Report No. KS-14-1 ▪ FINAL REPORT ▪ February 2014

Review and Analysis of Hamburg Wheel Tracking Device Test Data

Farhana Rahman, Ph.D., E.I.T
Mustaque Hossain, Ph.D., P.E.
Kansas State University Transportation Center

Kansas
Department of Transportation

This page intentionally left blank.

1 Report No. KS-14-1	**2 Government Accession No.**	**3 Recipient Catalog No.**

4 Title and Subtitle Review and Analysis of Hamburg Wheel Tracking Device Test Data	**5 Report Date** February 2014
	6 Performing Organization Code
7 Author(s) Farhana Rahman, Ph.D., E.I.T.; Mustaque Hossain, Ph.D., P.E.	**8 Performing Organization Report No.**
9 Performing Organization Name and Address Kansas State University Transportation Center 2118 Fiedler Hall Manhattan, Kansas 66506	**10 Work Unit No. (TRAIS)**
	11 Contract or Grant No. C1886
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Street Topeka, Kansas 66611-1195	**13 Type of Report and Period Covered** Final Report January 2011–August 2013
	14 Sponsoring Agency Code RE-0567-01

15 Supplementary Notes

For more information write to address in block 9.The appendix for this report contains two Excel files that are available from the KDOT Library upon request. Please email your request to library@ksdot.org or call 785.291.3854.

16 Abstract

The Hamburg Wheel Tracking Device (HWTD) test (TEX-242-F) and the Kansas Test Method KT-56 (KT-56), or modified Lottman test, have been used in Kansas for the last 10 years or so to predict rutting and moisture damage potential of Superpave mixes, especially mixes containing Reclaimed Asphalt Pavement (RAP). Thermal Stress Restrained Specimen Test (TSRST) was performed on selected mixes following AASHTO TP 10. All specimens tested were prepared with the Superpave gyratory compacter.

Results showed that the number of wheel passes and rut depth from the HWTD test are significantly different for Superpave mixes with various RAP content. Recycled Superpave mixtures with crushed gravel aggregates and sand significantly improve overall rutting performance compared to crushed stone or crushed stone and gravel combinations in the mix. Aggregate type also influences rutting performance of virgin Superpave mixtures. Rutting performance of Superpave mixes with or without RAP is significantly affected by the binder source.

Statistical analysis proved that the total number of wheel passes, creep slope, and stripping slope of Superpave mixes with RAP in HWTD tests are significantly affected by RAP content, binder grade, and asphalt sources at 90% confidence interval. RAP percentage in the mix, aggregate type, and interaction between RAP content and aggregate type also affect the pure stripping failure phase (stripping slope) and total wheel passes at the stripping inflection point. Analysis of variance (ANOVA) on Superpave mixtures with RAP showed the number of wheel passes at stripping inflection point and stripping slope are significantly affected by mix type and binder source. Rutting performance is highly influenced by voids in mineral aggregate (VMA) and RAP asphalt content. Superpave mixtures with higher RAP content also tend to fracture at higher temperatures in the Thermal Stress Restrained Specimen Test, indicating that these mixtures are more vulnerable to low-temperature cracking. Thus, low-temperature cracking potential of high RAP mixture must be evaluated during the mixture design process.

For virgin Superpave mixtures, total asphalt content plays a very important significant role in controlling overall rutting resistance of the mix. Moisture susceptibility of these mixtures is highly influenced by total asphalt content, VMA, VFA, and dust-to-binder ratio. Thus, accurate determination of volumetric properties is essential.

17 Key Words RAP, Superpave, Testing, Reclaimed Asphalt Pavement, Hamburg Wheel Tracking Device (HWTD), Pavement Preservation	**18 Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19 Security Classification (of this report) Unclassified	**20 Security Classification (of this page)** Unclassified	**21 No. of pages** 88	**22 Price**

Form DOT F 1700.7 (8-72)

Review and Analysis of Hamburg Wheel Tracking Device Test Data

Final Report

Prepared by

Farhana Rahman, Ph.D., E.I.T.
Mustaque Hossain, Ph.D., P.E.
Kansas State University

A Report on Research Sponsored by

KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

February 2014

NOTICE

The authors and the state of Kansas do not endorse products or manufacturers. Trade and manufacturers names appear herein solely because they are considered essential to the object of this report.

This information is available in alternative accessible formats. To obtain an alternative format, contact the Office of Transportation Information, Kansas Department of Transportation, 700 SW Harrison, Topeka, Kansas 66603 or phone (785) 296-3585 (Voice) (TDD).

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or the policies of the state of Kansas. This report does not constitute a standard, specification or regulation.

Abstract

The Hamburg Wheel Tracking Device (HWTD) test (TEX-242-F) and the Kansas Test Method KT-56 (KT-56), or modified Lottman test, have been used in Kansas for the last 10 years or so to predict rutting and moisture damage potential of Superpave mixes, especially mixes containing Reclaimed Asphalt Pavement (RAP). Thermal Stress Restrained Specimen Test (TSRST) was performed on selected mixes following AASHTO TP 10. All specimens tested were prepared with the Superpave gyratory compacter.

Results showed that the number of wheel passes and rut depth from the HWTD test are significantly different for Superpave mixes with various RAP content. Recycled Superpave mixtures with crushed gravel aggregates and sand significantly improve overall rutting performance compared to crushed stone or crushed stone and gravel combinations in the mix. Aggregate type also influences rutting performance of virgin Superpave mixtures. Rutting performance of Superpave mixes with or without RAP is significantly affected by the binder source.

Statistical analysis proved that the total number of wheel passes, creep slope, and stripping slope of Superpave mixes with RAP in HWTD tests are significantly affected by RAP content, binder grade, and asphalt sources at 90% confidence interval. RAP percentage in the mix, aggregate type, and interaction between RAP content and aggregate type also affect the pure stripping failure phase (stripping slope) and total wheel passes at the stripping inflection point. Analysis of variance (ANOVA) on Superpave mixtures with RAP showed the number of wheel passes at stripping inflection point and stripping slope are significantly affected by mix type and binder source. Rutting performance is highly influenced by voids in mineral aggregate (VMA) and RAP asphalt content. Superpave mixtures with higher RAP content also tend to fracture at higher temperatures in the Thermal Stress Restrained Specimen Test, indicating that these mixtures are more vulnerable to low-temperature cracking. Thus, low-temperature cracking potential of high RAP mixture must be evaluated during the mixture design process.

For virgin Superpave mixtures, total asphalt content plays a very important significant role in controlling overall rutting resistance of the mix. Moisture susceptibility of these mixtures is highly influenced by total asphalt content, VMA, VFA, and dust-to-binder ratio. Thus, accurate determination of volumetric properties is essential.

Acknowledgements

The authors would like to acknowledge the Kansas Department of Transportation (KDOT) for sponsoring this study. Special thanks are due to Mr. Cliff Hobson for his help in completing the database used in this study and a complete review of this report.

Table of Contents

This appendix contains two Excel spreadsheets that are available from the KDOT Library upon request. Please email your request to library@ksdot.org or call 785.291.3854.

