTCWeighted in Figure 30. Few observations can be drawn from this plot. First, the data appears to have quite a significant amount of spread; this is also evident from low R^2 for the fitted linear curve. Secondly, it can also be seen that the variation in the MTCWeighted is relatively small over large range of ITS (dry) values. Finally, it can also be seen that the data trend from the linear fit indicates that the mixes with greater ITS (dry) undergo higher amount of transverse cracking. The ITS (dry) is plotted against the MTCTotal, which represents sum total of low, medium and high severity transverse cracking amounts (c.f.Figure 31). Similar observations can be made with this plot as the previous one. The data scatter and linear regression fits for the longitudinal cracking measures are similar in nature to those for transverse cracking.

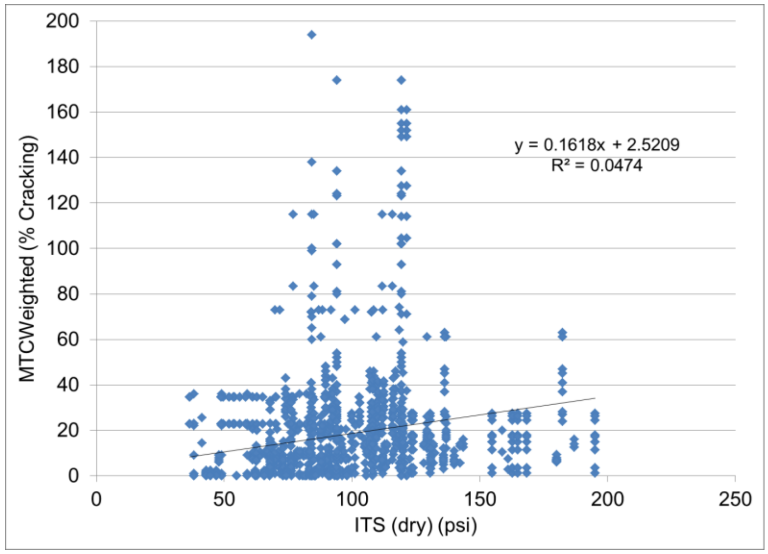


Figure 30: ITS (dry) and maximum total weighted transverse cracking (MTCWeighted)

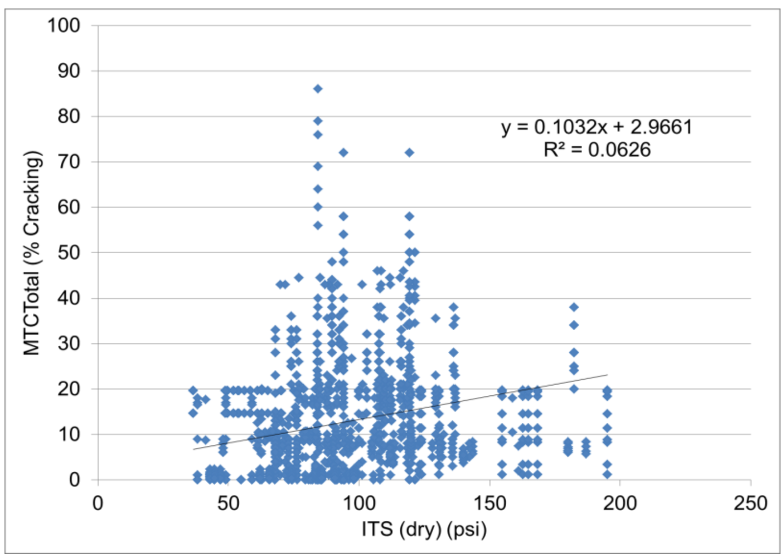


Figure 31: ITS (dry) and maximum total transverse cracking (MTCTotal)

3.4.1.2 ITS (wet)

The ITS (wet) data was analyzed in similar manner as the ITS (dry). The summary of statistical significance testing is presented in Table 24. The results for the ITS (wet) are analogous with those for ITS (dry). The transverse cracking measures (amount and rate) show statistically significant dependence on ITS (wet) and so do the longitudinal cracking amounts. However, the longitudinal cracking rates show minimal to no dependence on ITS (wet) of the asphalt mixes. The analysis of raw data (scatter) showed similar observations for ITS (wet) as ITS (dry), such that the data shows no consistent trend, have high amount of spread and a low coefficient of determination for the linear fit.

Table 24: Effect of ITS (wet) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to ITS (wet)?
MTCWeighted	0.0011	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	0.0031	yes
MLCRTotal	0.6079	no
MLCRWeighted	0.0356	yes (weak)

3.4.1.3 TSR

The dependence of maximum field cracking measures on the TSR was determined using the linear regression analysis. The results from this analysis are tabulated in Table 25. As with ITS (dry and wet), the linear regression indicates that the cracking measures depend on TSR, except for the MTCWeighted.

In order to further explore the dependence, a scatter plot has been generated between TSR and MTCTotal (Figure 32). Once again the plot unravels that while statistical test shows that MTCTotal is related to TSR, the change in MTCTotal with change in TSR is extremely small and the data has a large amount of spread. Similar observations were made for other transverse and longitudinal measures in context of TSR.

Table 25: Effect of TSR on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to TSR?
MTCWeighted	0.0647	no
MTCTotal	0.0070	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	0.0004	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

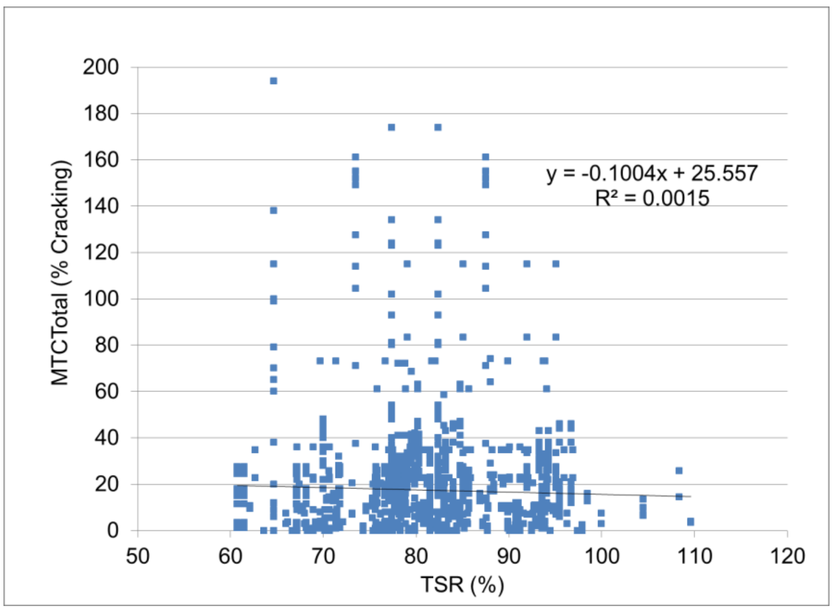


Figure 32: TSR and maximum total transverse cracking (MTCTotal)

3.4.2 Effects of ITS and TSR on Average Cracking Rates

The average longitudinal and transverse cracking rates were compared with the ITS (dry and wet) and TSR of asphalt mixes. The summary of the results are shown in Table 26. The results indicate that the ITS (dry and wet) have a statistically significant effect on the average transverse cracking rates whereas TSR does not. In order to quantify the extent of effect and to visualize the quality of fit between ITS and average transverse cracking rate, a scatter plot is presented in Figure 33. The scatter plot once again shows that while ITS (dry) is significant variable for ATCTotal, the amount of data scatter is very high and the fitted trend cannot be reliably used for purposes of prediction or as basis for development of specifications. The data analysis for ITS (wet) and TSR provided similar observations for average transverse cracking rates. The analysis of average longitudinal cracking rate data showed even greater spread in data, lower variation in cracking rate with changes in ITS (dry and wet) and TSR and lower coefficient of determination (R^2) for the linear fits.

Table 26: Effects of ITS (dry and wet) and TSR on measures of average field cracking rates

Mix Property	Average Cracking Rate	p-value	Field cracking rate is related to mix parameter?
ITS (dry)	ATC Total	< 0.0001	yes
	ATC Weighted	0.0027	yes
ITS (wet)	ATC Total	< 0.0001	yes
	ATC Weighted	0.0003	yes
TSR	ATC Total	0.0761	no
	ATC Weighted	0.3890	no
ITS (dry)	ALC Total	< 0.0001	yes
	ALC Weighted	0.0007	yes
ITS (wet)	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
TSR	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes

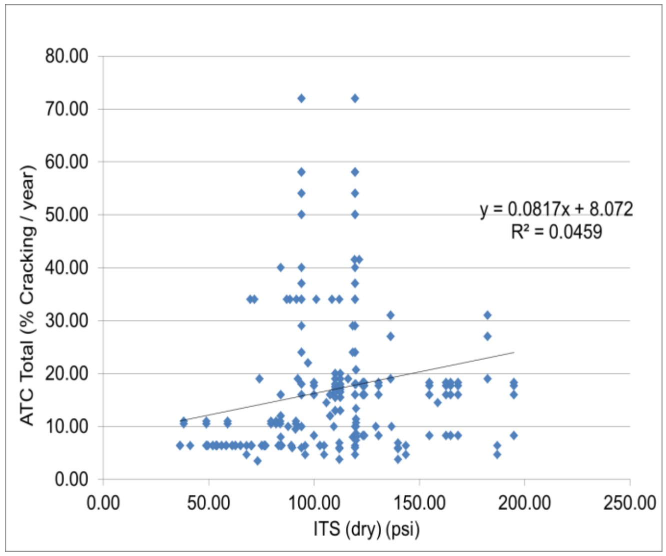


Figure 33: ITS (dry) and average total transverse cracking rate (ATCTotal)

3.5 Summary of Findings for use of ITS and TSR as Mix Performance Measures

Based on numerous data analysis described in this chapter of the report following key findings were inferred in context of using ITS (dry and wet) and TSR as asphalt mix performance measure:

- Most asphalt mix volumetric properties do not have significant effects on ITS and TSR.
- The asphalt binder grade has discernible effect on ITS, use of softer binder grade yields lower ITS values.
- The design traffic level (mix level) affects the ITS of the mix, with greater ITS values for higher traffic level mixes.

- Both ITS and TSR have a statistically significant effect on the asphalt pavement cracking performance. Mixes with higher ITS are expected to have a greater amount of cracking, and mixes with higher a TSR is expected to have lower amounts of cracking. The effect of ITS and TSR on the cracking amounts and cracking rates is relatively small.

- Both ITS and TSR are found to be poor candidates for use as performance measures for cracking in asphalt pavements. This is because of following reasons:

    - The ITS and TSR are independent of most asphalt mix design control measures (such as AFT or VMA), thus making them a difficult parameter to control for a mix designer.

    - The amount of scatter in the data is too high for ITS and TSR against the actual field cracking amounts and cracking rates. This will inherently lead to a very high number of outliers that will not follow the trends predicted using statistical analysis.

    - The variation in field cracking amounts with change in ITS and TSR was found to be relatively small to use either of these quantities as control measures.

    - The pavement cracking performance improves with decrease in ITS of the mix. Thus, use of ITS as performance measure would require limiting the maximum value of ITS. Use of such limit would have detrimental effects on other asphalt mix durability and strength properties.

CHAPTER 4: EFFECTS OF MIX DESIGN PARAMETERS ON FIELD CRACKING PERFORMANCE

4.1 Introduction

This chapter describes the statistical analysis that was conducted to evaluate the effects of various asphalt mix design parameters on field cracking performance. The field cracking measures that were analyzed are same as those discussed previously in Chapter 3. The mix design parameters that were studied herein include: Asphalt Film Thickness (AFT), Asphalt Binder Content (Percent Binder), Asphalt Binder Grade (PG Grade, PGLT and PG Spread), Presence of Recycled Materials and Voids in Mineral Aggregates (VMA). The field cracking performance measures that are used in this study include: Maximum Total Transverse Cracking Amount (MTCTotal), Maximum Total Weighted Transverse Cracking Amount (MTCWeighted), Maximum Total Transverse Cracking Rate (MTCRTotal), Maximum Total Weighted Transverse Cracking Rate (MTCRWeighted), Average Total Transverse Cracking Rate (ATCTotal), and Average Weighted Total Transverse Cracking Rate (ATCWeighted) for the transverse cracking. The corresponding field cracking measures for longitudinal cracking were also analyzed. The definitions of various cracking measures are provided in Chapter 2 of this report (c.f. Table 2).

The chapter is divided into two main sections; the first section evaluates the effects of mix design parameters on maximum transverse and longitudinal cracking amounts and their rates (MTCTotal, MTCWeighted, MTCRTotal, MTCRWeighted, MLCTotal, MLCWeighted, MLCRTotal, MLCRWeighted). The second portion compares the effect of mix parameters on average transverse and longitudinal cracking rates. While the data for these twelve field cracking measures were analyzed, the measure that is most relevant to this study is MTCWeighted, thus most graphical presentation of data is provided for this measure.

4.2 Analysis of BAB Pavements

The initial analysis of mix design parameters with respect to field cracking measures dealt with only conventional asphalt pavements (new construction or full reconstruction) which are typically referred to as Bituminous over Aggregate Base (BAB). The main reason to look only at BAB pavements was driven by the scope of this study which focused on transverse cracking in conventional asphalt pavements. Other pavement types included in the database are Bituminous on Bituminous (BOB), Bituminous on Stabilized Base (BFD), and Bituminous on Concrete (BOC).

Upon generating queries within the database to only return BAB pavements, it was found that an insufficient amount of records were returned for several mix parameters. This can be seen below in Table 27. For AFT adjusted, AFT unadjusted (AFT P_{be}), asphalt binder content, presence of recycled materials, and VMA, there were not enough results to conduct a reliable statistical analysis. Due to lack of sufficient amount of data for exclusively BAB pavements, the analysis to evaluate the effects of mix design parameters on the pavement cracking performance was conducted using all pavement types that have a bituminous surface course (BAB, BOB, BOC, and BFD). The subsequent sections present the effectiveness of mix design parameters on maximum and average cracking amounts and rates for all pavements with a bituminous surface.

Table 27: Average transverse cracking statistical analysis on BAB pavements

Mix Parameter	Average Cracking Rate	p-value	Field cracking rate is related to mix parameter?
AFT Adjusted	ALC Total	-	Not enough data
	ALC Weighted	-	Not enough data
AFT Pbe	ALC Total	-	Not enough data
	ALC Weighted	-	Not enough data
Percent Binder (Extracted)	ALC Total	-	Not enough data
	ALC Weighted	-	Not enough data
Percent Binder (Ignition)	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
PG Grade	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
PGLT	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
PG Spread	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
Presence of Recycled Material	ALC Total	-	Not enough data
	ALC Weighted	-	Not enough data
VMA (Extracted)	ALC Total	-	Not enough data
	ALC Weighted	-	Not enough data
VMA (Ignition)	ALC Total	0.0002	yes
	ALC Weighted	< 0.0001	yes

4.3 Effect of Mix Parameters on Maximum Cracking Amounts and Rates

4.3.1 Asphalt Film Thickness (AFT)

The effect of AFT on the field cracking measures were evaluated for both: AFT adjusted and AFT calculated based on the effective binder content (P_{be}). The results from the statistical analysis on the data are presented in Table 28 and Table 29. It can be seen that the measures for both transverse and longitudinal cracking show dependence on AFT adjusted, whereas only some of the longitudinal cracking measures show dependence on unadjusted AFT calculated from P_{be}.

Table 28: Effect of adjusted AFT on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to AFT adjusted?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

Table 29: Effect of AFT (P_{be}) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to AFT (Pbe)?
MTCWeighted	0.323	no
MTCTotal	0.751	no
MTCRTotal	0.5787	no
MTCRWeighted	0.3101	no
MLCTotal	0.037	yes
MLCWeighted	0.0708	no
MLCRTotal	< 0.0001	yes
MLCRWeighted	0.0006	yes

To further investigate the effect of AFT adjusted on the extent of transverse cracking, the data was converted to a normalized frequency. This was accomplished by first distributing the AFT adjusted into discrete intervals of 0.5 micron increments. These increments were assigned a character key, as seen in Figure 29. Next, the data for all pavement sections in each range of AFT adjusted data were analyzed to determine the percent of sections that have no cracking (MTCWeighted of 0 %/500 ft./year) and ones with cracking at 10, 20, 30, 40 and 50 %/500 ft./year respectively. The database consists of very few pavements with cracking amounts above 50 %, therefore cracking amounts above this percentage were not considered. Thereafter, the normalized frequencies for each of the cracking amounts were plotted for each adjusted AFT range. Figure 34 shows the normalized frequencies for MTCWeighted for various adjusted AFT levels.

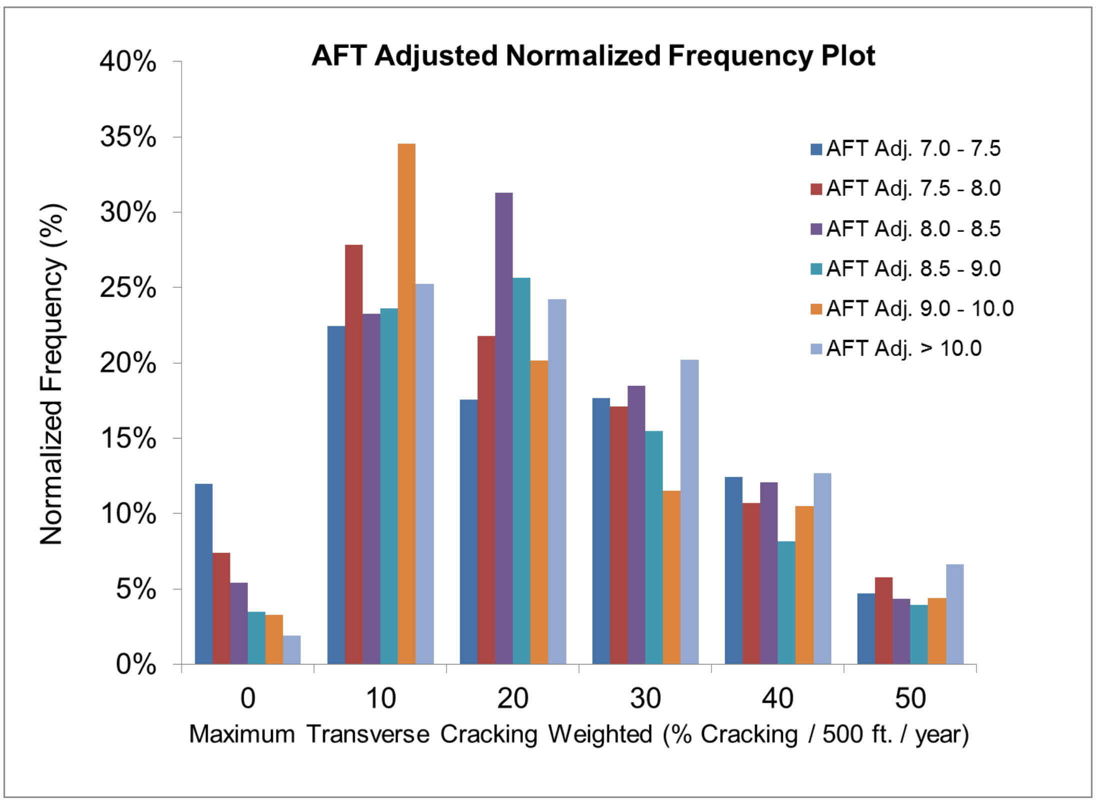


Figure 34: Normalized frequency plot of adjusted AFT with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.2 Asphalt Binder Amount (Percent Binder)

The asphalt binder contents determined using chemical extraction and ignition oven methods were used to determine their effects on the measures of transverse and longitudinal cracking. The statistical analysis for asphalt binder contents determined using both methods are presented in Table 30 and Table 31. The results show that irrespective of the measurement method, the asphalt binder content has significant effect on the amount of field cracking (both transverse and longitudinal).

In order to further evaluate this effect, the MTCWeighted data was analyzed to determine the normalized frequencies. The normalized frequencies of the transverse cracking amounts for various ranges of asphalt binder contents are plotted in Figure 35 for chemical extraction and Figure 36 for ignition oven methods. The results show that in general, a greater percent of pavements are free of transverse cracks for mixes with higher asphalt binder content. The data for mixes with greater than 6.0% asphalt binder content as determined using chemical extraction is the only outlier. The plots also show that the number of pavements with 20, 30 and 40 %/500 ft./year cracking increase as the amount of asphalt binder in mixes decrease. Specifically, the asphalt mixes with binder contents between 4.0 and 4.5% represent almost 10% more pavements with 20 and 30 %/500 ft./year cracking as compared to other mixes

Table 30: Effect of asphalt binder content (chemical extraction) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to percent binder?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	0.0005	yes

MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

Table 31: Effect of asphalt binder content (ignition oven) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to percent binder?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

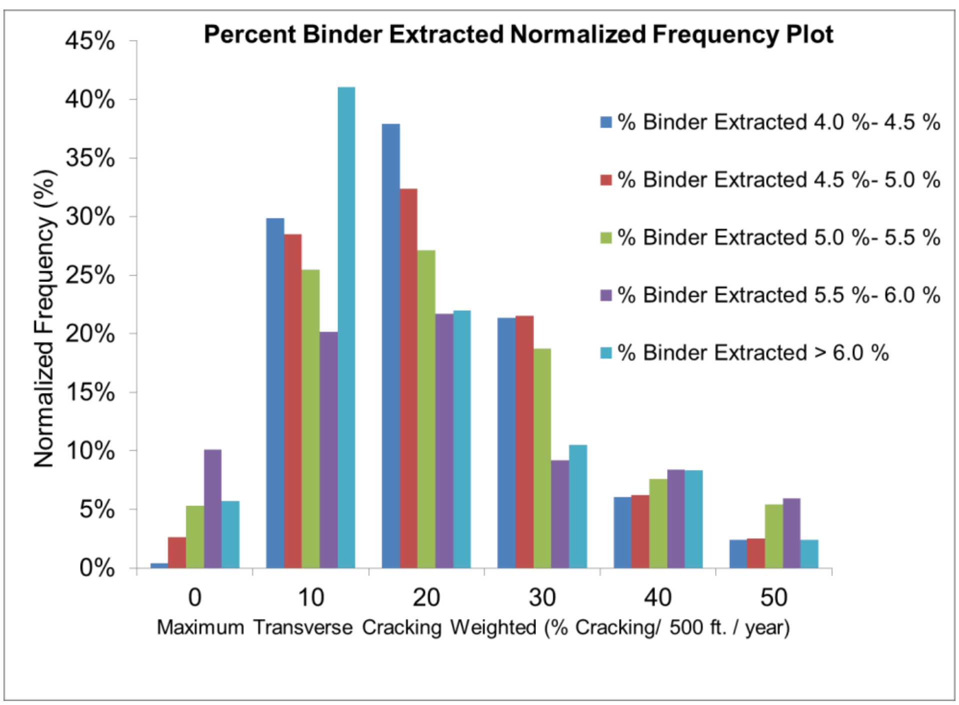


Figure 35: Normalized frequency plot of asphalt binder content (chemical extraction) with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

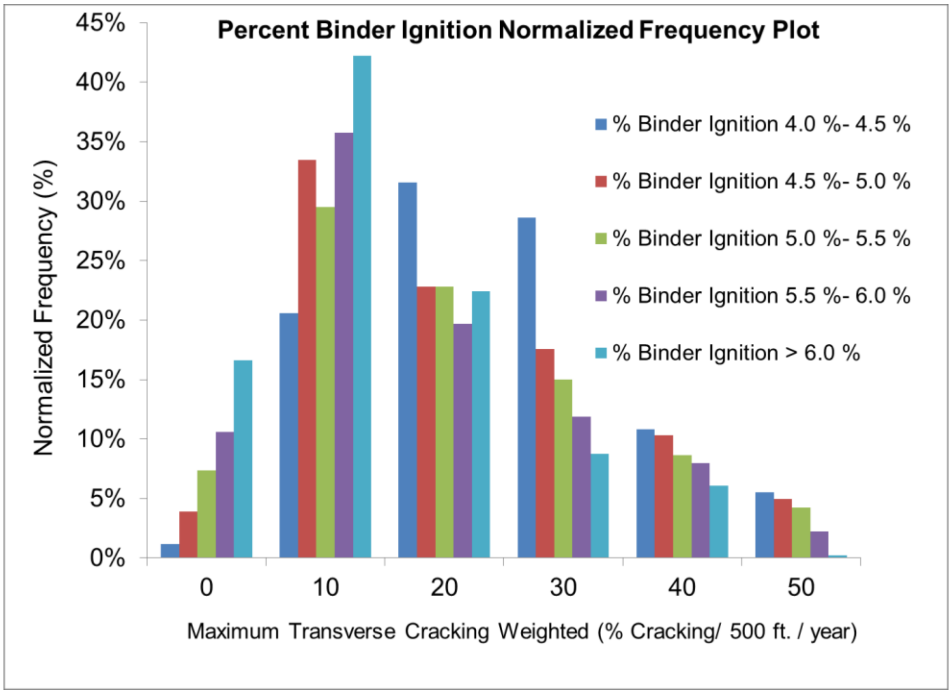


Figure 36: Normalized frequency plot of asphalt binder content (ignition oven) with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.3 Asphalt Binder Grade (PG, PGLT and PG Spread)

The asphalt binder grade (PG), the low temperature grading of the binder (PGLT) and the spread between the high and low temperature grading (PG Spread) information was used to conduct a statistical analysis. The results from the statistical analysis conducted to determine whether different field cracking measures depend on the asphalt binder grade and its derivatives are presented in Table 32, Table 33 and Table 34. The results show that the asphalt binder grade has significant effect on the amounts and rates of transverse and longitudinal cracking. The only exception is non-dependence of total amount of longitudinal cracking on the low temperature grade of the binder (PGLT)

Table 32: Effect of asphalt binder grade (PG) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to PG?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

Table 33: Effect of asphalt binder low temperature grade (PGLT) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to PGLT?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	0.0602	no
MLCWeighted	0.0035	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

Table 34: Effect of spread in asphalt binder grade (PG Spread) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to PG Spread?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

Similar to analysis of previous mix parameters, in order to determine the effects of asphalt binder grade on the amount of cracking, the PGLT data was used to generate normalized frequencies of the maximum weighted transverse cracking (MTCWeighted). The frequencies are plotted for PGLT of -28 and -34 °C. These two were selected as a majority of pavements in the database represent these types of binders. The results are plotted in Figure 37. The results show that significantly greater amount of pavements are crack free when containing mix with PGLT of -34. Furthermore larger number of pavements with higher transverse cracking amounts (20, 30 and 40 %/500 ft./year) have mixes with PGLT -28 binder.

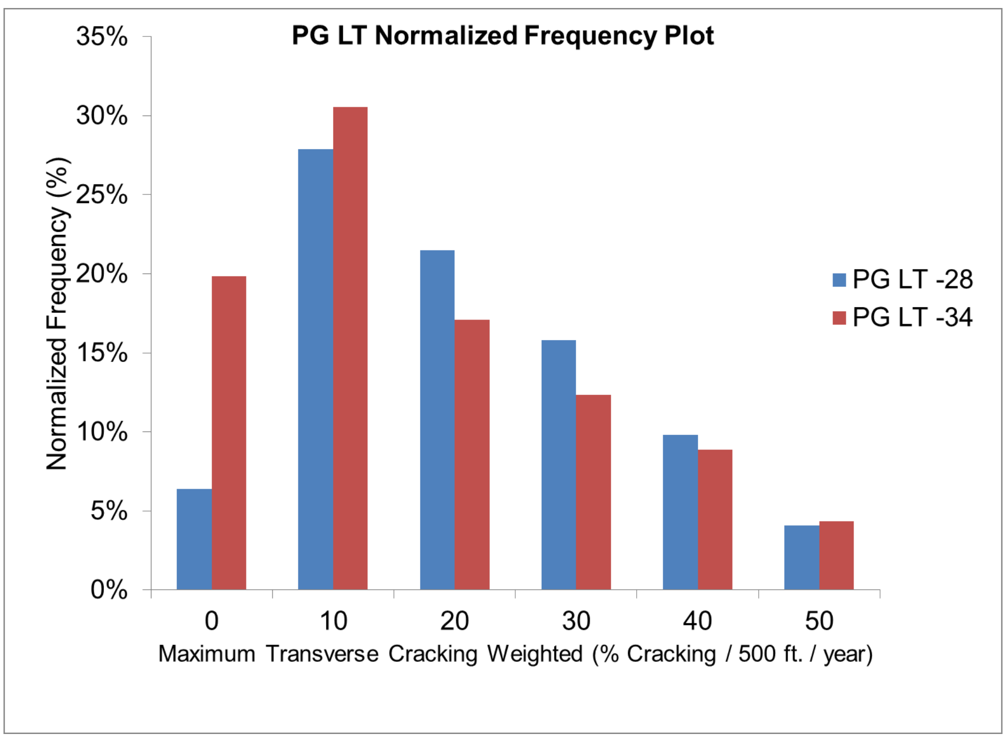


Figure 37: Normalized frequency plot of asphalt binder low temperature grade (PGLT) with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.4 Presence of Recycled Materials

The asphalt mixes in the database that consisted of either reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) or both were differentiated from the mixes without inclusion of these products. Thereafter, the field cracking performance for all mixes in each category was determined. In total 432 pavement sections were identified with mixes containing no recycled materials versus 27,877 sections with recycled materials. This indicates the widespread use of recycled materials in the asphalt mixes. The statistical analysis was conducted to determine whether presence of recycled material in asphalt mixes had a discernible effect on the field cracking performance. The results from statistical analysis are tabulated in Table 35

The results show that the maximum transverse and longitudinal cracking amounts (MTCTotal, MTCWeighted, MLCTotal and MLCWeighted) are related to the presence of recycled materials. The cracking rates are not related to presence of recycled materials except in case of maximum weighted transverse cracking rate (MTCRWeighted).

It should be noted that it was not possible to screen out the amount of recycled materials as the recycled material stockpile number in LIMS is variable and can change between mixes. The process to find out the amount of recycled materials in the mixes would require manual screening of each mix record. The associated time requirement with this was prohibitive.

The normalized frequencies were generated for various ranges of MTCWeighted for mixes with and without recycled materials. The normalized frequencies are plotted in Figure 38. It should be noted that the amount of data for pavements without recycled materials is quite small as compared to those with recycled materials (432 versus 27,877), thus these results should be treated as preliminary. The results show that a large percent of pavements with all virgin mixes are crack-free as compared to pavements with mixes containing recycled materials (32% for virgin mixes versus 10% for mixes with recycled materials). This trend is not consistent for the pavements with transverse cracking.

Table 35: Effect of presence of recycled material on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to presence of recycled material?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	0.2549	no
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	0.2784	no
MLCRWeighted	0.1367	no

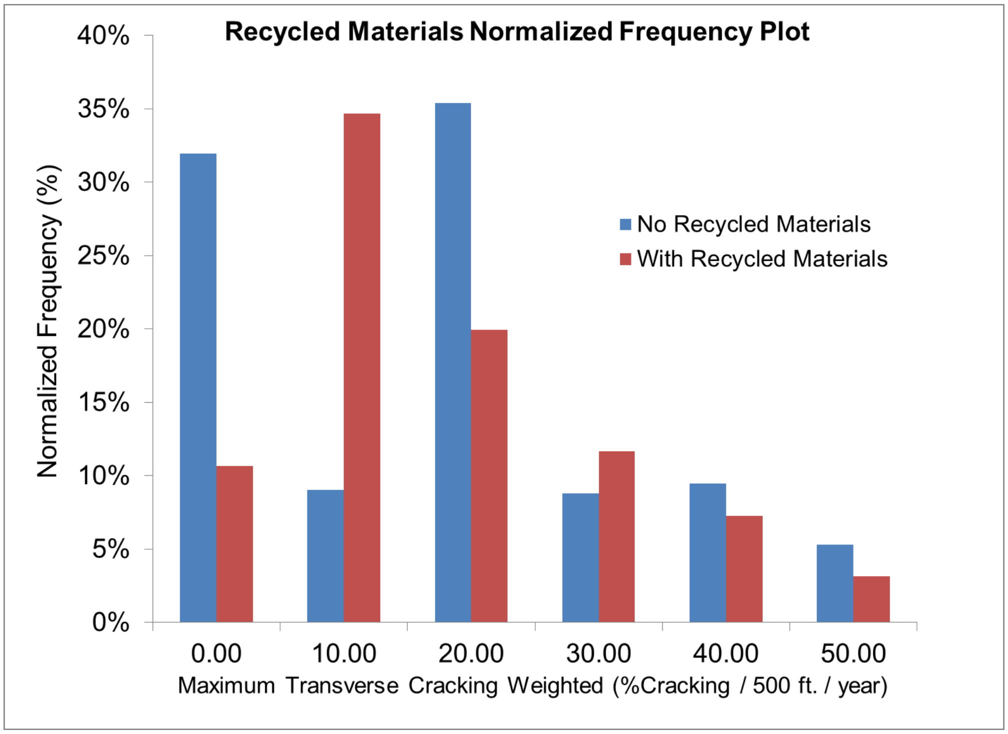


Figure 38: Normalized frequency plot of presence of recycled materials with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.5 Voids in Mineral Aggregates (VMA)

The VMA amounts determined using the chemical extraction and ignition oven methods were compared with the field cracking measures to determine if VMA showed a statistically significant relationship with cracking performance. The results from statistical testing are tabulated for VMA determined using chemical extraction and ignition oven methods in Table 36 and Table 37 respectively. The field cracking measures show statistically significant relationship with both types of VMA. Similar to percent asphalt binder content, the significance is weaker for certain field cracking measures when the VMA calculation was based on chemical extraction. This is not surprising since the chemical extraction method provides the asphalt binder content, which is in-turn used to calculate VMA. The normalized frequency plots for the VMA are presented in Figure 39 and Figure 40.

The normalized frequencies show that mixes with low VMA correspond to fewer pavements that are free of transverse cracks. The trends are not completely consistent for pavements containing cracks to make a general statement regarding preference towards low or high VMA.