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Approximately 89% of the paved-road network in Kansas is asphalt surfaced (bituminous and composite). According to the Kansas Department of Transportation (KDOT), typical design performance period of hot-mix asphalt (HMA) pavement for new construction or reconstruction is approximately 12 years. In most cases, these pavements are overlaid as they reach the end of their design life. Both bituminous and composite pavements are usually overlaid with Superpave HMA for pavement preservation. The new highway program of KDOT also emphasizes pavement preservation. KDOT is currently seeking to extend the lives of Superpave mixes for these overlays through educated better selection of asphalt and aggregates. Thus, KDOT is contemplating use of the Hamburg Wheel Tracking Device (HWTD) as a performance tester.

For fast and reliable performance testing of HMA mixes, the HWTD is gaining popularity (Yildrim et al. 2007; Liddle and Choi 2007; Lu and Harvey 2006a; Lu and Harvey 2006b). The HWTD was originally manufactured in the 1970s by Esso, A. G. of Helmut-Wind Inc., Hamburg, Germany. The HWTD test was initially intended for measuring rutting behavior but was later found to be capable of identifying mixes with potential moisture resistance. The device was introduced to the United States in the early 1990s by pavement engineers and officials following a European asphalt study tour for technology transfer (European Asphalt Study Tour 1991; Yildrim and Kennedy 2001). This introduction of the HWTD initiated research to evaluate this equipment to characterize moisture sensitivity of asphalt mixes and to predict field performance (Liddle and Choi 2007; Lu and Harvey 2006a; Lu and Harvey 2006b; Aschenbrenner 1995; Aschenbrenner 1994; Aschenbrenner and Far 1994). The HWTD was found to be sensitive to aggregate quality, asphalt cement stiffness, short-term aging duration, asphalt source or refining processes, antistripping treatments, and compaction temperatures (Aschenbrener 1994; Aschenbrener 1995; Aschenbrener and Far 1994). The HWTD has been steadily gaining popularity for testing rutting and stripping potential of asphalt pavements (Yildrim et al. 2007; Liddle and Choi 2007; Gogula et al. 2003; Izzo and Tahmoressi 1999).

1.2 Problem Statement

Similar to other state DOTs, dwindling budgets for pavement construction/reconstruction programs are requiring KDOT and other highway agencies to consider a pavement preservation program. One common pavement rehabilitation action of KDOT is a thin overlay (1 to 4 inches thick) of Superpave HMA mixture with virgin aggregates (designated as SM) or with Reclaimed Asphalt Pavement (RAP) materials (knows as SR). KDOT is currently striving to improve overlay performance; thus, an analysis of Superpave mixture performance in thin overlays is necessary.

In 2000, Kansas State University (KSU) procured a Hamburg Wheel Tracking Device (HWTD) manufactured by PMW, Inc. of Salina, Kansas. Since that time, KSU has conducted tests on numerous mixtures for research projects as well as tests on production mixtures from actual construction projects. Although research project data has been analyzed in detail and widely reported, a comprehensive analysis of HWTD test data for construction projects is yet to be done. The Texas Department of Transportation (TxDOT) conducted a similar project from 2003 to 2004 which implemented the HWTD in their mix design process (Yildrim et al. 2007). That particular project and the subsequent requirement of HWTD as a screening tool for Texas Superpave mixes have been credited with minimizing cracking, rutting, and stripping on Texas highways (TxDOT 2006).

1.3 Objective

Two objectives of this study include:

1. Building a database of KDOT-related Hamburg Wheel Tracking Device (HWTD) test results from tests done at KSU to date, and
2. Analyzing HWTD test data base generated in objective #1 at KSU and correlating that data with different mixture variables and performance.

1.4 Report Outline

This report contains five chapters. Chapter 1 presents the introduction, problem statement, research objectives, and report outline. Chapter 2 provides a literature review of brief descriptions of HWTD, KT-56 and Thermal Stress Restrained Specimen Test (TSRST) procedures, and related research work. Chapter 3 describes test equipment and specimen preparation. Chapter 4 presents results obtained from HWTD and KT-56 tests. Statistical analysis of the results is also included. Chapter 5 presents conclusions from this project. Recommendations for future research are also presented.

Chapter 2: Literature Review

2.1 Superpave

Approximately 94% of paved roads in the United States are asphalt surfaced. Currently, the United States has nearly 4,000 asphalt plants producing 500 to 550 million tons of pavement material annually, worth more than $30 billion (National Asphalt Pavement Association-Asphalt Pavement Overview 2011). Before the introduction of Superpave (Superior Performing Asphalt Pavements), asphalt mixtures were designed using empirical laboratory design procedures, thereby requiring field experience in order to determine if laboratory analysis correlated with pavement performance (Asphalt Institute 1995). Superpave is the final product of the $50-million Strategic Highway Research Program (SHRP) which represents an improved system for specifying asphalt binders and mineral aggregates, developing asphalt mixture design, and analyzing and establishing pavement performance predictions. The system includes 1) new binder specifications that use new binder physical properties tests such as dynamic shear rheometer (DSR), rotational viscometer (RV), bending beam rheometer (BBR), direct tension tester (DTT), rolling thin film oven (RTFO), and pressure aging vessel (PAV); 2) series of aggregate tests and specifications such as coarse and fine aggregate angularity, flat and elongated particles (for coarse aggregate), and sand equivalent test (for fine aggregate); and 3) a hot-mix asphalt (HMA) design using the Superpave gyratory compactor (SGC) (Asphalt Institute 1995). However, the system is flawed in that the design and analysis of asphalt mixtures are purely volumetric and mixture performance is evaluated through certain volumetric criteria established under limited conditions with no stability or rut test to verify designed mixes.

2.2 Hamburg Wheel Tracking Device Test

The HWTD measures combined effects of rutting and moisture damage and is gaining popularity because of fast and reliable testing of various HMA mixes (Yildirim et al. 2007; Lu and Harvey 2006a).

The HWTD test indicates susceptibility to premature failing of HMA mixtures due to weak aggregate structure, inadequate binder stiffness, moisture damage, and inadequate adhesion between aggregate and binder. HWTD results are influenced by aggregate quality, binder stiffness, duration of short-term aging, binder source, anti-stripping treatments, and compaction temperature (Aschenbrener 1995; Aschenbrener 1994; Aschenbrener and Far 1994).

HWTD was based upon a similar British device which utilizes rubber tires instead of steel wheels. The device is operated by moving a pair of reciprocating steel wheels across the surface of HMA specimens (cylindrical or slab/cubicle) submerged in hot water, generally held at 50°C. The device is capable of testing a pair of specimens simultaneously, and specimens are compacted to 7±1 percent air voids. The steel wheels have a diameter of 203 mm (8 inches), a width of 47 mm (1.85 inches), and are capable of generating 53±2 passes per minute. Each steel wheel weighs 158 lbs. Typical length of the slabs are 320 mm (12.6 inches) long by 260 mm (10.2 inches) wide, thickness varies from 40 mm (1.6 inches) to 80 mm (3.2 inches) and dimensions of cylindrical specimens are 150 mm (6 inches) in diameter and 62 mm (2.5 inches) in height, as shown in Figure 2.1. Linear variable differential transformers (LVDTs) measure rut depth or deformation at 11 points along the length of each specimen at an accuracy of 0.01 mm. The device automatically ends the test when the preset number of wheel passes is reached or a rut depth of 20 mm (0.8 inch), whichever occurs first. Duration of the test (considering 20,000 passes) is approximately seven hours, including initial wait time of 30 minutes. However, in some tests the specimens fail early and test times are shorter.