Table 36: Effect of VMA (chemical extraction method) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to VMA (extracted)?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	0.0456	yes
MTCRWeighted	0.0006	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	0.0005	yes

Table 37: Effect of VMA (ignition oven method) on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to VMA (ignition)?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	< 0.0001	yes
MLCWeighted	< 0.0001	yes
MLCRTotal	< 0.0001	yes
MLCRWeighted	< 0.0001	yes

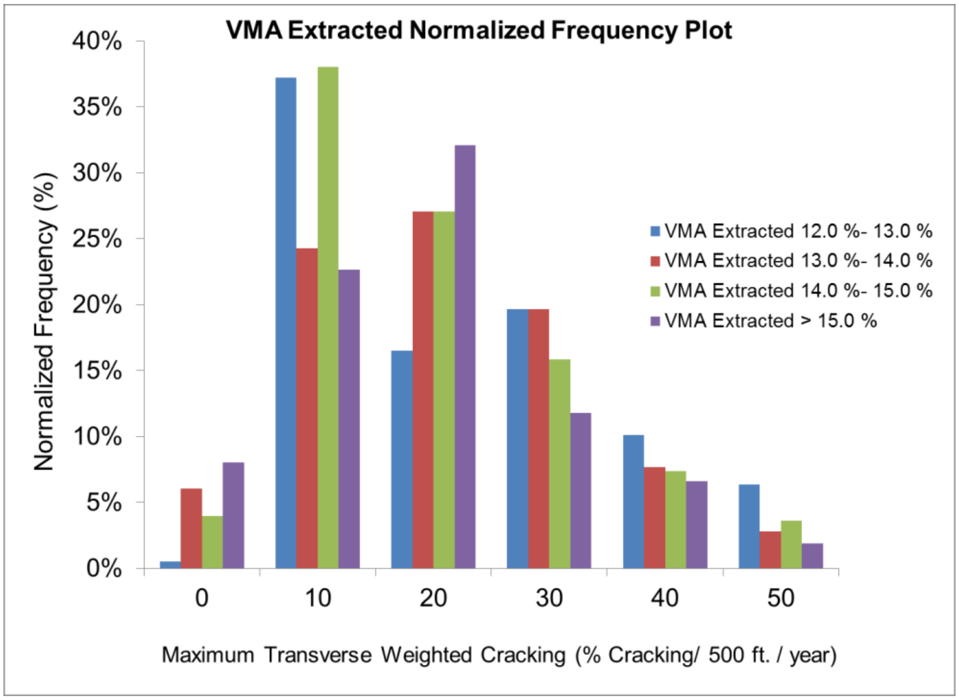


Figure 39: Normalized frequency plot of VMA (chemical extraction) with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

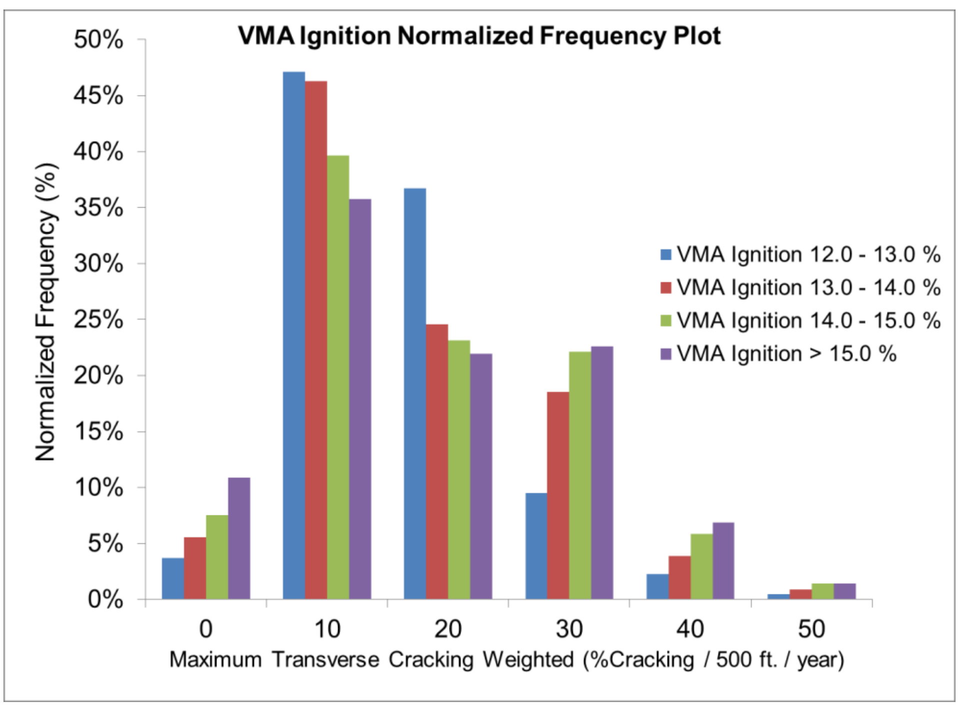


Figure 40: Normalized frequency plot of VMA (ignition oven) with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.6 Designed Air Voids

The design air void levels that were analyzed consisted of 3.0 %, 3.5 %, and 4.0 % air voids. Mixes containing these levels of air voids were compared with field cracking measures to see if a statistically significant relationship existed. The results from the statistical analysis are listed in Table 38. These results show a statistically significant relationship exists between designed air voids levels and all cracking measurements with exception to MLCTotal and MCLWeighted. The cracking measure with the highest correlation to field cracking is MTCRTotal, while all other field cracking measures have a weaker relationship. The normalized frequency plot for design air voids is presented in Figure 41. The amount of data for design air voids of 3.5 % was much lower than that of 3.0 % and 3.5 %, thus they were not included in the plot. There was no noticeable trend between the amount of cracking of pavements between design air void levels of 3.0 % and 4.0 %. However, the design air void level of 3.0% has a slightly higher amount of crack free pavements or pavements that exhibit 10% / 500 ft. / year. This relationship however does not continue with higher amounts pavements with transverse cracking.

Table 38: Effect of designed air voids on measures of maximum field cracking

Cracking Measure	p-value	Field Cracking is related to Design Air Voids?
MTCWeighted	0.0391	yes
MTCTotal	0.0214	yes
MTCRTotal	<0.0001	yes
MTCRWeighted	0.0007	yes
MLCTotal	0.548	no
MLCWeighted	0.7233	no
MLCRTotal	0.0371	yes
MLCRWeighted	0.0104	yes

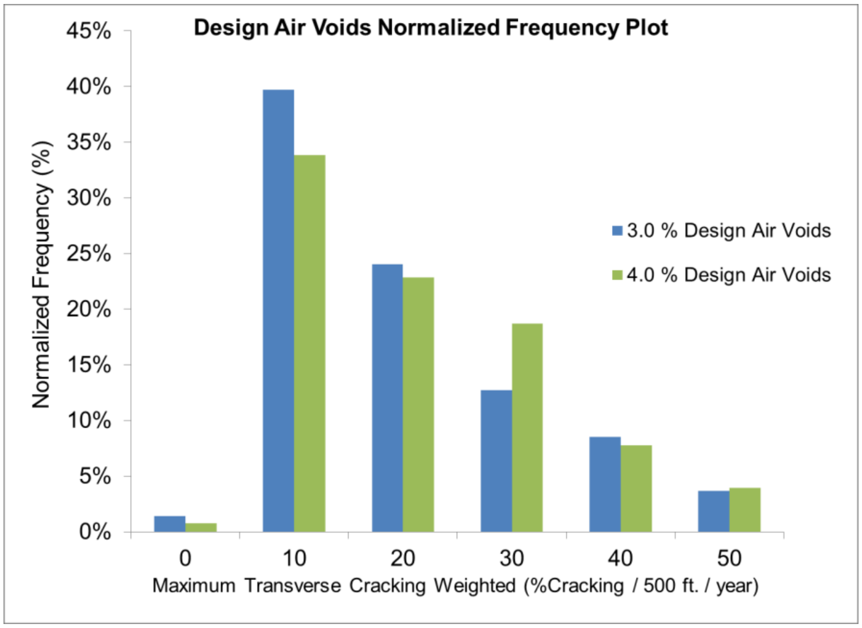


Figure 41: Normalized frequency plot of design air voids with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.7 Measured Air Voids

The measured air voids present in asphalt mixes was compared to field cracking performance. The results of the statistical analysis are presented in Table 39. All transverse cracking measures show a strong relationship to field cracking, while most longitudinal cracking measures show no relationship. The longitudinal measure of MLCTotal does show a weak relationship.

Table 39: Effect of measured air voids on measures of maximum field cracking

Cracking Measure	p-value	Field Cracking is related to measured air voids?
MTCWeighted	< 0.0001	yes
MTCTotal	< 0.0001	yes
MTCRTotal	< 0.0001	yes
MTCRWeighted	< 0.0001	yes
MLCTotal	0.0086	yes
MLCWeighted	0.051	no
MLCRTotal	0.412	no
MLCRWeighted	0.658	no

4.3.8 Mix Size (Nominal Maximum Aggregate Size)

The NMAS of sizes 1/2 in., 3/4 in., and 3/8 in. were compared with field cracking results. The #4 size was not analyzed due to an absence of field cracking data existing for this size. The results from the statistical analysis are listed in Table 40.

All of the transverse cracking measures have a strong relationship to aggregate mix size, while the longitudinal cracking data showed no relationship with the exception of an extremely weak relationship with MLCRTotal. The normalized plot is shown in Figure 42. For mix sizes of 3/4 in., only a small amount of data was available, thus they were omitted from the plot. It can be seen that the mix size of 3/8 in. exhibits more pavements with no cracking or cracking of 10% / 500 ft. / year. As cracking increases to 20, 30, and 40% / 500 ft./ year, more pavements of mix size 1/2 in. are prevalent. This normalized plot shows that a trend exits of mix size 1/2 in. corresponding to more pavements with higher amounts of transverse cracking.

Table 40: Effect of mix size on measures of maximum field cracking

Cracking Measure	p-value	Field cracking is related to aggregate mix size (NMAS)?
MTCWeighted	<0.0001	yes
MTCTotal	<0.0001	yes
MTCRTotal	<0.0001	yes
MTCRWeighted	<0.0001	yes
MLCTotal	0.2582	no
MLCWeighted	0.1888	no
MLCRTotal	0.0491 (extremely weak)	yes
MLCRWeighted	0.2036	no

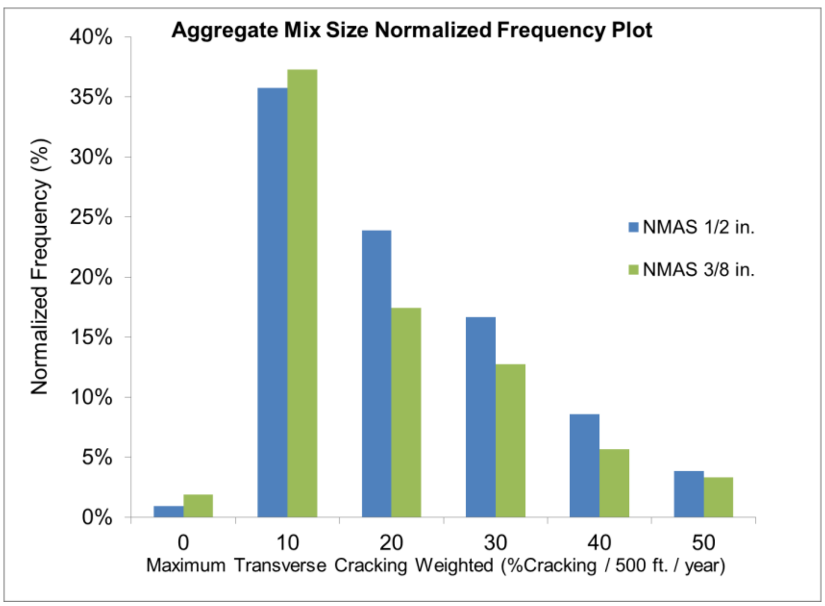


Figure 42: Normalized frequency plot of aggregate mix size with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.9 Design Traffic Level

The design traffic levels were statistically analyzed and compared with field cracking results. Table 41 shows the results from this analysis. All transverse field cracking measures show significance with the traffic level, while the longitudinal cracking measures show no relationship. A normalized plot of the data is presented in Figure 43. It can be seen that a large amount of traffic level 5 pavements experience Cracking of 10%/ 500 ft. / year. At larger cracking amounts, no real trend is evident among the differing design traffic levels. It should be noted that a very small amount of cracking data was available for traffic level 5.

Table 41: Effect of design traffic level on measures of maximum field cracking

Cracking Measure	p-value	Field Cracking is related to Traffic Level?
MTCWeighted	<0.0001	yes
MTCTotal	<0.0001	yes
MTCRTotal	<0.0001	yes
MTCRWeighted	0.0002	yes
MLCTotal	0.4379	no
MLCWeighted	0.7148	no
MLCRTotal	0.1582	no
MLCRWeighted	0.3019	no

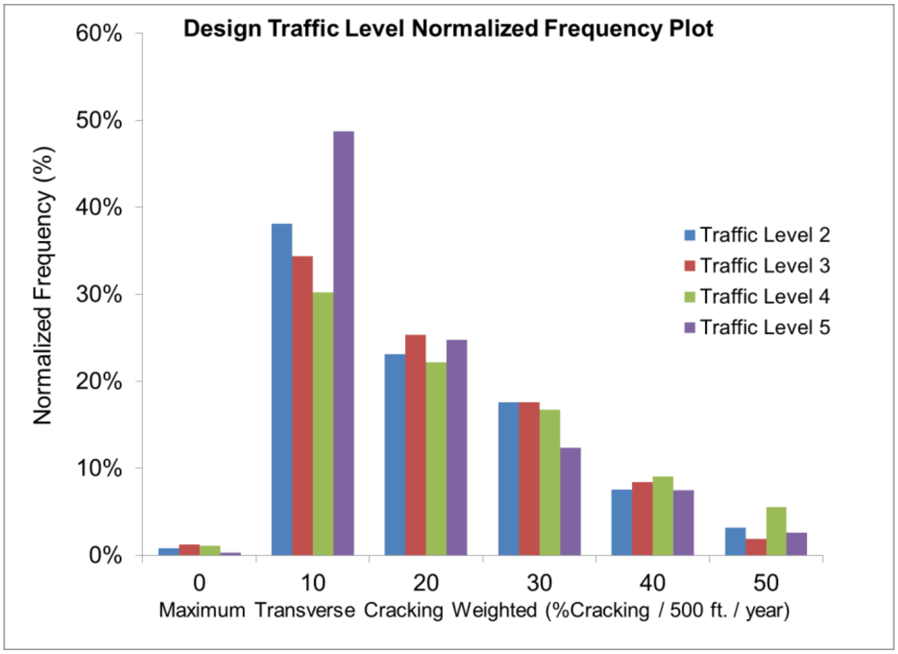


Figure 43: Normalized frequency plot of design traffic level with various ranges of weighted maximum transverse cracking amounts (MTCWeighted)

4.3.10 Average Daily Truck Traffic

The average daily truck traffic (ADTT) was calculated and statistically analyzed against the field performance cracking. The ADTT was calculated by taking the percentage of truck traffic recorded for the traffic count given by MnDOT, and multiplying the average annual daily traffic by this value. The ADTT was analyzed to give better insight into how the traffic level effects the pavement field performance. The results of the statistical analysis can be seen in Table 42. The only cracking measures that show a significant relationship the ADTT are MTCWeighted and MTCTotal. As can be seen, these relationships are weak. All longitudinal cracking measures as well as MTCRTotal and MTCRWeighted show no significant relationship with

Table 42: Effect of average daily truck traffic on measures of maximum field cracking

Cracking Measure	p-value	Field Cracking is related to ADTT?
MTCWeighted	0.0047	yes
MTCTotal	0.0014	yes
MTCRTotal	0.795	no
MTCRWeighted	0.4389	no
MLCTotal	0.0584	no
MLCWeighted	0.1064	no
MLCRTotal	0.0719	no
MLCRWeighted	0.182	no

A graph of this data was made to visually illustrate the data being analyzed. The graph of MTCWeighted and ADTT can be seen in Figure 44. A slight increase in cracking is evident with an increase in ADTT, but not one significant enough to indicate a trend is occurring.

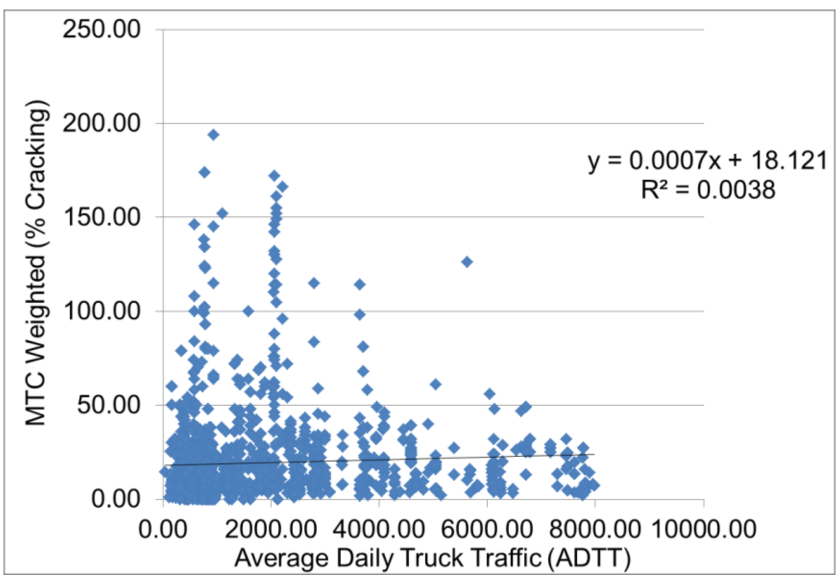


Figure 44: Average Daily Truck Traffic versus MTCWeighted

4.4 Effects of Mix Design Parameters on Average Cracking Rates

The average transverse and longitudinal cracking rates were statistically tested against various mix design parameters that were discussed in the previous section. The main reason for this set of analysis was to determine whether the findings from previous section, which dealt with looking at the maximum cracking amounts and maximum cracking rates, were applicable when looking at rate of crack development as average over the survey period for a pavement section.

The statistical testing was conducted to determine the significance of various mix design parameters in affecting the average cracking rates. The results are presented for the average transverse cracking rates (both total: ATC Total and weighted: ATC Weighted) in Table 43. Similar to the maximum cracking amount and rate, the average transverse cracking rates show a statistically significant relationship to almost all mix design parameters except the unadjusted AFT as calculated from P_{be}. The overall trends of data for the average transverse cracking rate were similar to the maximum transverse cracking amounts and rates for various mix design parameters.

The average longitudinal cracking rates for the pavement sections were statistically analyzed to determine if they were significantly related to various mix design parameters. The results from this set of analysis are tabulated in Table 44.

The results show that the average longitudinal cracking rates are related to all mix design parameters except the PGLT. The dependence of average longitudinal cracking rates on unadjusted AFT is not as strong as other mix design parameters. Unlike the maximum longitudinal cracking rate, the average rate depends on the presence of recycled materials.

Table 43: Effect of mix design parameters on average transverse cracking rates

Mix Parameter	Average Cracking Rate	p-value	Field cracking rate is related to mix parameter?
AFT Adjusted	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
AFT Pbe	ATC Total	0.4948	no
	ATC Weighted	0.4835	no
Percent Binder (Extracted)	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
Percent Binder (Ignition)	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
PG Grade	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
PGLT	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
PG Spread	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
Presence of Recycled Material	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
VMA (Extracted)	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
VMA (Ignition)	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes
Design Air Voids	ATC Total	0.0102	yes
	ATC Weighted	0.0079	yes
Actual Air Voids	ATC Total	0.1639	no
	ATC Weighted	0.1638	no
Aggregate Mix Size (NMAS)	ATC Total	0.0003	yes
	ATC Weighted	< 0.0001	yes
Traffic Level	ATC Total	0.011	yes
	ATC Weighted	0.0028	yes
Average Daily Truck Traffic (ADTT)	ATC Total	< 0.0001	yes
	ATC Weighted	< 0.0001	yes

Table 44: Effect of mix design parameters on average longitudinal cracking rates

Mix Parameter	Average Cracking Rate	p-value	Field cracking rate is related to mix parameter?
AFT Adjusted	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
AFT Pbe	ALC Total	0.0031	yes
	ALC Weighted	0.0112	yes
Percent Binder (Extracted)	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
Percent Binder (Ignition)	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
PG Grade	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
PGLT	ALC Total	0.7698	no
	ALC Weighted	0.1804	no
PG Spread	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
Presence of Recycled Material	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
VMA (Extracted)	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
VMA (Ignition)	ALC Total	< 0.0001	yes
	ALC Weighted	< 0.0001	yes
Design Air Voids	ALC Total	0.0004	yes
	ALC Weighted	0.0009	yes
Actual Air Voids	ALC Total	0.5416	no
	ALC Weighted	0.2425	no
Aggregate Mix Size (NMAS)	ALC Total	0.0042	yes
	ALC Weighted	0.0019	yes
Traffic Level	ALC Total	0.0178	yes
	ALC Weighted	0.0251	yes
Average Daily Truck Traffic (ADTT)	ALC Total	0.5209	no
	ALC Weighted	0.6916	no

4.5 Summary of Effects of Mix Design Parameters on Field Cracking Performance

From the statistical analysis as well as the normalized frequency analysis, the following findings were realized to describe the effects mix design parameters on field cracking performance:

- Both transverse and longitudinal cracking depend on adjusted AFT, while only some longitudinal cracking measures depend on the unadjusted AFT
    - AFT adjusted with lower values correlate to a higher amount of pavements with no transverse cracking (MTCWeighted = 0 %/500 ft./year), There was no observable trend with pavements containing cracking amounts of 10, 20, 30, 40, or 50 (%/500 ft. / year).
- The amount of asphalt binder, both calculated by means of chemical extraction and ignition oven, showed significant effect on both transverse and longitudinal field cracking performance
    - Mixes with higher asphalt contents corresponded to a greater percent of pavements with low transverse cracking. Specifically with pavements containing 20, 30, or 40 (%/ 500 ft./year), the cracking amounts are higher for with mixes containing low amounts of asphalt binder.
- The PG binder grade, PGLT, and PG Spread do have an effect on transverse and longitudinal cracking amounts, with the exception of PGLT which showed minimal effect on the amount of longitudinal cracking

    - Mixes with PGLT -34 have higher amounts of transverse crack free pavements as compared the mixes with PGLT -28. A higher amount of 20, 30, and 40 (%/ 500 ft./ year) cracking occurred for mixes with PGLT -28 binder.

- Only a small amount of pavements with no recycled materials were available for analysis and these results should be treated as preliminary findings

    - Maximum transverse and longitudinal cracking (MTCTotal, MTCWeighted, MLCTotal, and MLCWeighted) showed dependence on presence of recycled materials;

    - A large percentage of pavements containing no recycled materials were crack free (MTCWeighted 0%/500ft./year); and,

    - The trend of virgin mixes having low amounts of cracking was not consistent within the MTCWeighted normalized frequency plot.

- VMA (determined by both chemical extraction and ignition oven) showed a statistically significant relationship with transverse and longitudinal field cracking

    - Pavements with lower VMA values resulted in fewer pavements with no transverse cracking. This trend was not consistent with cracking of 20, 30, 40, and 50 (%/ 500ft. / year).

- Designed air voids showed correlations to transverse cracking and weakly to longitudinal cracking.
    - The normalized frequency plot allowed further insight to show that no trend occurs between the amount of air voids present and percentage of cracked pavements.
- Measured air voids also showed a statistically significant relationship to transverse cracking, with weak to no correlation with longitudinal cracking.
- The design traffic level was found to have a statistically significant relationship with transverse cracking. However, the traffic level had no relationship to longitudinal cracking measures. There was also no noticeable trend among the different traffic levels and cracking, as seen in the normalized frequency plot.
- The mix size showed to have a statistically significant relationship with transverse cracking, with a very weak to no relationship to longitudinal cracking.
    - The normalized frequency plot showed that the larger mix size of 1/2 in. contained more pavements with higher amounts of cracking as compared to the mix size of 3/8 in.
- Average transverse cracking showed relationship to all mix design parameters except for actual air voids and unadjusted AFT

    - Trends for average transverse cracking were similar to both maximum transverse cracking amounts and maximum transverse cracking rates (MTCTotal/Weighted, MLCTotal/Weighted, MTCRTotal/Weighted, MLCRTotal/Weighted) for various mix design parameters.

- Average longitudinal cracking is related to all mix design parameters except PGLT and actual air voids.
    - Average longitudinal cracking does depend on the presence of recycled materials, unlike MLCRTotal and MLCRWeighted.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

The research presented in this thesis undertook three primary research efforts that are briefly described as follows:

(1) Development of a comprehensive database that includes asphalt material property data (mix design records), bituminous pavement construction information (SP information, location, construction year) and the pavement management information (section locations, survey years, cracking data). The development of the comprehensive database is described in Chapter 2 of this report. The database was developed using the Microsoft Access software.

(2) The second effort involved determination of whether the indirect tensile strength (ITS) from the modified Lottman tests (AASHTO T-283) can be used as a cracking performance measure. The Modified Lottman test is conducted routinely as part of the mix design process, thus if ITS can be used as a performance measure a new specification control could be added with minimal additional testing requirements. The evaluation of ITS as performance measure was done in two phases. The first phase evaluated whether ITS is dependent on asphalt mix design parameters such as, binder grade, binder content, volumetric measures, mix size and design traffic level. The second phase evaluated whether ITS of mix has a statistically significant effect on the field cracking performance as well as the consistency with which ITS affects the field cracking performance.

(3) The effects of mix design parameters (mix volumetrics, mix design (traffic) level, asphalt binder amounts and grades, use of recycled materials) on the pavement cracking performance was evaluated. The findings from this effort allow identification of mix design parameters that affect pavement cracking performance. The study also determined the effects of the mix design choices on the cracking performance such as, use of -28 grade asphalt binder as compared to -34 grade binder.

The analyses conducted in listed efforts above of 2 and 3 always dealt with very large amounts of data (over 12,000 material records and over 58,000 pavement management data points were included). For such large data it is necessary to use statistical analysis for determining effects of one parameter on another. It is also important to note that the statistical testing for significance between two parameters should be scrutinized before drawing conclusions. In this study, the parameters that showed a statistically significant relationship were further evaluated to determine the strength of relationship and the extent to which one parameter affected the other.

Based on the three efforts listed above, a number of findings were made. These are described in detail at the end of chapter 3 and 4. The key conclusions drawn from this study and the corresponding recommendations are discussed in the subsequent sections.

5.2 Research Assumptions and Implications

Several assumptions were made in this research regarding factors that were unable to be thoroughly investigated with respect to deviations within each assumption.

These assumptions ultimately led to some limitations within the research. Both the research assumptions and implications are as follows:

- Condition of underlying pavement
    - The type of pavement to be investigated in this research was initially typical pavement of type Bituminous over Aggregate Base (BAB). Due to only a small amount of records being returned for pavements of this type, the scope of pavements to be investigated expanded to included flexible pavements of unconventional types as well, such as Bituminous on Bituminous (BOB), Bituminous on Stabilized Base (BFD), and Bituminous on Concrete (BOC). The small amount of data for only BAB pavements can be attributed to the small number of newly constructed roads that are being done in Minnesota. Most pavement projects are done as part of maintenance and rehabilitation efforts, indicated by pavement type BOB, BFD, and BOC. One limitation of analyzing these pavement types is not knowing the condition of the underlying pavement structure. Preexisting distresses present in the underlying pavement could be also attributing to the distresses forming on the surface, in the new pavement structure. Investigating the distresses present in the underlying pavements and their effects on the newly

constructed asphalt pavement layer should be done in future research efforts.

- Climate
  - For all pavements investigated, the climate was assumed to be uniform. Within the state of Minnesota, climate can change drastically from one location to another. Climatic changes, specifically low temperatures, are a huge factor for a pavements potential to form thermal cracks. Allowing for insight into climate difference pavements are experiencing throughout the state can give better insight into the driving factor of distresses that are occurring in the pavement. Gaining access to records of snowfall and rainfall from past years would also be valuable climatic factors that can also contribute to pavement distresses.
- Traffic
  - The traffic conditions assumed in this research were done regarding the designed traffic level as well as truck traffic taken from a traffic count from one year. Taking traffic counts for multiple years will give better insight into the differing traffic conditions and their effect on field performance of the asphalt pavements.

- Recycled Materials
    - To investigate the effect of recycled materials on pavement field performance, a qualitative versus quantitative measure was done. This fails to give insight as to how the quantity of recycled materials effects pavement performance. In future research efforts, the quantity of recycled materials present in the asphalt pavement should be found and recorded. This will allow for a more in depth analysis of effects of recycled materials on pavement performance.

5.3 Conclusions

The findings from this study resulted in several conclusions regarding the ITS of asphalt mixes and the effects of mix design parameters on field cracking performance of asphalt pavements. Please note that these conclusions are limited for traditional hot mix asphalt manufactured according to MnDOT 2360 specifications. Also notice that a small number of traditional asphalt pavements (BAB: bituminous on asphalt base) are constructed in the past decade, thus the analyses conducted in this study included pavements with all types of asphalt surfaces (BAB, BOB, BOC and BFD). The key conclusions drawn from this study are as follows:

- The indirect tensile strength (ITS) of the asphalt mixes, as determined using the AASHTO T-283 specifications, is found to be a poor measure of pavement cracking performance.

- A higher percentage of crack free pavements were represented by asphalt mixes that have lower adjusted asphalt film thickness (AFT) and higher voids in mineral aggregates (VMA). For pavements that have cracks present in them, neither adjusted AFT or VMA showed consistent trends.

- Asphalt binder grade has a significant effect on the pavement cracking performance. Mixes containing 34 asphalt binders have significantly greater amount of crack-free pavements as compared to mixes containing -28 binders. Fewer percent of pavements with significant amounts of transverse cracking are represented by mixes with -34 binder grades as compared to those with -28 binder grades.

- The amount of asphalt binder has a significant effect on field cracking performance. The mixes with higher asphalt content showed lower amounts of cracking.

- The pavements with mix size of 3/8 in. were found to have a higher percentage of roadways with either little or no cracking. A trend of higher amount of pavements with greater cracking was observed for mixes of 1/2 in. size. This can be attributed to a larger mix size (1/2 in. as compared to 3/8 in.), containing lower percentages of asphalt binder. As described in previous conclusion the lower the asphalt binder present the greater the tendency of cracking distresses to occur.

- Very few pavements constructed with all virgin materials were present in the database, thus limited data was available to make final conclusions regarding presence of recycled materials on cracking performance. For the limited data, a larger fraction of crack free pavements are represented by all virgin mixes as compared to mixes containing recycled materials.

5.4 Recommendations

Generating a comprehensive database and the subsequent statistical analysis of ITS and asphalt mix design parameters in context of field cracking performance helped make several observations regarding future recommendations. The key recommendations from the research efforts of this study are as follows:

- The development of a comprehensive database required developing an extensive search algorithm to map the cracking data from pavement management highway sections onto the material records from the laboratory information system and the construction records. If the future versions of the pavement management system can include a variable that tracks the highway construction information (for example, project SP), the development of a comprehensive database, such as one developed in this study, will require a significantly fewer amount of human resources and computational efforts.

- The asphalt binder amount and grade play an important role in the cracking performance of bituminous pavements and overlays. The asphalt binder grade recommendations along with the potential for use of a minimum asphalt binder amount in the specifications should be reevaluated. The future tasks of the current project will provide additional information on this topic through field and laboratory evaluation of several pavement sections.

- The disk-shaped compact tension fracture and dynamic modulus testing are planned to be conducted in the future. The data and findings from this research should be revisited for evaluating the suitability of those tests for prediction of pavement cracking performance.

- It was not possible to analyze the effects of the amount of recycled materials on pavement cracking performance. Future research projects should evaluate this effect. A major challenge is the quantification of the percent of recycled material in asphalt mixes which would require manual scrutiny of each mix design record, one at a time. If the future version of mix design records can be modified to explicitly report the percent of recycled materials, the future data analysis can be automated to analyze the effects of amount of recycled materials on pavement performance.

- In general, the volumetric quantities determined using chemical extraction process (binder content, VMA, VFA etc.) showed inferior correlation with ITS and field cracking amounts as compared to same quantities determined using the ignition oven method. This is very peculiar, as the volumetric quantities as anticipated to be comparable between the two binder content determination methods. The data should be further analyzed to determine if there exists a consistent bias between the two methods.

- The data analysis presented herein did not normalize the field cracking performance measured against the amount of traffic. The future data analysis should consider this effect to determine if the cracking amounts and rates are significantly affected by traffic level and whether the effects of mix design parameters on cracking are altered by the effects of traffic.

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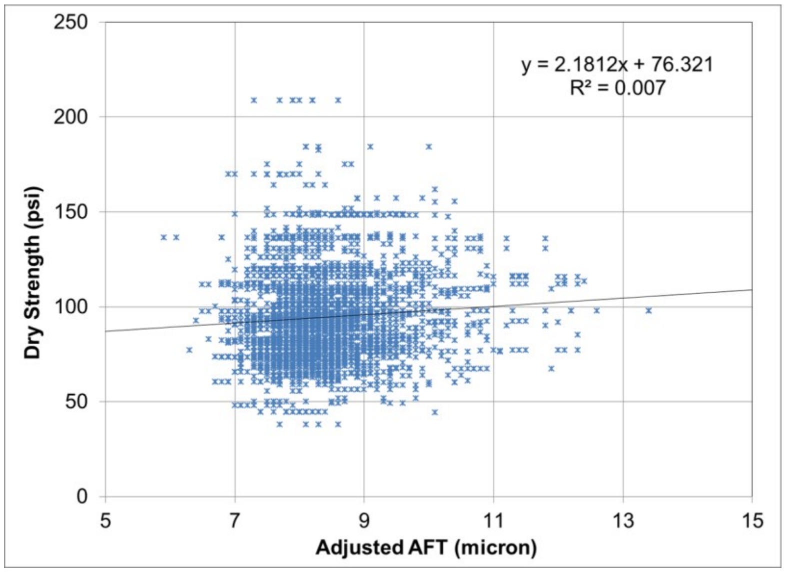
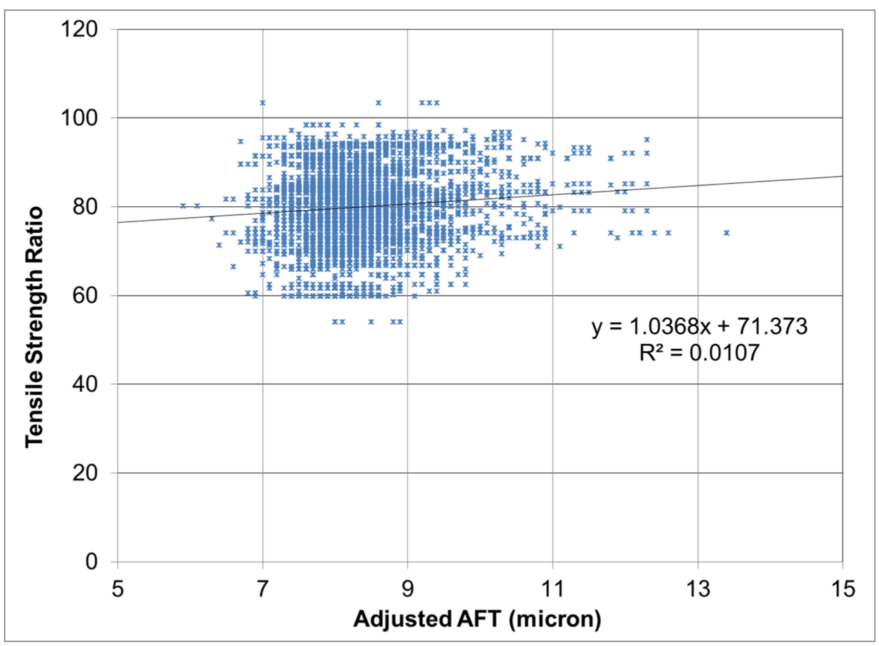
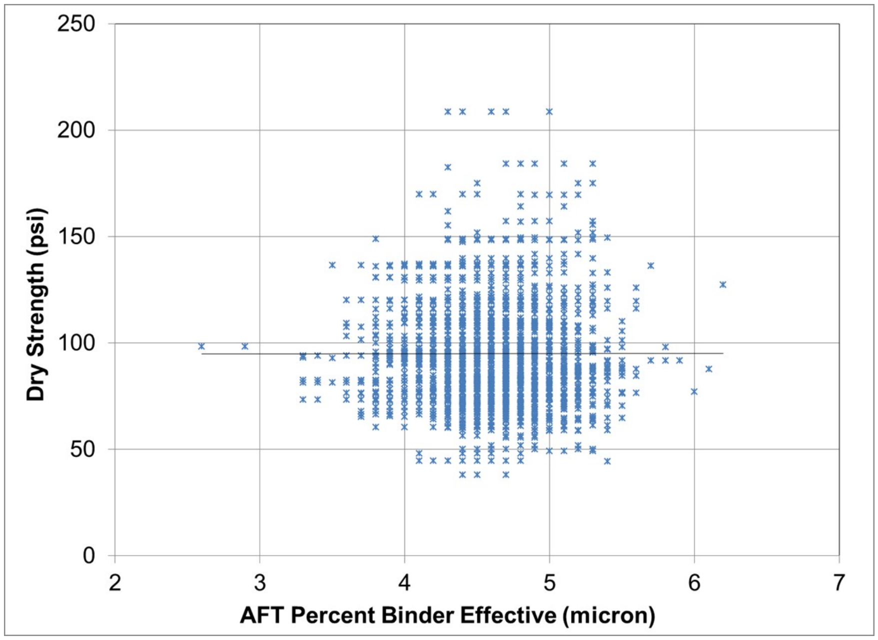
APPENDIX A: ADDITIONAL PLOTS AND TABLES FOR INDIRECT TENSILE STRENGTH AND TENSILE STRENGTH RATIO