FIGURE 2.1
(Clockwise) Final Test Setup of Hamburg Wheel Tracking Device, Close-Up of Specimens under the Wheel Load, Specimens Ready for Testing in HWTD, and Failed Specimens with High Rut Depth

HWTD test outputs include post-compaction consolidation, creep slope, stripping slope, and stripping inflection point, as illustrated in Figure 2.2. These parameters are obtained by plotting a curve between rut depth and number of wheel passes. Post-compaction consolidation is deformation (mm) at 1,000 wheel passes. It is assumed the wheel densifies the mixture within the first 1,000 passes and consequently is called post-compaction consolidation. Creep slope is the inverse of the rate of deformation in the linear region of plot between post compaction and stripping inflection point (if stripping occurs). Creep slope relates to rutting primarily due to plastic flow and is the number of wheel passes required to create 1 mm of rut depth. Stripping inflection point and stripping slope are related to moisture resistance of HMA. Stripping inflection point is the number of wheel passes at the intersection of creep slope and stripping slope. Stripping slope is the inverse rate of deformation after the stripping inflection point. It relates to rutting primarily due to moisture damage and is the number of wheel passes required to create 1 mm of rut depth after stripping inflection point (Yildirim et al. 2007).

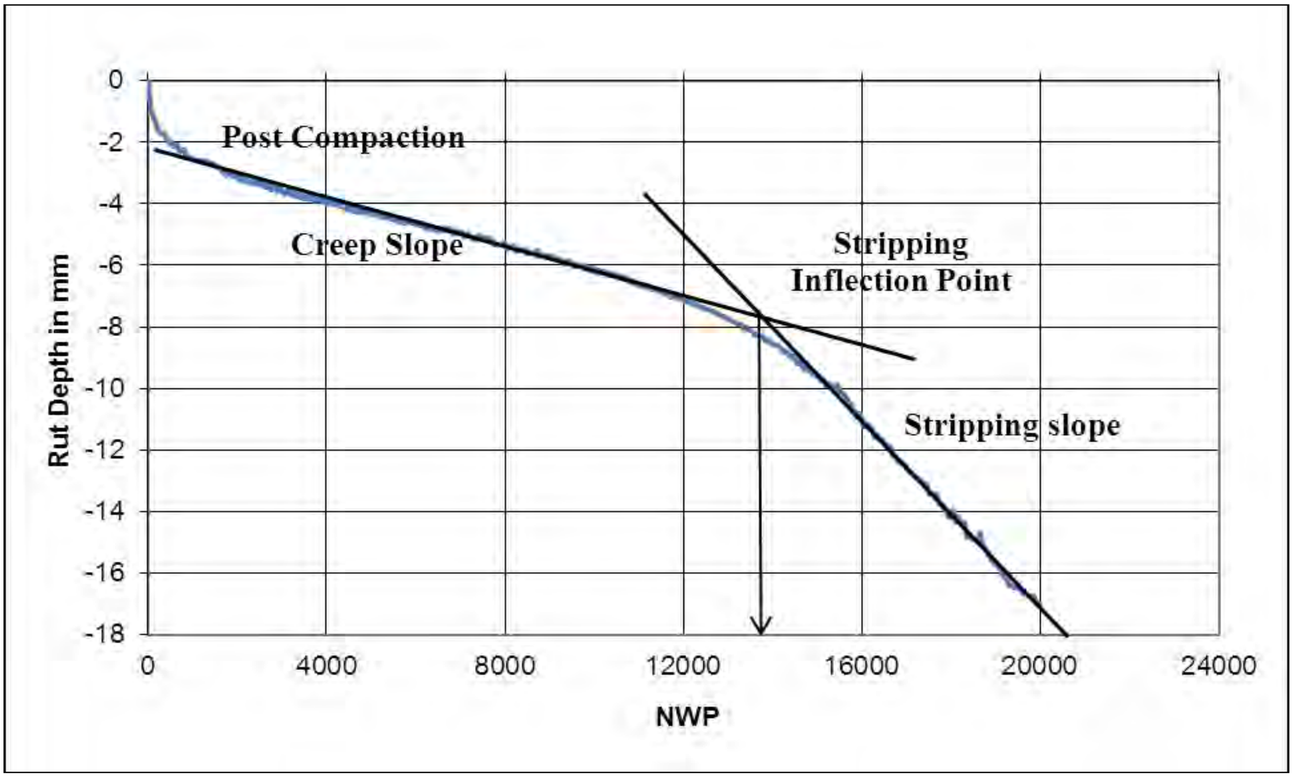


FIGURE 2.2
Typical Hamburg Wheel Tracking Device Test Results

2.2.1 Past Research and Experience

Since HWTD was introduced in the United States, various agencies have utilized it to evaluate moisture susceptibility of HMA mixtures. However, test procedures and specifications may vary slightly from one agency to another depending on mixture type. For example, Hamburg, Germany, specifies allowable rut depth of less than 4 mm at 20,000 passes. The Colorado Department of Transportation (CDOT) uses a test temperature according to the site and specifies a rut depth of less than 10 mm after 20,000 passes (Izzo and Tahmoressi 1999). The TxDOT follows their TEX-242-F procedure. Requirements for results of TEX-242-F tests are listed in Table 2.1.

TABLE 2.1
Hamburg Wheel Tracking Device Test Criteria

High-Temperature Binder Grade	Number of Wheel Passes	Maximum Rut Depth
PG 64	10,000	12.5 mm (0.5 in)
PG 70	15,000	12.5 mm (0.5 in)
PG 76	20,000	12.5 mm (0.5 in)

(Source: Zhou et al. 2005)

Aschenbrener (1995) evaluated factors that influence HWTD results. He conducted tests on 20 different mixtures whose stripping performance was known and then compared their field performance with the test results obtained. Excellent correlation between these two sets of data was obtained. The study concluded that HWTD results are sensitive to quality of aggregate, asphalt cement stiffness, short-term aging duration, refining process, liquid anti-stripping agents, hydrated lime additives, and compaction temperature.

Izzo and Tahmoressi (1999) evaluated the HWTD and its capability to assess moisture susceptibility of HMA in Texas. Six different mixtures were prepared with and without antistripping additives and tested at 40°C and 50°C. Mixtures were modified with hydrated lime and liquid antistripping additives. Asphalt binder used for all mixtures was identical (AC-20). For mixtures tested at 40°C, use of anti-stripping additives improved mixture performance. Mixtures with hydrated lime performed better than the mixtures modified with liquid anti-stripping additive. Worst performance was observed for mixtures without any additives. For mixtures tested at 50°C, results were inconsistent (Izzo and Tahmoressi 1999).

In another study, Gogula et al. (2003) showed the effect of performance-grade binder and air voids on HWTD results. PG 52-28, PG 64-22, PG 58-28, and PG 70-28 were studied and the mixture with PG 70-28 performed better than the mixtures with any other binder type. Their study also indicated mixtures with lower air voids (7%) performed better when compared to mixtures compacted to 2 percent higher air voids (9%).

2.3 Kansas Test Method KT-56 (Resistance of Compacted Asphalt Mixture to Moisture-Induced Damage) or Modified Lottman Test

The KT-56 method, commonly known as Modified Lottman Test, is used to evaluate Superpave HMA mixtures to see if they are susceptible to moisture or stripping (Hossain et al. 2011). This test compares the average indirect tensile strength of unconditioned specimens to that of conditioned specimens.

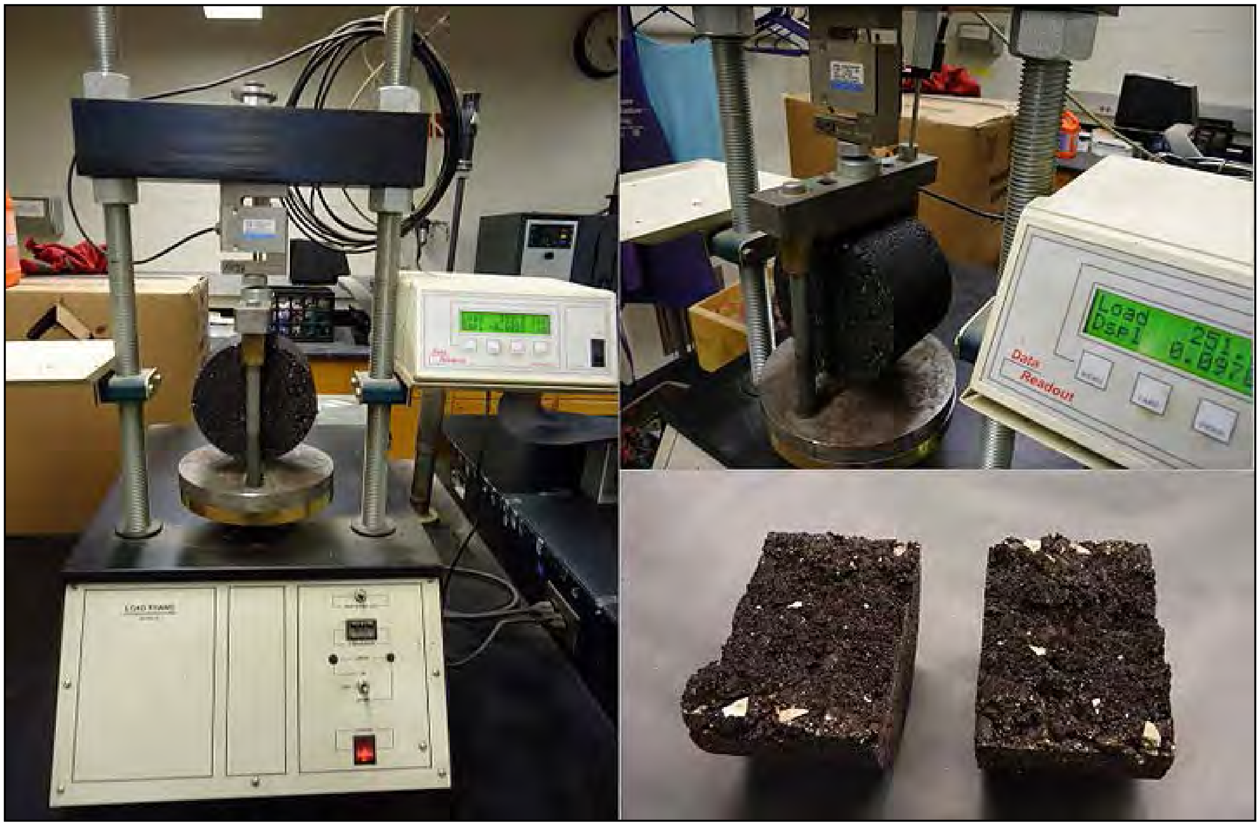


FIGURE 2.3
(Clockwise) Specimen Loaded in Tensile Strength Machine, Close-Up of Specimen in Load Frame, Specimen after Broken in Tensile Strength Machine

A total of six specimens were fabricated using the Superpave gyratory compactor. Air voids of these specimens should be 7±0.5 percent, and specimens should be 6 inches (150 mm) in diameter and 3.75±0.2 inches (95±5 mm) in height. Specimens were divided into two subsets so that average air voids of both are approximately equal. One subset was kept at room temperature without any conditioning until testing for indirect tensile strength, and the other subset was subjected to conditioning, including a freeze-thaw cycle. Each specimen of this subset was first submerged in a vacuum container filled with water and, with the use of a vacuum pump, had a partial vacuum of 25 to 66 cm (10 to 26 inches) of Hg applied for a short time to bring the specimen saturation to 70 to 80% of air voids. After the specimens were saturated, they were subjected to freezing at a temperature of 0±5°F (-18^0±3°C) for a minimum of 16 hours, followed by a thaw cycle in which the specimens were kept at 140±2°F (60±1°C) in a water bath for 24±1 hours. The final step in the conditioning process was to store the specimens in a water bath maintained at 77±1°F (25±0.5°C). Then all specimens were tested for indirect tensile strength at 77±1°F (25±0.5°C) at a loading rate of 2 inches per minute (51 mm per minute), and the corresponding peak loads and displacements were recorded. The ratio of tensile strength of conditioned subset to unconditioned subset was calculated as the tensile strength ratio, which should be a minimum of 0.8 (or 80%) as adopted by the Superpave mix design and KDOT. Tensile strength is given by the following equation:

$$S_t = \frac{2000 \times P}{\Pi \times t \times D} \qquad \textbf{Equation 2.1}$$

where S_t = tensile strength, psi (kPa),

P = maximum load, lbf (N),

t = specimen thickness in (mm), and

D = specimen diameter in (mm).

The tensile strength ratio (TSR) in percent is calculated as follows

$$\text{TSR} = \frac{T_2}{T_1} \times 100 \qquad \textbf{Equation 2.2}$$

where TSR = tensile strength ratio,

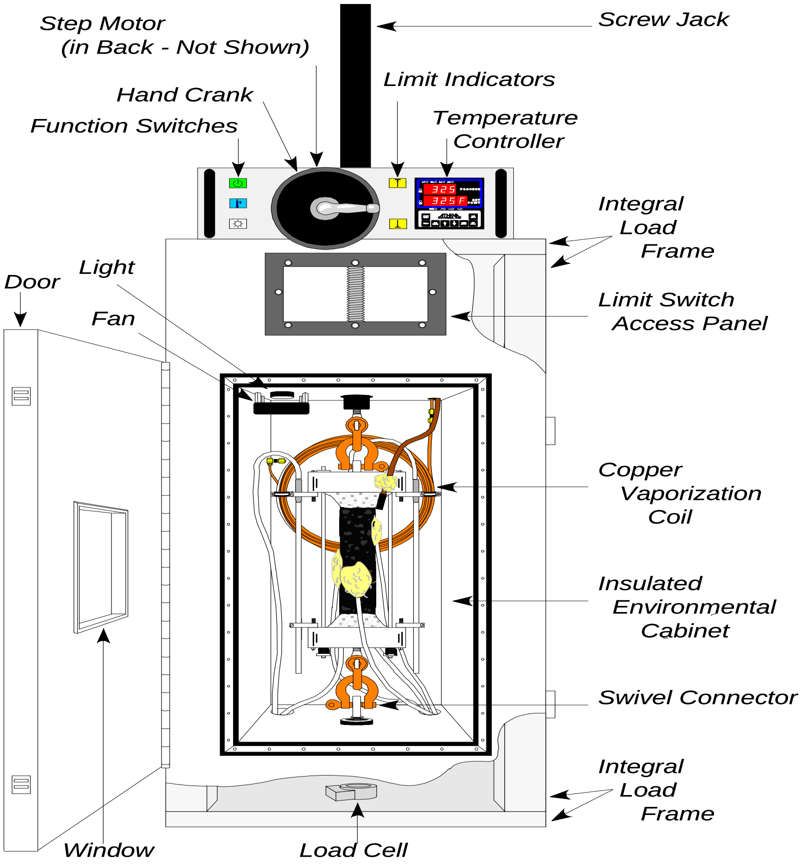
T_1 = average tensile strength of unconditioned subset, and