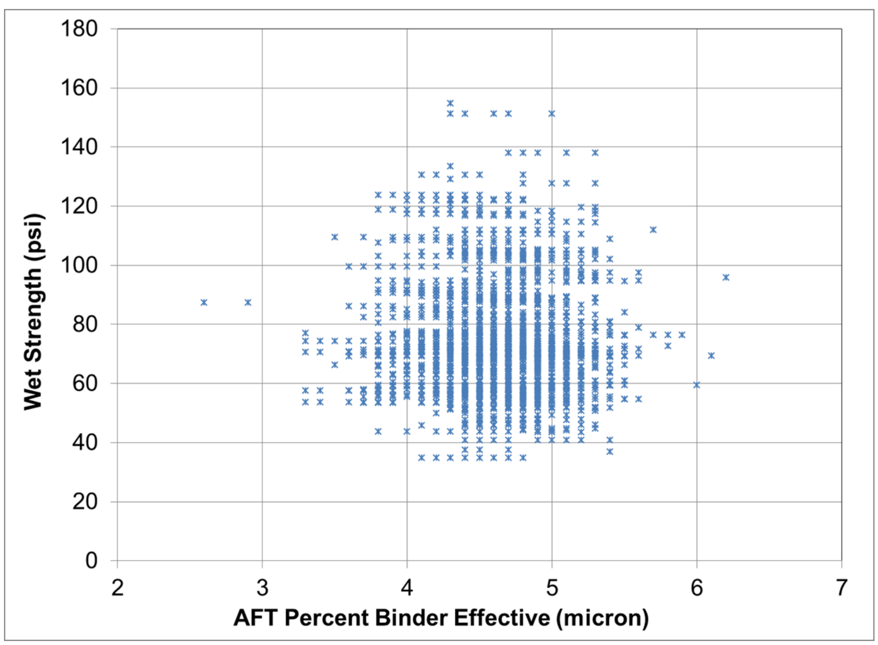
Adjusted Asphalt film thickness versus ITS (dry)



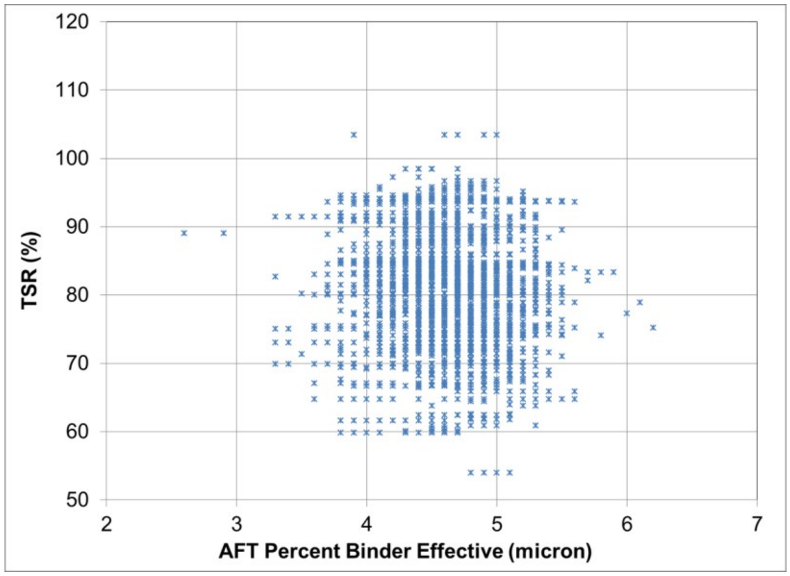
Adjusted Asphalt film thickness versus TSR



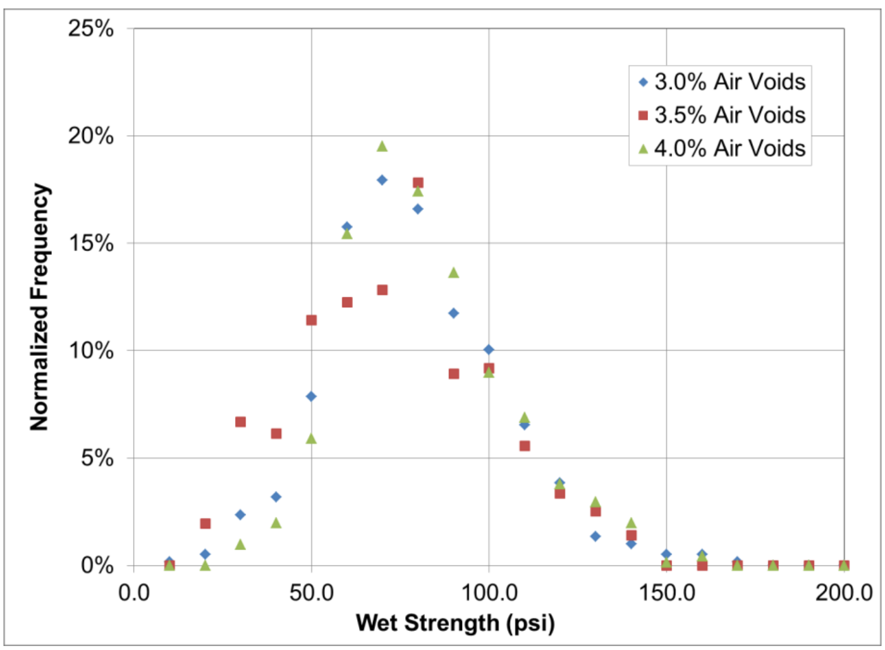
Asphalt film thickness versus ITS (dry)



Asphalt film thickness versus ITS (wet)



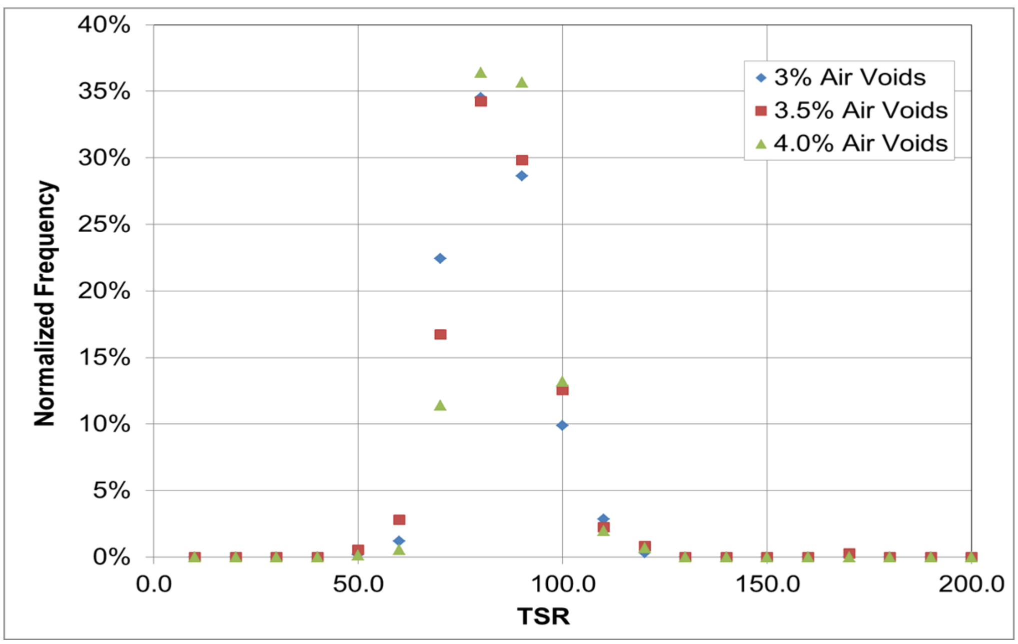
Asphalt film thickness versus TSR



Normalized frequency plot of ITS (wet) for various design air void percentages

ITS (wet) and design air void percentages statistics

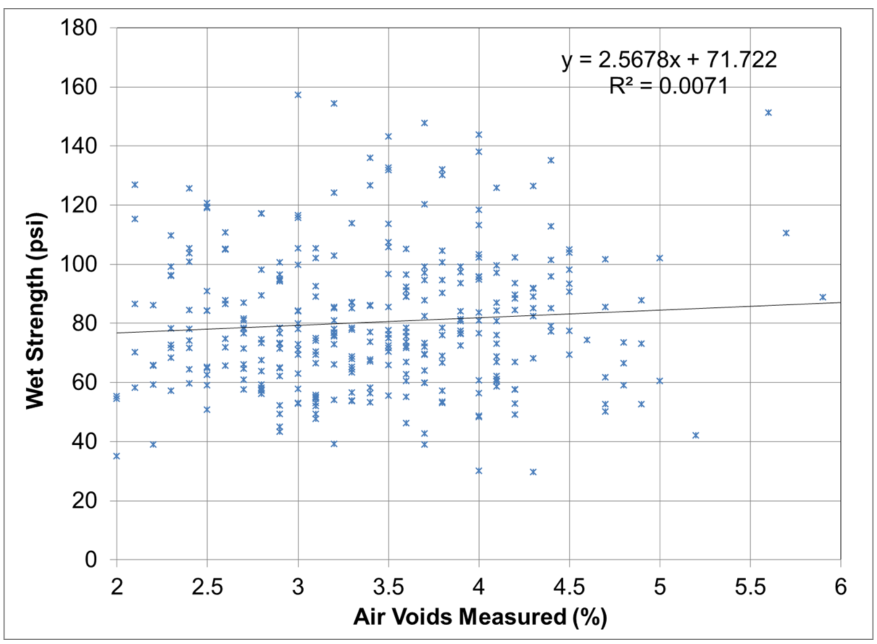
	Wet Strength (psi)		
	3.0% Air Voids	3.5% Air Voids	4.0 % Air Voids
Median	71.4	68.4	73.1
Average	73.8	69.0	76.6
Standard Deviation	24.2	26.7	23.1



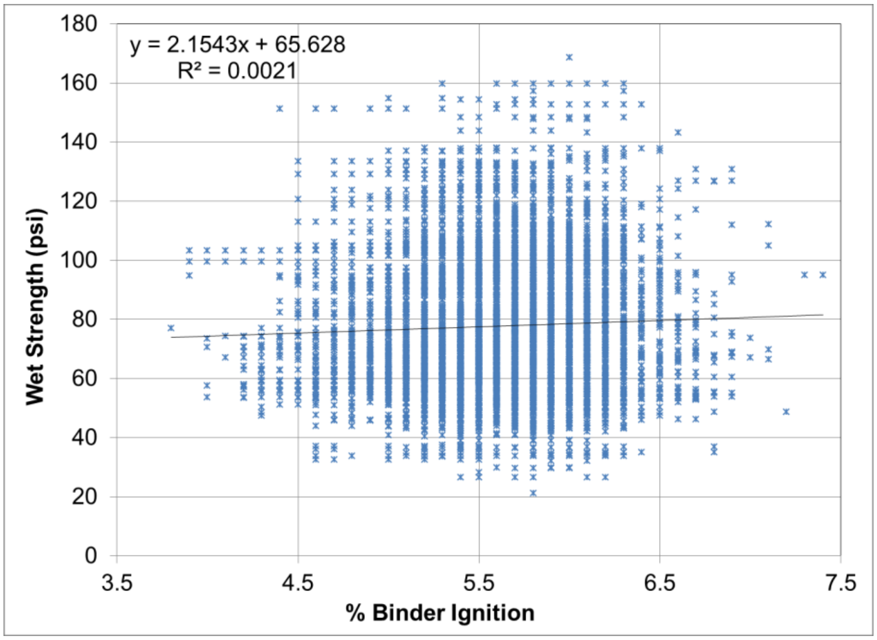
Normalized frequency plot of TSR for various design air void percentages

TSR and design air void percentages statistics

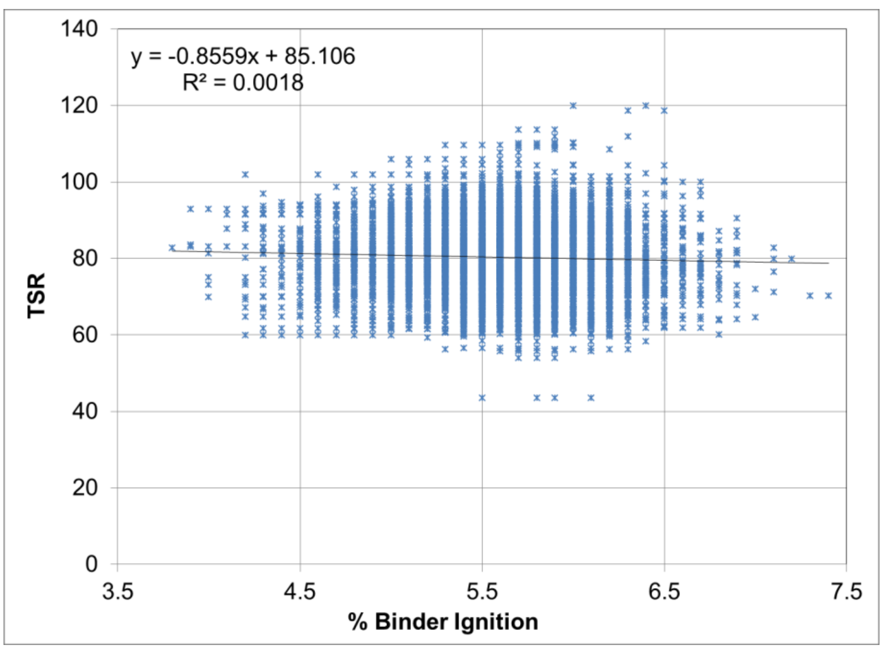
	TSR (%)		
	3.0% Air Voids	3.5% Air Voids	4.0 % Air Voids
Median	77.8	78.9	80.5
Average	78.5	79.2	80.7
Standard Deviation	10.7	11.8	9.5



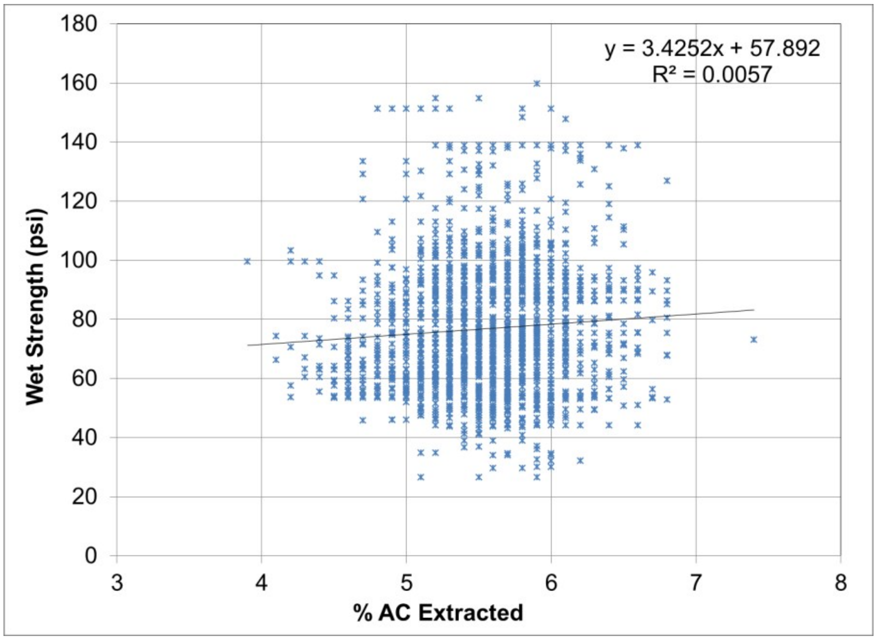
Measured air voids versus ITS (wet)



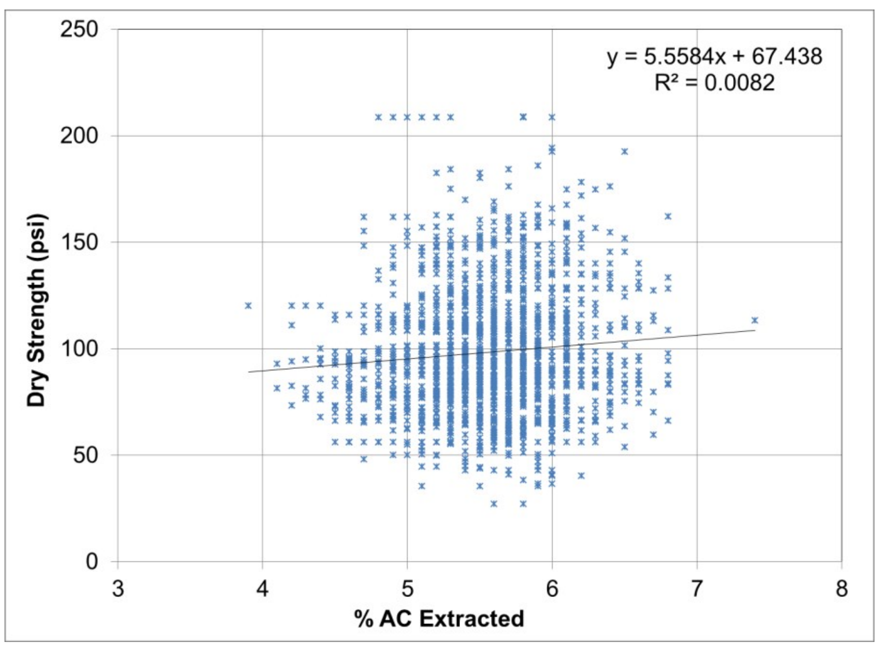
Percent asphalt binder content (ignition) versus ITS (wet)



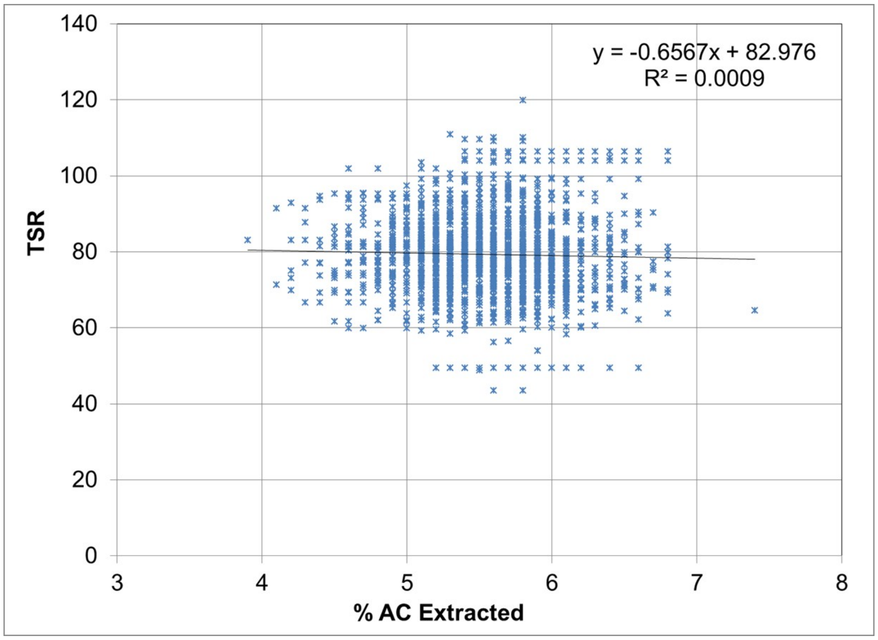
Percent asphalt binder content (ignition) versus TSR



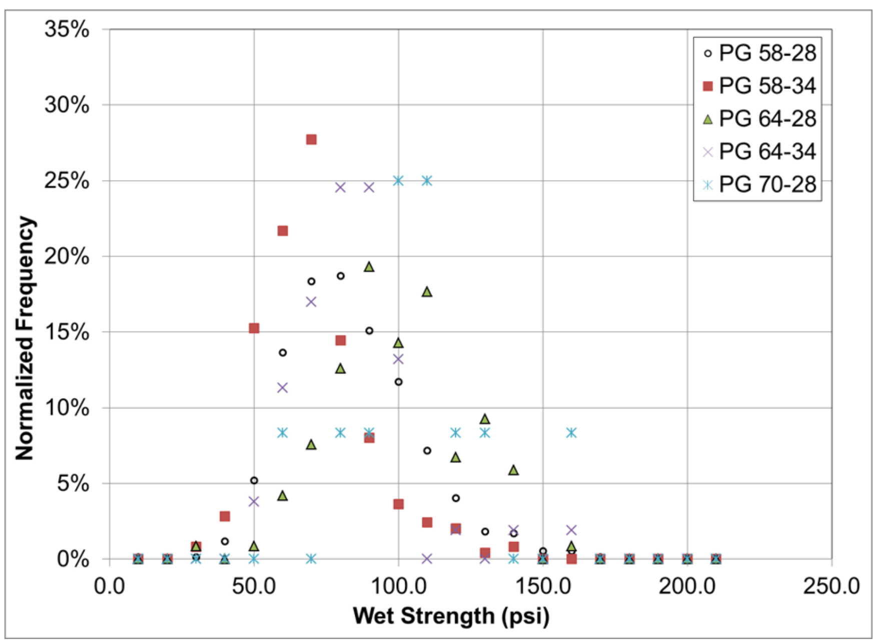
Percent asphalt binder content (extracted) versus ITS (wet)



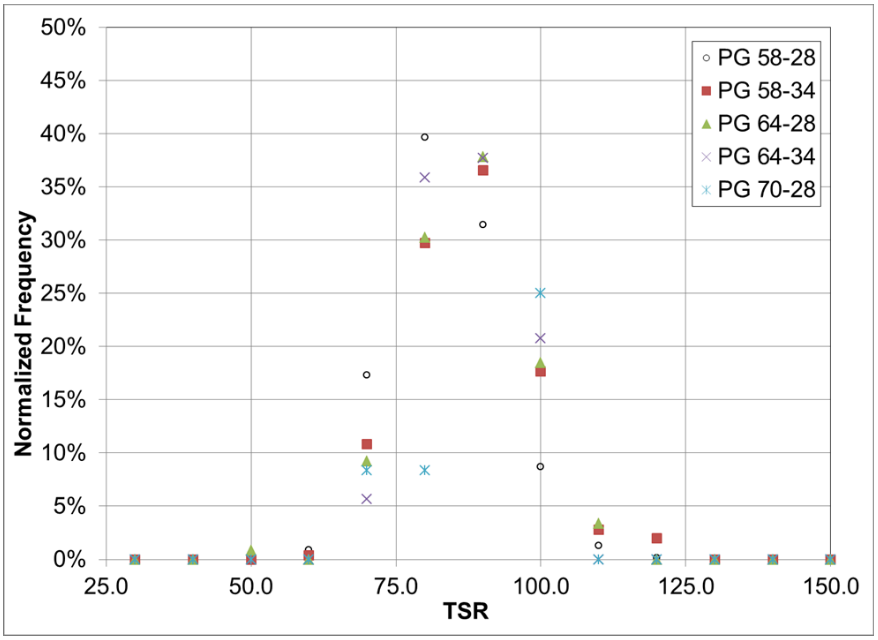
Percent asphalt binder content (extracted) versus ITS (dry)



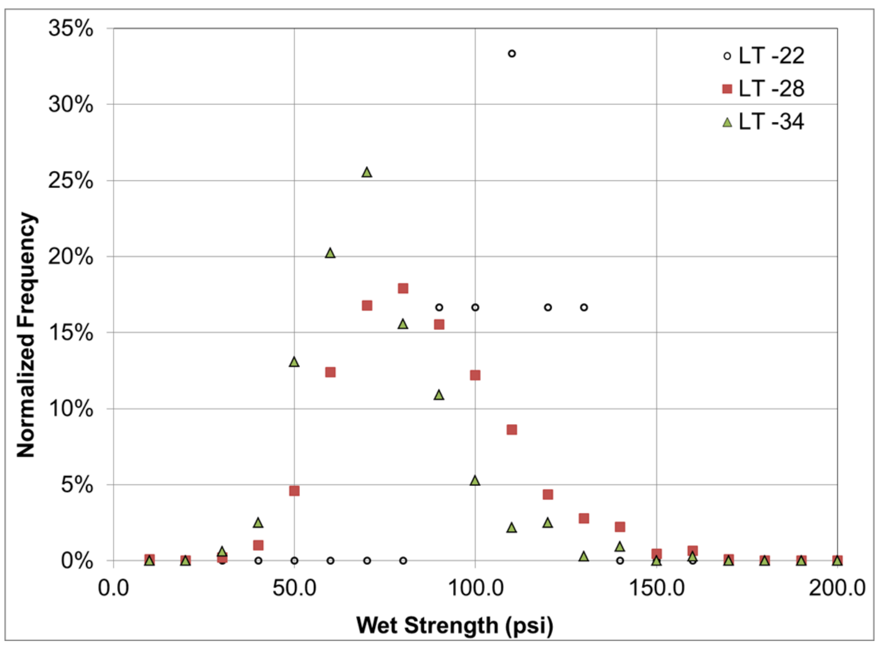
Percent asphalt binder content (extracted) versus TSR



Normalized frequency plot of ITS (wet) for various asphalt binder grades (PG)



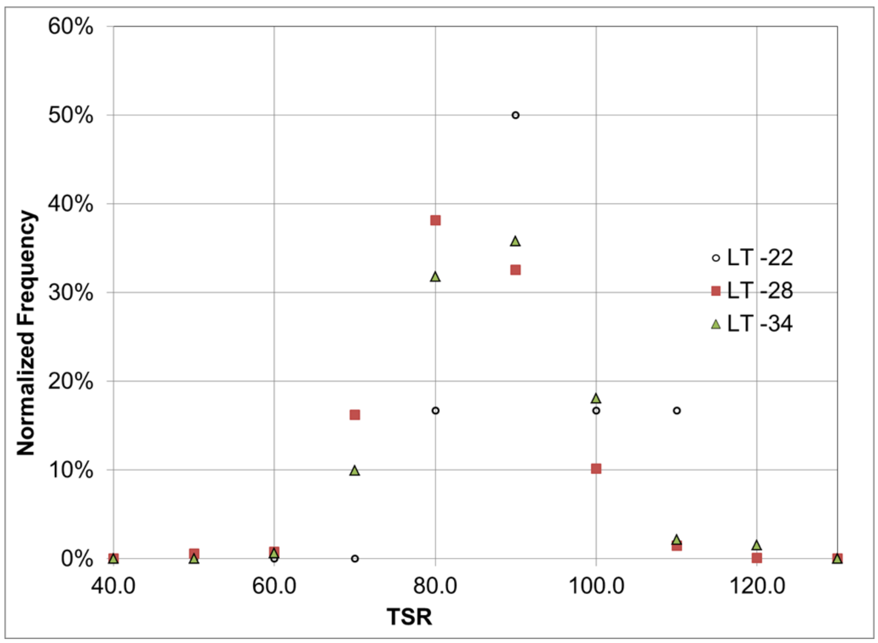
Normalized frequency plot of TSR for various asphalt binder grades (PG)



Normalized frequency plot of ITS (wet) for various low temperature asphalt binder grades (PG)

ITS (wet) for various low temperature asphalt binder grades (PGLT) statistics

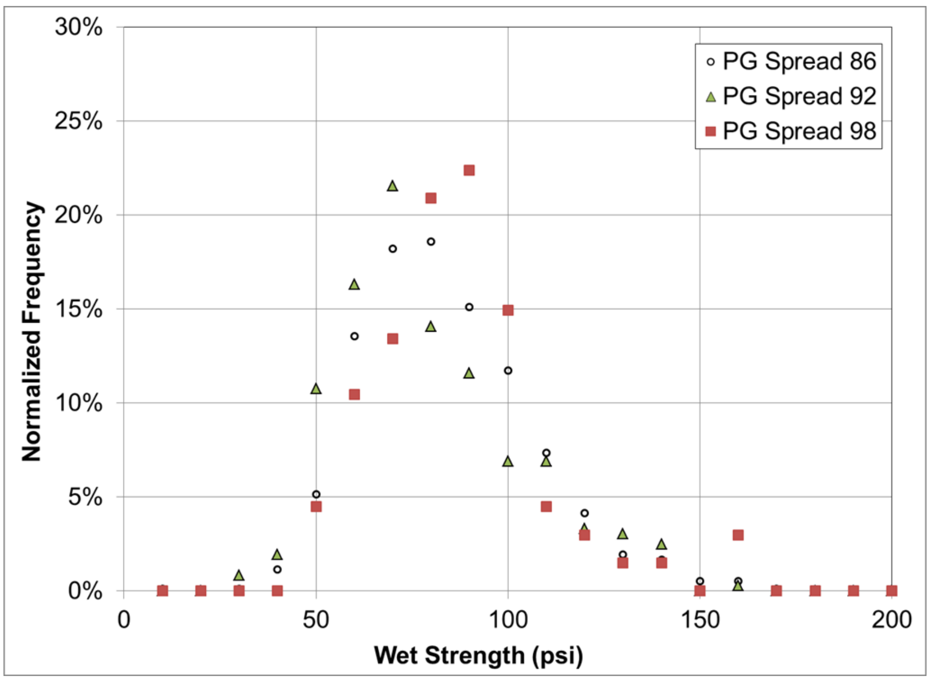
	Wet Strength (psi)			
	PGLT - 22	PGLT - 28	PGLT - 34	PGLT - 40
Median	103.8	78.1	65.7	66.8
Average	104.5	80.8	68.0	66.8
Standard Deviation	14.5	23.0	19.5	21.4



Normalized frequency plot of TSR for various low temperature asphalt binder grades (PG LT)

TSR for various low temperature asphalt binder grades (PGLT) statistics

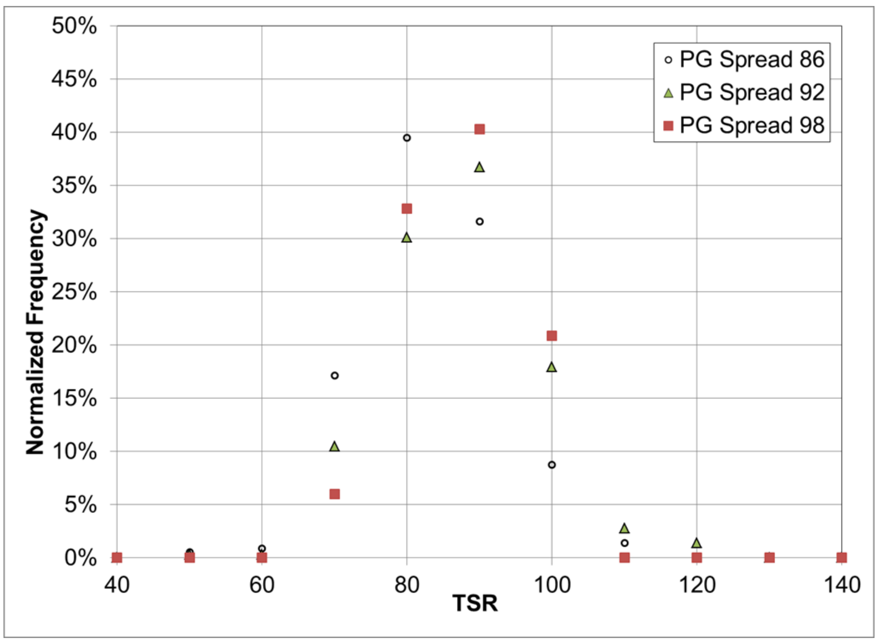
	TSR (%)			
	PGLT -22	PGLT -28	PGLT -34	PGLT -40
Median	85.3	78.6	81.9	77.9
Average	87.5	78.8	82.5	77.9
Standard Deviation	8.3	9.6	10.3	0.6



Normalized frequency plot of ITS (wet) for various spreads of asphalt binder grades (PG Spread)

ITS (wet) for various spreads of asphalt binder grades (PG Spread) statistics

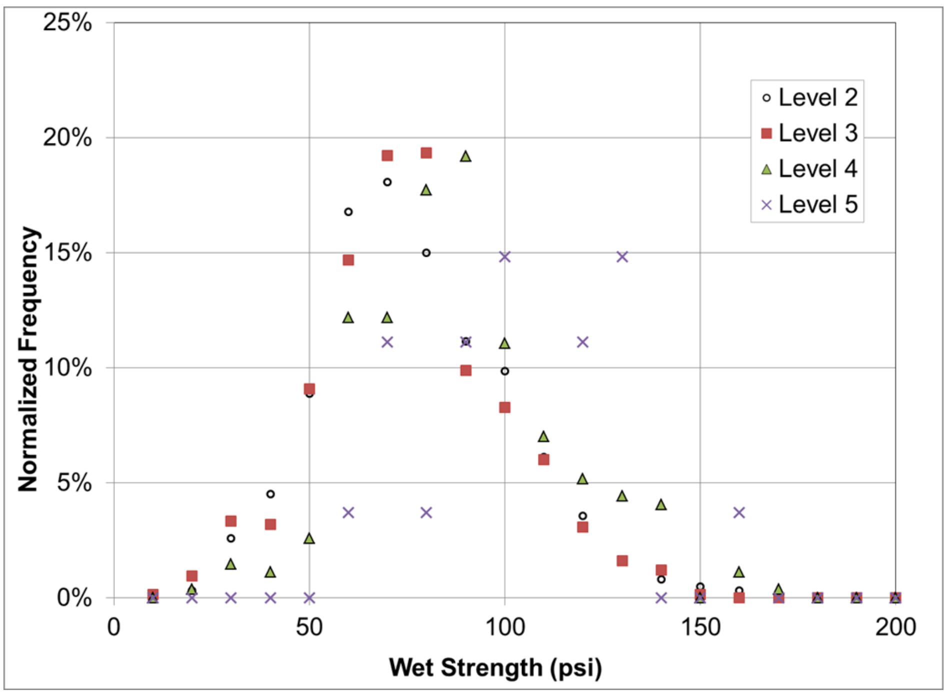
	Wet Strength (psi)			
	PG Spread 86	PG Spread 92	PG Spread 98	PG Spread 104
Median	76.20	69.45	80.60	91.35
Average	78.78	74.17	82.73	91.35
Standard Deviation	22.32	23.82	22.06	---