T_2 = average strength of conditioned subset.

2.4 Thermal Stress Restrained Specimen Test (TSRST)

The Thermal Stress Restrained Specimen Test (TSRST) was developed as part of the SHRP Project A-003A “Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures.” The test evaluates low-temperature cracking susceptibility of Superpave mixtures. AASHTO TP 10 method is followed in performing TSRST tests. The device, as shown in Figure 2.4, consisted of an environmental chamber, a load frame, a data acquisition system, a temperature controller, two LVDTs, four thermistors, a load cell, and a specimen alignment stand. The test setup cooled a prism or cylindrical specimen while preventing contraction. As the temperature dropped, thermal stresses began to build and increase until the specimen fractured.

The test specimen was set up with an alignment stand and glued to two end platens with an epoxy compound. The specimen was then cooled to 5°C for one hour to establish thermal equilibrium prior to testing and placed in an environmental chamber. LVDTs were attached to the top and bottom clamps to measure specimen deformation. As the temperature was reduced, thermal contraction was measured by LVDTs and used as feedback by the closed-loop load frame to “restrain” (load) the specimen back to original length. Throughout the test, temperature and tensile load were recorded and the thermal stress-temperature curve was plotted. Three or four thermistors were attached to the specimen surface to measure specimen temperature. A resistance temperature detector was used to monitor chamber temperature and control the cooling rate, which can be preselected. In this study, a system manufactured by OEM, Inc., was used for the tests and surface temperature and load were recorded until the specimen failed. The cooling rate used in this study was 10°C/hr. Tests were conducted on specimens prepared from Superpave mixtures with RAP and on specimens prepared from Superpave mixtures with RAP that were aged per AASHTO R 30 in a forced draft oven for five days (120 hours) at 85°C to simulate seven to 10 years of service.



(Source: OEM, Inc.)

FIGURE 2.4
(a) Schematic of TSRST Set Up

FIGURE 2.4
(b) KDOT TSRST Test Set Up

Jung and Vinson (1994) tested four asphalt binders and two aggregates at two levels of air voids (4% and 8%) and four cooling rates (1, 2, 5, and 10°C/hour). They ranked low temperature cracking resistance of asphalt mixtures based on fracture temperature and found good agreement with the ranking of asphalt binders used. Soft asphalt binders and aggregates with rough surface texture and angular shape resulted in higher fracture strength values and colder fracture temperatures of asphalt mixtures. The long-term aged specimens displayed warmer fracture temperatures, and specimens with high air voids content (8%) had lower fracture strength than those with low air voids content (4%). Furthermore, cooling rate significantly affected experimental measurements of TSRST, although it did not change the ranking of asphalt mixtures. Jung and Vinson (1994) recommended fracture temperature be used to rank low temperature cracking resistance of asphalt mixtures. Since penetration of asphalt cement at 15°C correlated well with the fracture temperature of asphalt mixtures, they also suggested using penetration of binders as a reasonable indicator of low temperature resistance. Recently, Pucci et al. (2004) studied the correlation between asphalt mixture TSRST results and asphalt mixture Direct Tension Test (DTT) results. Using a cooling rate of 10°C/hour, they observed that the slope of the thermal stress-temperature curve started to decrease at an initial temperature that is higher than fracture temperature. A similar observation was made by Fortier and Vinson (1998) for mixes with modified asphalt binders.

Chapter 3: Test Methodologies

3.1 Data Sources for the HWTD Database

The HWTD database contains test results from tests performed on HWTD samples fabricated in the laboratory by mixing binders and aggregates or on HWTD samples prepared from the plant-mixed HMA mixtures. The plant-mixed samples did not need to be short-term aged in the laboratory, but the laboratory-mixed samples were aged for two hours at compaction temperature before sample compaction in the Superpave Gyratory Compactor. All HWTD test results in this project database are related to KDOT research or construction projects.

3.2 Preparation of Samples for Hamburg Wheel Tracking Device Test and KT-56 Test with RAP

Specimens were prepared following the Kansas Test Method KT-58 Procedure: Method for preparing and determining the density of HMA specimens by means of the Superpave gyratory compactor. The steps involved in preparing HWTD specimens included drying aggregates to constant weight, batching aggregates, heating aggregates and binder to mixing temperature, mixing binder and aggregates, conditioning (short-term aging) and compacting the specimen to appropriate percent air voids using the Superpave gyratory compactor. Detailed steps involved in specimen preparation are described below and shown in Figure 3.1.

1. All required aggregates were weighed in steel pans separately and combined to form a desired batch weight. Typically, a batch weight of 13,800 to 14,000 grams of aggregate produces five HWTD specimens (150±2 mm in diameter and 62±2 mm in height), 1,500 grams of G_{mm} sample, and 5% wastage, considering a combined aggregate bulk-specific gravity between 2.55 and 2.70.
2. Batched aggregates and binder were heated in the oven to an appropriate mixing temperature based on the PG binder grade. Since the study contained mixtures with RAP material, this material was heated separately (approximately 140°F), i.e., much lower than the mixing temperature to prevent additional hardening of RAP asphalt cement. Virgin aggregates were heated above the mixing temperature

to compensate for the lower mixing temperature of RAP, so that total mix temperature was within the actual range of the mixing temperature.

3. After aggregates and binder reached the mixing temperature, heated aggregates were introduced to a mechanical mixer and a crater was formed. The required amount of binder and additive was added and mixing continued until every particle was uniformly coated with binder. Since the mixture contained RAP material, the amount of binder to be added was adjusted because RAP material also contained some binder. The weight of new binder to be added was calculated as follows:

$$\frac{\textbf{Percent binder(total)} \times \textbf{Total weight}}{\textbf{100}} - (\textbf{weight of binder in RAP}) \qquad \textbf{Equation 3.1}$$

where, weight of binder in RAP= (percent binder in RAP) × (weight of RAP)

4. After mixing, the mixture was placed in a pan, spread evenly, and transferred to an oven at compaction temperature for approximately 2 hours ± 5 minutes for short-term aging that simulates asphalt mixture production in the plant. The mixture was stirred after 60±5 minutes to maintain uniform aging.
5. The mixture then was ready to be compacted using the Superpave gyratory compactor (SGC).

(a) Heating aggregate to mixing temperature in oven

(b) Adding asphalt to the aggregate in the mixer

(c) Mixing of asphalt and aggregate in the mixer

(d) Mixture kept at compaction temperature for 2 hrs (short-term aging)

FIGURE 3.1
HMA Mixing Process

3.2.1 Compaction Using Superpave Gyratory Compactor (SGC) (Kansas Test Method KT-58)

Molds, plates of SGC, and pouring pan were preheated to compaction temperature for approximately 45 to 60 minutes before the start of compaction. The SGC was switched on and all required settings, such as height of specimen, number of gyrations, angle of gyration, pressure, etc., were configured. Compaction parameters for all mixture types (SM/SR-9.5A, SM/SR-12.5A and SM/SR-19A) are listed in Table 3.1. KDOT defines the Superpave mixtures by the nominal maximum aggregate sizes. "SM" indicates Superpave mixtures with virgin aggregates whereas "SR" indicates Superpave mixtures with reclaimed asphalt pavement (RAP) materials in it. The "A" indicates the blend aggregate gradation in the mixtures passes above the maximum density line in the sand sizes. These mixtures may contain up to 35% natural or river sand.

TABLE 3.1
Compacting Parameters for Superpave Gyratory Compactor

Parameter	HWTD	KT-56
Specimen height	62	95
Pressure	600±18 kPa	600±18 kPa
Angle of gyration	1.16° ± 0.02°	1.16° ± 0.02°
Number of gyrations	$N_{initial}$=7,N_{design}=75,N_{max}=115	$N_{initial}$=7,N_{design}=75,N_{max}=115
Speed of rotation	30±0.5 gyrations per minute	30±0.5 gyrations per minute

The mold and base plate were removed from the oven and the mold was charged with the required amount of mixture using a pouring pan. The mixture was leveled with a spatula and the top plate was placed in the mold. To avoid the mixture sticking to the plates, paper disks were placed in between the plates and mixture. The mold was then transferred into the SGC and the mixtures were compacted with applicable parameters listed in the mixture design for each project. The SGC stopped automatically when the specified number of gyrations was reached. The mold was then removed from the SGC and the sample was extruded from the mold and cooled for five minutes in front of a fan as shown in Figure 3.2.

(a) Pine Superpave Gyratory Compactor

(b) Pouring HMA into SGC mold

(c) Extruding the specimen from the mold

FIGURE 3.2
Compacting Specimen Using Superpave Gyratory Compactor

3.2.2 Determining the Weight of Mixture Required to Produce a Specimen with Desired Percent Air Voids

The weight of mixture needed to produce a specimen with specified air voids (7±1 % air voids for HWTD and 7±0.5 % air voids for KT-56) was determined theoretically by the following equation:

Weight of specimen 'W'= $\%G_{mm}$ @N_f $\times G_{mm}$ × volume of sample

where, $\%G_{mm}$ @ $N_f = 0.93$ (for HWTD and KT-56 test specimens);

G_{mm}= theoretical maximum specific gravity of loose mixture; and

Volume=$\frac{\Pi d^2 \mathrm{h}}{4}$; d=150 mm, h=62 mm for HWTD specimen and 95 mm for KT-56 specimen, respectively.

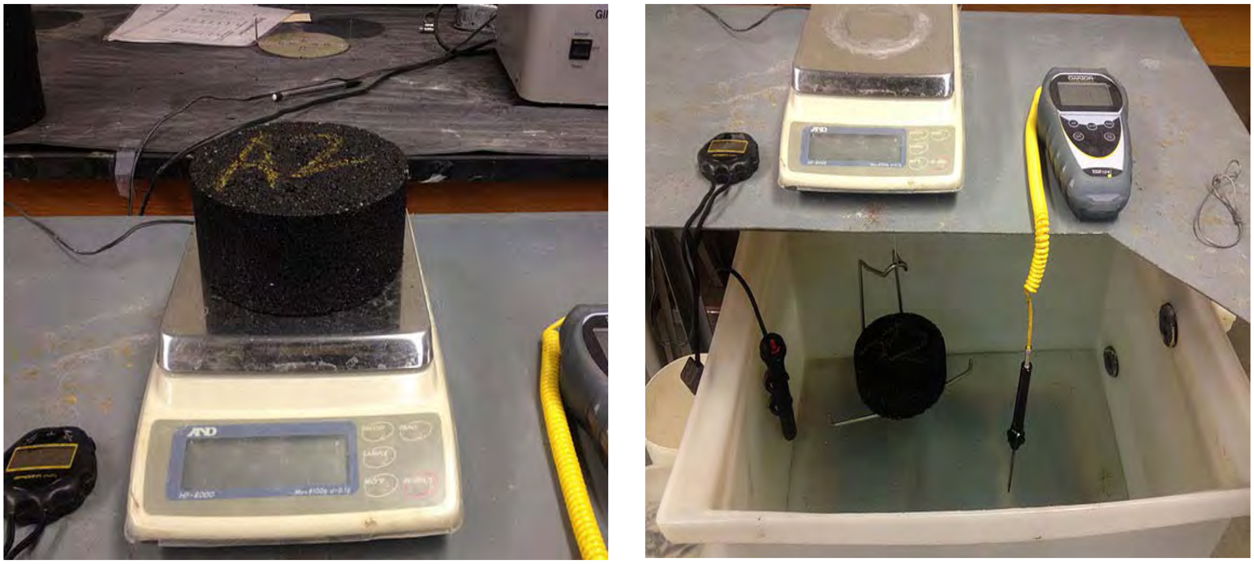
After obtaining theoretical weight of the specimen, three trial specimens were prepared with the theoretical weight of specimen W, W+10 grams, and W-10 grams, to calculate the exact weight of mixture needed to produce a compacted specimen with air voids in the desired range.

3.2.3 Determining Bulk-Specific Gravity of Compacted Specimen (G_{mb}) and Theoretical Maximum Specific Gravity of Uncompacted HMA Mixture (G_{mm}) (Kansas Test Methods KT-15 and KT-39)

Bulk-specific gravity (G_{mb}) of compacted specimens was determined following Kansas Test Method KT-15 (Procedure III), as shown in Figure 3.3. The following steps were undertaken:

1. The specimen was dried to a constant mass, weighed at room temperature (77° ± 2F or 25±1° C) to the nearest 0.1 grams, and recorded as A.
2. The specimen was immersed in the water bath at 77° ± 2F or 25±1° C and saturated for 4±1 minutes. The submerged mass was recorded as C.
3. The submerged specimen was brought to saturated-surface dry (SSD) condition using terry cloth. The SSD specimen was weighed and recorded as B.