Normalized frequency plot of TSR for various spreads of asphalt binder grades (PG Spread)

TSR for various spreads of asphalt binder grades (PG Spread) statistics

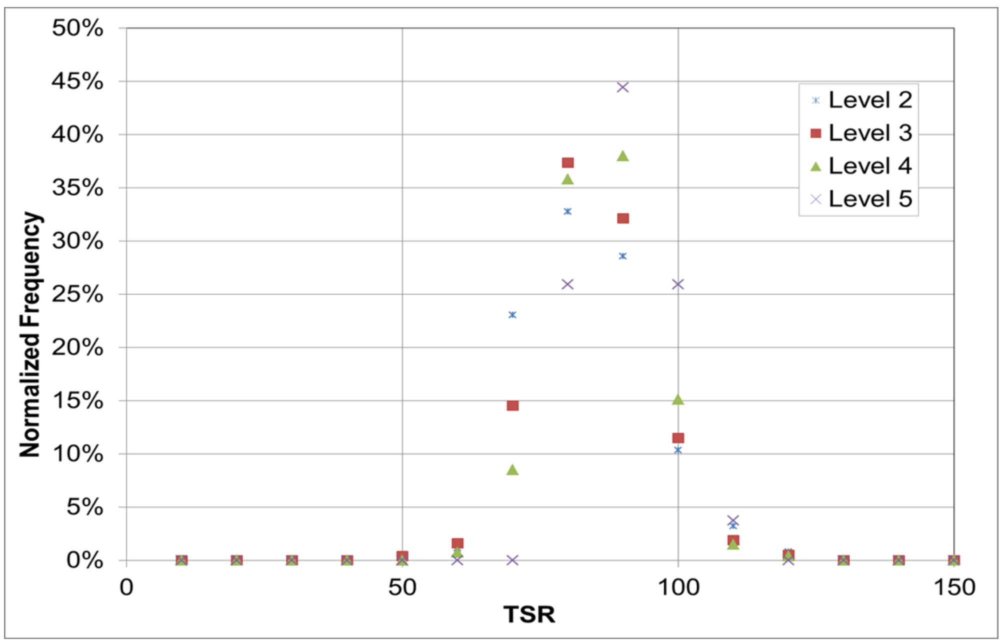
	TSR (%)			
	PG Spread 86	PG Spread 92	PG Spread 98	PG Spread 104
Median	78.10	81.90	83.10	87.85
Average	78.31	82.44	82.97	87.85
Standard Deviation	9.59	10.25	8.55	---



Normalized frequency plot of ITS (wet) for various design traffic levels

ITS (wet) for various design traffic levels statistics

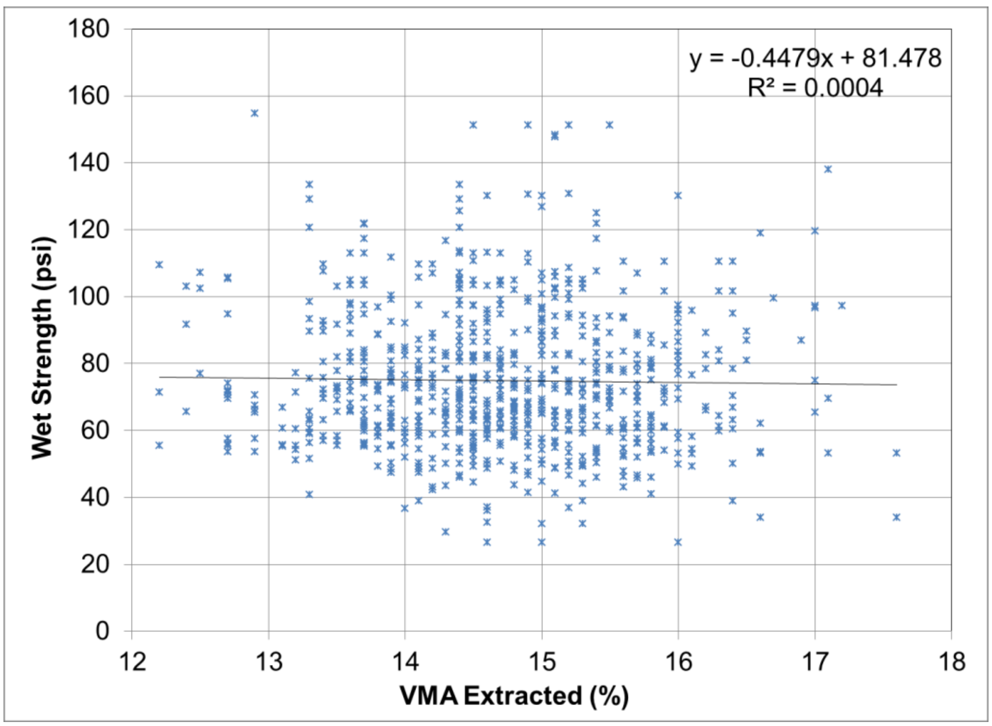
	Wet Strength (psi)			
	Traffic Level 2	Traffic Level 3	Traffic Level 4	Traffic Level 5
Median	69.3	69.65	81.5	102.0
Average	72.0	71.26	83.3	99.3
Standard Deviation	23.8	23.35	25.4	22.9



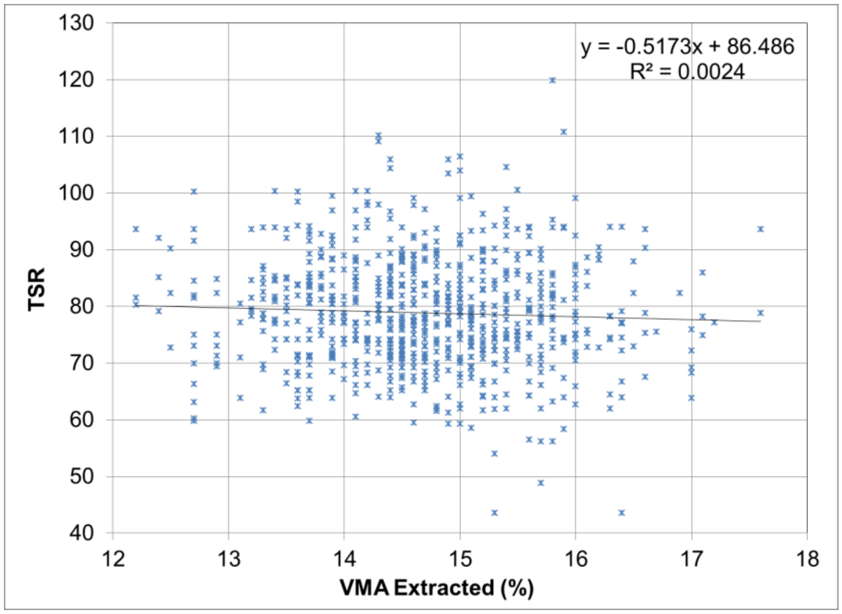
Normalized frequency plot of TSR for various design traffic levels

TSR for various design traffic levels statistics

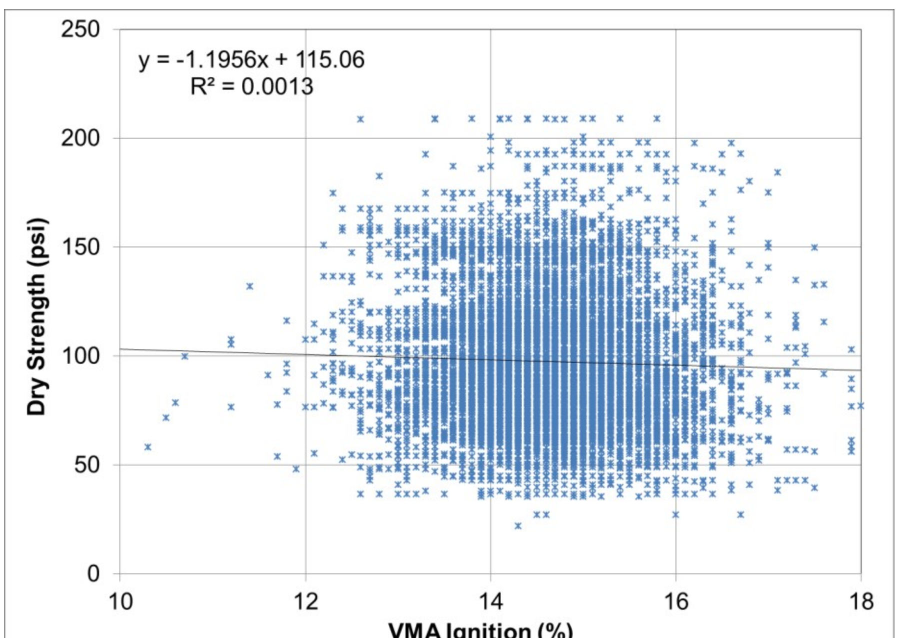
	TSR (%)			
	Traffic Level 2	Traffic Level 3	Traffic Level 4	Traffic Level 5
Median	78.4	78.9	81.5	83.8
Average	78.9	79.28	81.5	85.3
Standard Deviation	11.1	10.48	9.0	9.3



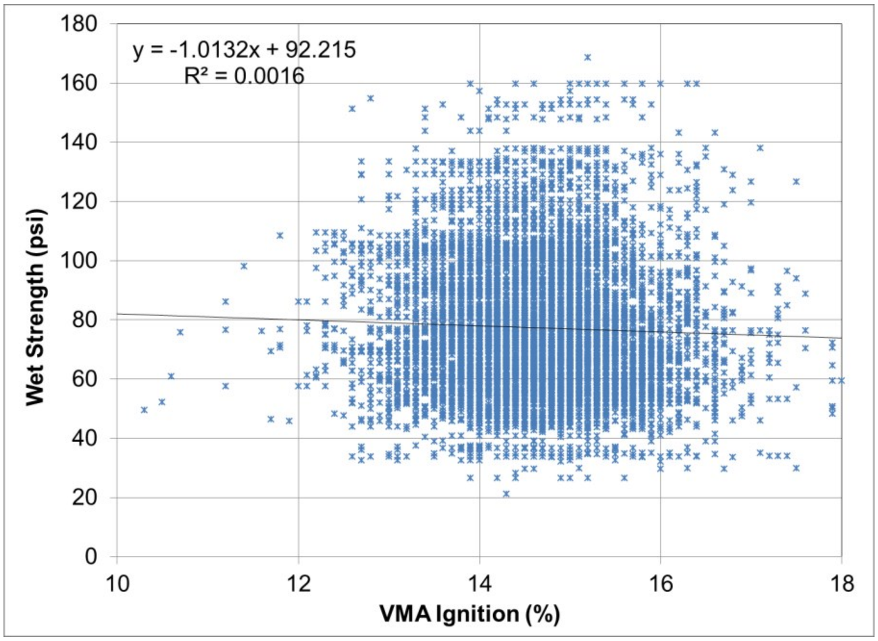
Voids in mineral aggregate (VMA chemical extraction method) versus ITS (wet)



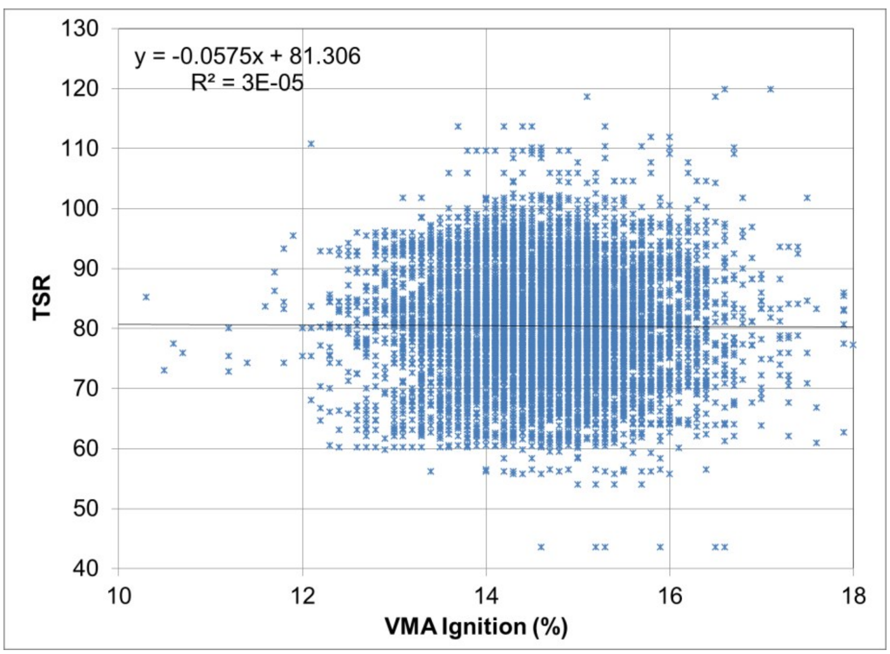
Voids in mineral aggregate (VMA chemical extraction method) versus TSR



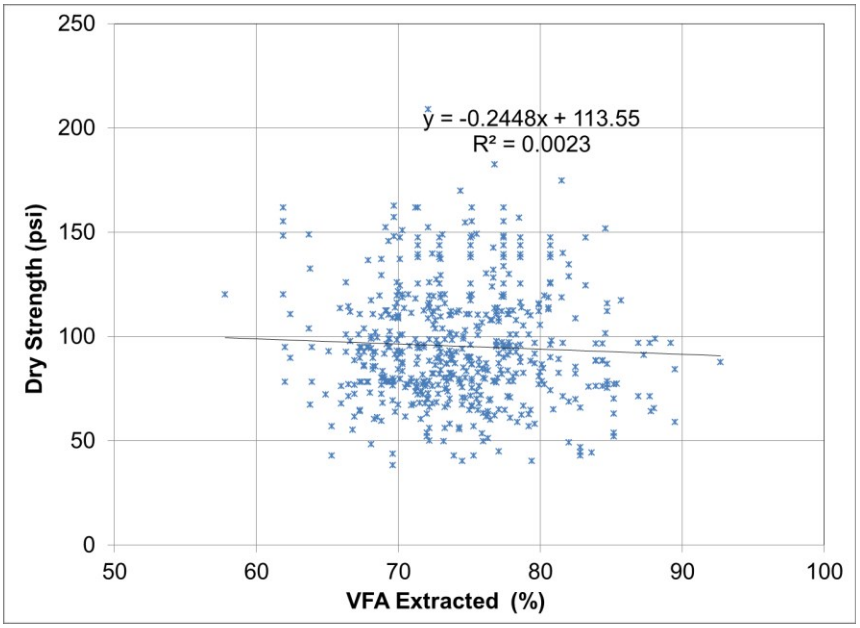
Voids in mineral aggregate (VMA ignition oven method) versus ITS (dry)



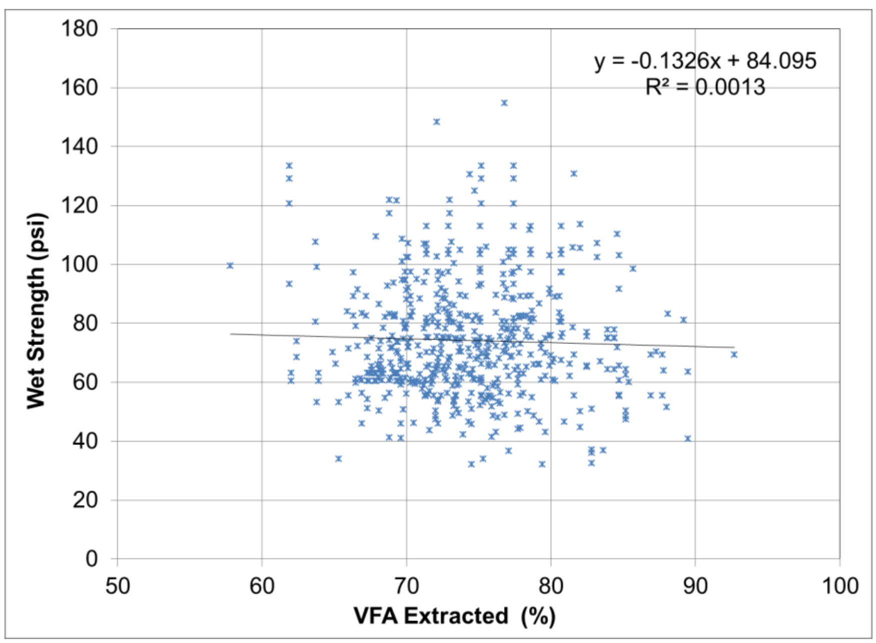
Voids in mineral aggregate (VMA ignition oven method) versus ITS (wet)