Bulk specific gravity, G_{mb}= $\frac{\boldsymbol{A}}{(\boldsymbol{B}-\boldsymbol{C})}$ **Equation 3.2**



Dry mass in air

Mass in water

Making of SSD

SSD mass in air

FIGURE 3.3
Process of Determining the Bulk-Specific Gravity of the Compacted Specimen

Theoretical maximum specific gravity of the asphalt paving mixture (G_{mm}) was determined using Kansas Test Method KT-39, as shown in Figure 3.4. The steps involved were:

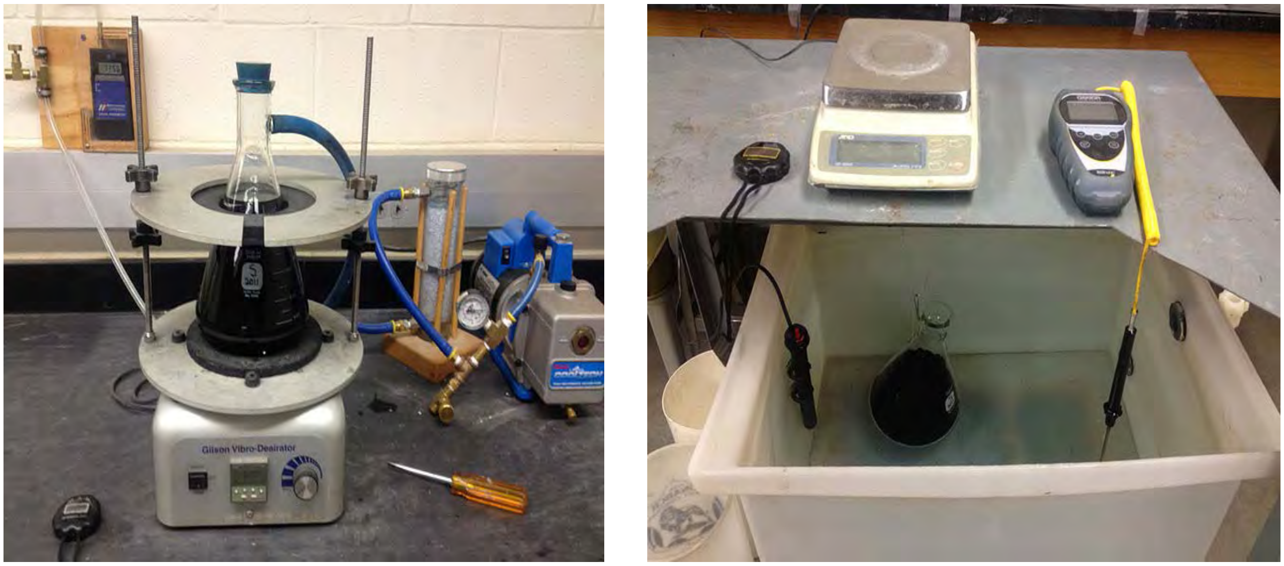
1. The laboratory-mixed sample was taken from the oven after short-term aging and cooled to room temperature. During this cooling process, the particles separated so that no particle was larger than 6.3 mm (1/4 inch).
2. A sample of known mass was loaded into a calibrated conical flask and the flask mass with the sample was recorded as B.

3. The flask was filled with water until the sample was fully submerged.
4. Using a vacuum pump, a partial pressure of 27±3 mm of Hg was applied for 15 minutes to remove trapped air in the sample.
5. The conical flask was submerged in the water for 10±1 minutes and the weight was recorded as C. The temperature of water should be 77 ± 2°F or 25±1°C.
6. The mass of conical flask in air was recorded as A and the mass of conical flask in water after 10 minutes immersion was recorded as D.
7. Theoretical maximum specific gravity of the uncompacted HMA mixture is given by

$$G_{mm} = \frac{(B-A)}{(B+D)-(A+C)}$$

Making of loose sample

Mass of sample + flask in air



Expelling air using vacuum apparatus

Mass of sample + flask in air

FIGURE 3.4
Determining Theoretical Maximum Specific Gravity (G_{mm}) of Loose HMA Mixture

3.3 Performance Testing Procedures

3.3.1 Hamburg Wheel Tracking Device Procedure (TEX-242-F 2009)

HWTD used in this study was manufactured by Precision Machine & Welding Company, Salina, Kansas. TEX-242-F procedure was followed for the HWTD tests. The laboratory-molded specimens were placed in a cutting template under the masonry saw to cut across the specimen, as shown in Figure 3.5, in order to fit into the HWTD polyethylene molds used to secure the specimens. Specimens were then placed into the polyethylene mold and mounted into the tray. If a gap was present in between specimens, the gap was filled with Plaster of Paris and allowed to set for one hour before starting the procedure. Mounting trays with the samples in the molds were placed in an empty water bath. The computer control was activated via a software and required information entered. Test specifications were as follows:

a) Testing temperature: 122±1.8°F (50±1°C).
b) Load: 158 lb. ± 5 lb. (705±22 N).
c) Number of passes per minute: 50±2.
d) Maximum number of passes setting: 20,000
e) Maximum speed of wheel: 1.1 ft./sec (approximately)
f) Maximum rut depth: 20 mm
g) Rut-depth measurements: every 100 passes.

Water was then turned on and once water reached the designated temperature, the specimen was saturated for an additional 30 minutes. After saturation, the arms with wheels were lowered so they rested on the specimen and the test was begun. The testing device automatically stopped when either operator-specified maximum rut depth or the maximum number of wheel passes was reached, whichever occurred first. Linear variable differential transducers (LVDTs) connected to the machine on either side measured vertical deformation (rut depth) at 11 different points along the wheel path of the specimen. Rut depth was recorded using a computer-based automated data acquisition system connected to the HWTD device. Post compaction, creep slope, stripping inflection point, and stripping slope were obtained from the plot of the number of wheel passes versus rut depth.

(a) Specimen being cut along edge of the mold using masonry saw

(b) Vertical-cut specimens (approx. 5/8 inch)

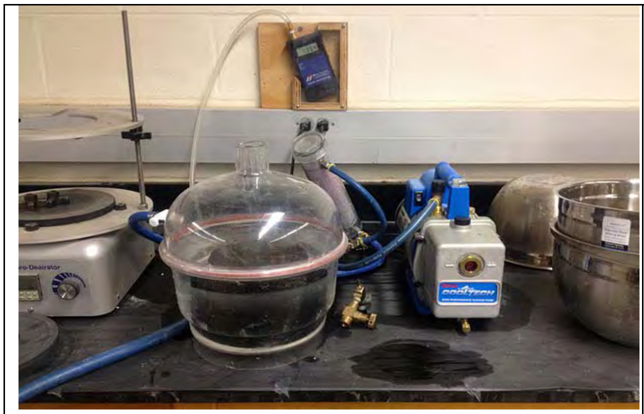
(c) Specimens placed in molds and mounted in tray, ready for testing

(d) Failed specimen (rut depth>20mm)

FIGURE 3.5
Testing Steps in Hamburg Wheel Tracking Device

3.3.2 Resistance of Compacted Asphalt Mixture to Moisture-Induced Damage (Kansas Test Method KT-56)

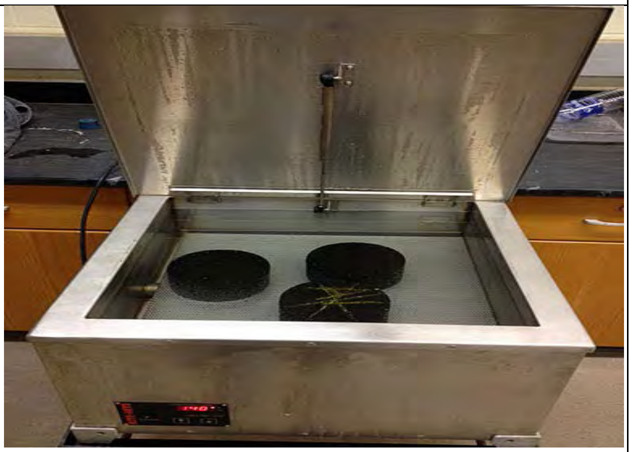
The steps of procedure KT-56 were previously discussed in Chapter 2 and are shown in Figure 3.6. Using a SGC, a minimum of six compacted specimens was produced at approximately 7±0.5 percent air voids. Some compacted specimens were found to be out of the prescribed air-void range and were discarded.