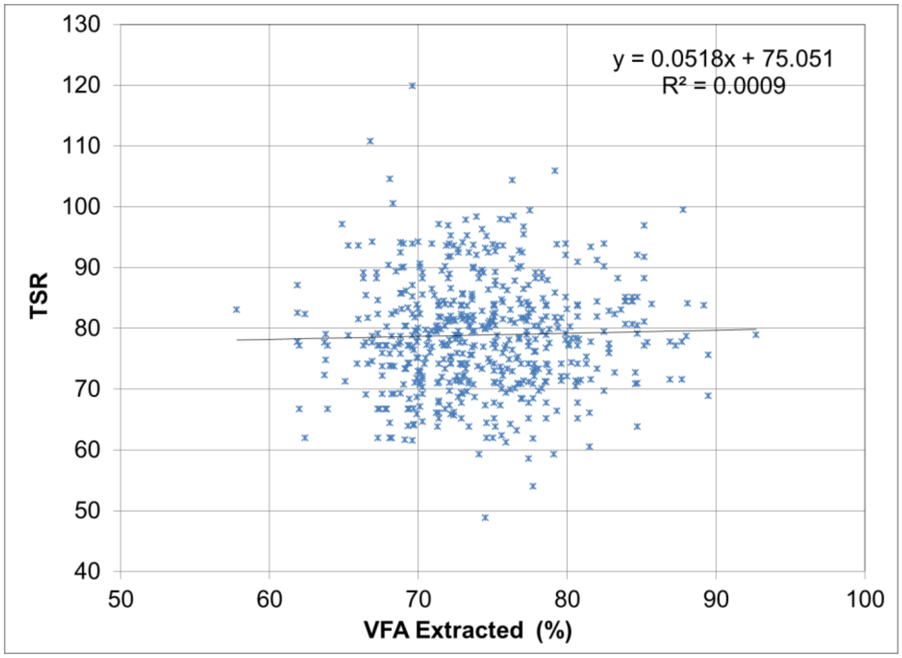
Voids in mineral aggregate (VMA ignition oven method) versus TSR



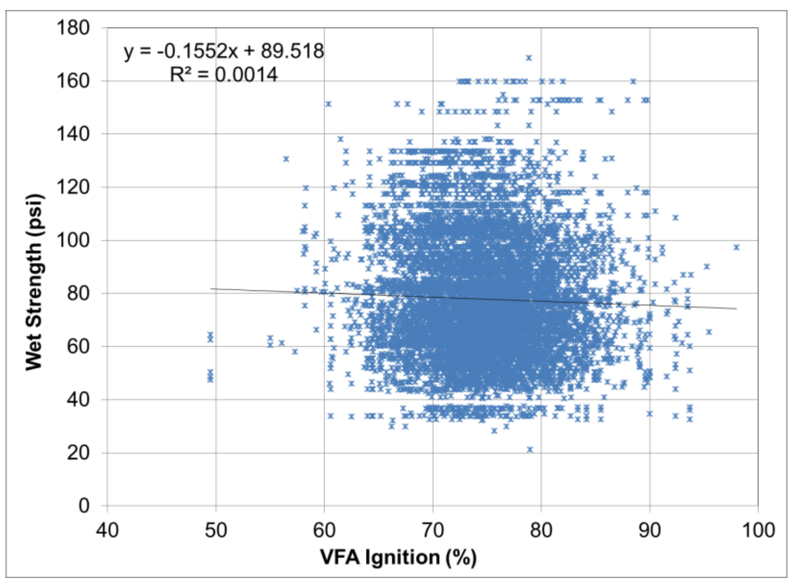
Voids filled with asphalt (VFA chemical extraction method) versus ITS (dry)



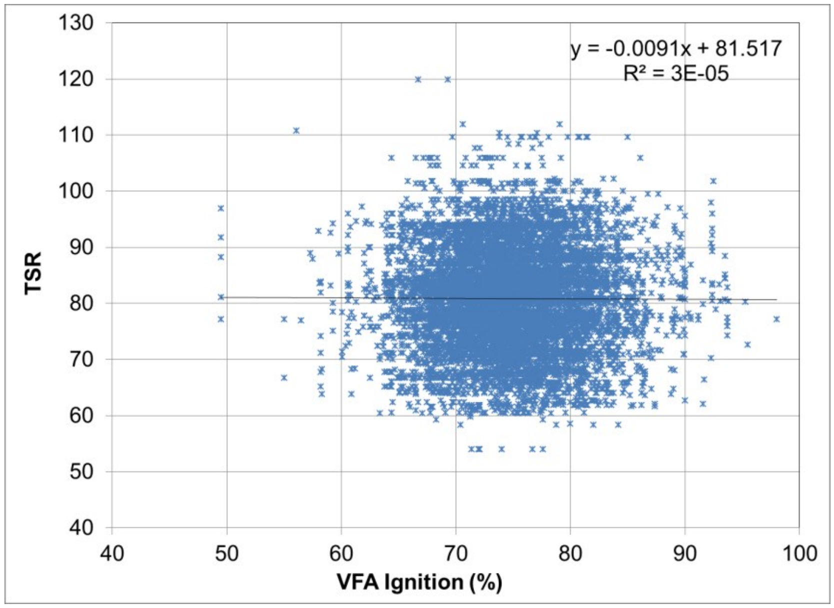
Voids filled with asphalt (VFA chemical extraction method) versus ITS (wet)



Voids filled with asphalt (VFA chemical extraction method) versus TSR



Voids filled with asphalt (VFA ignition oven method) versus ITS (wet)



Voids filled with asphalt (VFA ignition oven method) versus TSR

APPENDIX B: SELECTED STATISTICAL ANALYSIS OUTPUT TABLES GENERATED BY SAS

AFT Adjusted and Percent Binder Extracted

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	41445.8916	881.8275	1.04	0.4139
Error	286	243175.8554	850.2652		
Corrected Total	333	284621.7471			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.145617	30.33549	29.15931	96.12275

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTAdj	7	3318.18412	474.02630	0.56	0.7901
BinderExtracted	24	23829.57470	992.89895	1.17	0.2708
AFTAdj*BinderExtract	16	14298.13282	893.63330	1.05	0.4029

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTAdj	7	8232.51300	1176.07329	1.38	0.2121
BinderExtracted	24	20724.57358	863.52390	1.02	0.4458
AFTAdj*BinderExtract	16	14298.13282	893.63330	1.05	0.4029

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	22758.9458	484.2329	1.03	0.4289
Error	286	134671.8457	470.8806		
Corrected Total	333	157430.7915			

R-Square	Coeff Var	Root MSE	WetStrength Mean
0.144565	28.23962	21.69978	76.84162

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTAdj	7	3887.38082	555.34012	1.18	0.3145
BinderExtracted	24	6962.46716	290.10280	0.62	0.9218
AFTAdj*BinderExtract	16	11909.09782	744.31861	1.58	0.0731

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTAdj	7	5774.63157	824.94737	1.75	0.0969
BinderExtracted	24	5223.26003	217.63583	0.46	0.9867
AFTAdj*BinderExtract	16	11909.09782	744.31861	1.58	0.0731

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	28	3632.95916	129.74854	1.69	0.0190
Error	285	21928.13399	76.94082		
Corrected Total	313	25561.09315			

R-Square	Coeff Var	Root MSE	TSR Mean
0.142128	11.08822	8.771592	79.10732

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTAdj	7	954.427063	136.346723	1.77	0.0927
BinderExtracted	5	136.285185	27.257037	0.35	0.8793
AFTAdj*BinderExtract	16	2542.246912	158.890432	2.07	0.0099

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTAdj	7	1621.472024	231.638861	3.01	0.0046
BinderExtracted	5	162.619195	32.523839	0.42	0.8328
AFTAdj*BinderExtract	16	2542.246912	158.890432	2.07	0.0099

AFT Adjusted and Percent Binder Ignition

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	36	73183.461	2032.874	3.95	<.0001
Error	3231	1662324.103	514.492		
Corrected Total	3267	1735507.565			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.042168	23.86625	22.68242	95.03972

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTAdj	7	16666.24619	2380.89231	4.63	<.0001
BinderIgnition	6	23839.72393	3973.28732	7.72	<.0001
AFTAdj*BinderIgnitio	23	32677.49122	1420.76049	2.76	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTAdj	7	14850.89972	2121.55710	4.12	0.0002
BinderIgnition	6	4068.20061	678.03343	1.32	0.2453
AFTAdj*BinderIgnitio	23	32677.49122	1420.76049	2.76	<.0001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	36	83038.722	2306.631	6.67	<.0001
Error	3231	1117023.490	345.721		
Corrected Total	3267	1200062.212			

R-Square	Coeff Var	Root MSE	WetStrength Mean
0.069195	24.50569	18.59357	75.87448

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTAdj	7	31449.54923	4492.79275	13.00	<.0001
BinderIgnition	6	22563.11583	3760.51930	10.88	<.0001
AFTAdj*BinderIgnitio	23	29026.05689	1262.00247	3.65	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTAdj	7	22058.14573	3151.16368	9.11	<.0001
BinderIgnition	6	4293.53666	715.58944	2.07	0.0536
AFTAdj*BinderIgnitio	23	29026.05689	1262.00247	3.65	<.0001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	36	10618.0918	294.9470	3.86	<.0001
Error	3231	246936.4275	76.4272		
Corrected Total	3267	257554.5192			

R-Square	Coeff Var	Root MSE	TSR Mean
0.041227	10.90456	8.742268	80.17078

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTAdj	7	5367.797213	766.828173	10.03	<.0001
BinderIgnition	6	1618.112767	269.685461	3.53	0.0017
AFTAdj*BinderIgnitio	23	3632.181780	157.920947	2.07	0.0020

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTAdj	7	3010.064615	430.009231	5.63	<.0001
BinderIgnition	6	594.691044	99.115174	1.30	0.2549
AFTAdj*BinderIgnitio	23	3632.181780	157.920947	2.07	0.0020

AFT Effective and Percent Binder Extracted

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	15493.871	2213.410	4.04	0.0002
Error	2539	1391390.613	548.007		
Corrected Total	2546	1406884.483			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.011013	24.51997	23.40956	95.47138

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTEff	1	11.17191	11.17191	0.02	0.8865
BinderExtracted	6	15482.69888	2580.44981	4.71	<.0001
AFTEff*BinderExtract	0	0.00000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTEff	1	4.11027	4.11027	0.01	0.9310
BinderExtracted	6	15482.69888	2580.44981	4.71	<.0001
AFTEff*BinderExtract	0	0.00000	.	.	.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	15989.0596	2284.1514	6.10	<.0001
Error	2539	951339.7674	374.6907		
Corrected Total	2546	967328.8269			

R-Square	Coeff Var	Root MSE	WetStrength Mean
0.016529	25.35735	19.35693	76.33655

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTEff	1	6.48934	6.48934	0.02	0.8953
BinderExtracted	6	15982.57023	2663.76171	7.11	<.0001
AFTEff*BinderExtract	0	0.00000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTEff	1	26.29004	26.29004	0.07	0.7911
BinderExtracted	6	15982.57023	2663.76171	7.11	<.0001
AFTEff*BinderExtract	0	0.00000	.	.	.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	1618.8519	231.2646	3.06	0.0033
Error	2539	191790.8632	75.5380		
Corrected Total	2546	193409.7151			

R-Square	Coeff Var	Root MSE	TSR Mean
0.008370	10.82512	8.691257	80.28787

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AFTEff	1	29.888473	29.888473	0.40	0.5294
BinderExtracted	6	1588.963434	264.827239	3.51	0.0019
AFTEff*BinderExtract	0	0.000000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AFTEff	1	25.454427	25.454427	0.34	0.5616
BinderExtracted	6	1588.963434	264.827239	3.51	0.0019
AFTEff*BinderExtract	0	0.000000	.	.	.

PG Grade and AFT Adjusted

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	38	429329.573	11298.147	24.63	<.0001
Error	2321	1064658.162	458.707		
Corrected Total	2359	1493987.735			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.287372	21.75290	21.41744	98.45784

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	6	393552.2730	65592.0455	142.99	<.0001
AFTAdj	7	4255.5315	607.9331	1.33	0.2339
PGGrade*AFTAdj	25	31521.7682	1260.8707	2.75	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	6	90586.09966	15097.68328	32.91	<.0001
AFTAdj	7	7643.26045	1091.89435	2.38	0.0200
PGGrade*AFTAdj	25	31521.76818	1260.87073	2.75	<.0001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	38	379634.9625	9990.3937	37.42	<.0001
Error	2321	619668.6535	266.9835		
Corrected Total	2359	999303.6160			

R-Square	Coeff Var	Root MSE	WetStrength Mean
0.379900	20.58666	16.33963	79.37000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	6	364588.3356	60764.7226	227.60	<.0001
AFTAdj	7	2219.5179	317.0740	1.19	0.3063
PGGrade*AFTAdj	25	12827.1090	513.0844	1.92	0.0040

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	6	66625.47296	11104.24549	41.59	<.0001
AFTAdj	7	3303.36483	471.90926	1.77	0.0895
PGGrade*AFTAdj	25	12827.10897	513.08436	1.92	0.0040

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	38	24987.8737	657.5756	11.23	<.0001
Error	2321	135886.8390	58.5467		
Corrected Total	2359	160874.7127			

R-Square	Coeff Var	Root MSE	TSR Mean
0.155325	9.450518	7.651580	80.96466

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	6	21318.66317	3553.11053	60.69	<.0001
AFTAdj	7	1507.03227	215.29032	3.68	0.0006
PGGrade*AFTAdj	25	2162.17825	86.48713	1.48	0.0600

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	6	4499.349041	749.891507	12.81	<.0001
AFTAdj	7	593.837818	84.833974	1.45	0.1812
PGGrade*AFTAdj	25	2162.178250	86.487130	1.48	0.0600

PG Grade and Percent Binder Extracted

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	25	190720.3306	7628.8132	9.04	<.0001
Error	926	781225.9010	843.6565		
Corrected Total	951	971946.2316			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.196225	27.84683	29.04577	104.3055

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	6	156065.7901	26010.9650	30.83	<.0001
BinderExtraction	4	16652.5134	4163.1283	4.93	0.0006
PGGrade*BinderExtrac	15	18002.0271	1200.1351	1.42	0.1292

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	6	112323.2778	18720.5463	22.19	<.0001
BinderExtraction	4	4497.6546	1124.4137	1.33	0.2559
PGGrade*BinderExtrac	15	18002.0271	1200.1351	1.42	0.1292

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	25	122802.8713	4912.1149	11.16	<.0001
Error	926	407617.2597	440.1914		
Corrected Total	951	530420.1311			

R-Square	Coeff Var	Root MSE	WetStrength Mean
0.231520	25.83451	20.98074	81.21208

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	6	110018.9437	18336.4906	41.66	<.0001
BinderExtraction	4	4707.2388	1176.8097	2.67	0.0309
PGGrade*BinderExtrac	15	8076.6888	538.4459	1.22	0.2474

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	6	75265.30278	12544.21713	28.50	<.0001
BinderExtraction	4	1000.22961	250.05740	0.57	0.6859
PGGrade*BinderExtrac	15	8076.68883	538.44592	1.22	0.2474

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	25	6652.84084	266.11363	2.82	<.0001
Error	926	87462.44184	94.45188		
Corrected Total	951	94115.28268			

R-Square	Coeff Var	Root MSE	TSR Mean
0.070688	12.31683	9.718636	78.90536

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	6	4324.762444	720.793741	7.63	<.0001
BinderExtraction	4	1278.603111	319.650778	3.38	0.0093
PGGrade*BinderExtrac	15	1049.475288	69.965019	0.74	0.7439

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	6	1183.754029	197.292338	2.09	0.0522
BinderExtraction	4	334.592506	83.648126	0.89	0.4719
PGGrade*BinderExtrac	15	1049.475288	69.965019	0.74	0.7439

PG Grade and Percent Binder Ignition

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	39	2012247.125	51596.080	59.63	<.0001
Error	7919	6852193.158	865.285		
Corrected Total	7958	8864440.283			

R-Square	Coeff Var	Root MSE	DryStrength Mean
0.227002	29.23860	29.41573	100.6058

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	8	1842434.403	230304.300	266.16	<.0001
BinderIgnition	6	71981.532	11996.922	13.86	<.0001
PGGrade*BinderIgniti	25	97831.190	3913.248	4.52	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	8	125732.9492	15716.6187	18.16	<.0001
BinderIgnition	6	13602.0369	2267.0061	2.62	0.0154
PGGrade*BinderIgniti	25	97831.1899	3913.2476	4.52	<.0001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	39	1449773.492	37173.679	83.46	<.0001
Error	7919	3527382.014	445.433		
Corrected Total	7958	4977155.506			

R-Square	Coeff Var	Root MSE	WetStrength Mean
0.291286	26.29026	21.10528	80.27794

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	8	1371831.996	171478.999	384.97	<.0001
BinderIgnition	6	28461.459	4743.577	10.65	<.0001
PGGrade*BinderIgniti	25	49480.037	1979.201	4.44	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	8	130343.7526	16292.9691	36.58	<.0001
BinderIgnition	6	5799.5711	966.5952	2.17	0.0428
PGGrade*BinderIgniti	25	49480.0366	1979.2015	4.44	<.0001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	39	72593.2959	1861.3666	23.17	<.0001
Error	7919	636148.2040	80.3319		
Corrected Total	7958	708741.4999			

R-Square	Coeff Var	Root MSE	TSR Mean
0.102426	11.08706	8.962806	80.84024

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PGGrade	8	63711.33586	7963.91698	99.14	<.0001
BinderIgnition	6	3191.21648	531.86941	6.62	<.0001
PGGrade*BinderIgniti	25	5690.74359	227.62974	2.83	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGGrade	8	5252.518719	656.564840	8.17	<.0001
BinderIgnition	6	1077.808435	179.634739	2.24	0.0370
PGGrade*BinderIgniti	25	5690.743586	227.629743	2.83	<.0001