(a) Saturating the specimen using vacuum apparatus

(b) Specimen wrapped with plastic film enclosed in heavy-duty, leak-proof bag with 10 ml of water

(c) Specimen freezing @ -18°C for at least 16 hours



(d) Specimen in water bath at 60°C for 24 hours

(e) Indirect tensile strength determination

(f) Inspection of stripping on interior surface

FIGURE 3.6
Steps Involved in Determination of Tensile Strength of Conditioned Samples (KT-56)

3.3.3 Thermal Stress Restrained Specimen Test (TSRST) (TP 10)

AASHTO TP 10 was followed in performing the TSRST test. Sample preparation and test procedure are described here.

3.3.3.1 Compaction Procedure for Molding TSRST Specimens

The following procedure was followed for molding TSRST specimens:

- For the given mix, the mix design was obtained and the compaction temperature range was located.
- The Superpave mix material was placed in a draft oven set at 110°C, for at least 2-4 hours.
- If necessary, a sample was split out for a KT-39 or AASHTO T209 test.
- After discovering the Gmm, the correct mix amount was calculated in order to obtain the following sample parameters: 150 mm for diameter, 203 mm for height, and 7 ± 0.5% air void content.
- The specimen was compacted using the Superpave Gyratory Compactor
- Typically after the specimen has cooled to room temperature of 25 ± 3°C (77 ± 5°F), bulk specific gravity was performed on the entire molded specimen, following KT-15 Proc. III, or AASHTO T-166 Method A.
- The specimen was placed in a coring apparatus and, using a 50 mm inner diameter core bit, three 50 mm specimens were drilled from the compacted specimen.
- The specimens were trimmed to a length of 50 mm.
- After the specimens were dry and at room temperature, another bulk specific gravity was performed on each specimen.

Figure 3.7 showcases the system manufactured by OEM, Inc. used by KDOT for tests in this study. The cooling rate used was 10°C/hr. The test procedure closely followed steps described by Jung and Vinson (1999):

1. Clean the platens and make sure the surface is rough.

2. Prepare the epoxy.
3. Attach end platens to the specimen alignment stand and place the specimen between platens with epoxy. Make sure the specimen is aligned.
4. Leave the specimen in the stand for at least 24 hours so that the epoxy is cured.
5. Remove the specimen with the end platens from the stand and store at 5°C for one hour for precooling
6. Attach the specimen-platen system in the TSRST machine. Mount the LVDTs.
7. Attach four thermistors on the sides of the specimen at different locations. Close the cooling chamber.
8. Set the cooling rate at 10°C/hour with the temperature controller and apply a very small initial tension load before starting the test.
9. Start the computer program to automatically maintain the original specimen length and to record surface temperature and load until the specimen fails.

FIGURE 3.7
TSRST Test System at KDOT

Chapter 4: Results and Discussion

4.1 HWTD Database

Using Microsoft Access, the HWTD test database was compiled for all test results from KSU related to KDOT research or construction projects since 2000. The database also contains results for Superpave mixtures no longer used in Kansas. For this study, a new database with HWTD test results for Superpave mixtures with RAP (designated as SR rather than SM) was also generated and analyzed. The database contains 54 data points in which each point includes 12 significant fields of information, such as project name, project identification number, mix design identification number, aggregate type, mix type, percentage of recycle materials, asphalt source, binder type, percentage of additives used, the design traffic level, mix design volumetric properties (air voids, virgin asphalt content, RAP asphalt content, design binder content, voids in mineral aggregate, voids filled with asphalt, and dust-to-binder ratio), and HWTD test results. Test results were recorded in terms of number of wheel passes and corresponding rut depth where each specimen from the field mix was subjected to 20,000 repetitions or 20-mm rut depth, whichever came first. In this study, average rut depths at 10,000 and 15,000 repetitions (if available) were also extracted and included in the database. Other important HWTD test parameters, such as creep slope, stripping slope, and stripping inflection point data, were calculated and included in the Access database. Table 4.1 summarizes major input fields and performance data examples from database for each variable group considered during study.

4.2 Recycled Superpave (SR) Mixture

Several variables expected to affect the rutting and stripping performance of Superpave mixes with RAP have been included in the database. The selected variables are RAP content (ranged from 10% to 50%), binder source, binder grade (PG 58-28, PG 64-22, and PG 70-28), aggregate type (crushed gravel with sand, crushed stone with sand, and crushed stone and gravel combination with sand in the aggregate blend), and mix design volumetric properties. Rutting and stripping performance output parameters/response variables from the database include the total number of wheel passes, rut depth, creep slope, stripping inflection point, and stripping slope.

TABLE 4.1
Example of Major Fields of HWTD Test Database

	Major Field		Input Values		
			Example 1	Example 2	Example 3
1	Project Name		KDOT District 5 APAC 35% FRAP	KDOT District-2	KDOT District 3 APAC
2	Project ID		281-4KA1459-01	4-106KA1034-01	23-90KA1429-01
3	Mix ID No.		5G09002A	2G08002A	3G09006A
4	Aggregate Type		Crushed stone, River and Manufactured sand	Crushed stone, River sand	Crushed gravel, River sand
5	Mix Type		SR 12.5A	SR 12.5A	SR 19A
6	RAP Content (%)		35	30	25
7	Asphalt Source		Flint Hills	SEM Halstead	Flint Hills
8	Binder Type		PG 58-28	PG 58-28	PG 58-28
9	% Additives		0.75	0.0	0.3
10	Design ESALs (Millions)		2	0.3	1.4
11	Mix Design Volumetric Propertied	Virgin Asphalt Content (%)	3.85	3.6	3.57
		Asphalt from RAP (%)	1.67	1.6	1.28
		Design Asphalt Content (%)	5.52	5.2	4.85
		Air Voids (%)	4.48	4.64	4.44
		VMA (%)	16	14.1	15
		VFA (%)	73	66	71
		Dust-to-Binder Ratio	0.6	0.8	0.9
12	HWTD Test Outputs	Avg. No. of Wheel Pass	20,000	8,150	20,000
		Avg. Rut Depth, (mm)	6.55	20.0	13.35
		Creep Slope, (No. of wheel pass/mm rut depth)	2,674	737	3,244
		Stripping Inflection Point, (No. of wheel pass)	9,400	4,480	13,100
		Stripping Slope, (No. of wheel pass/mm rut depth)	1,435	600	2,374

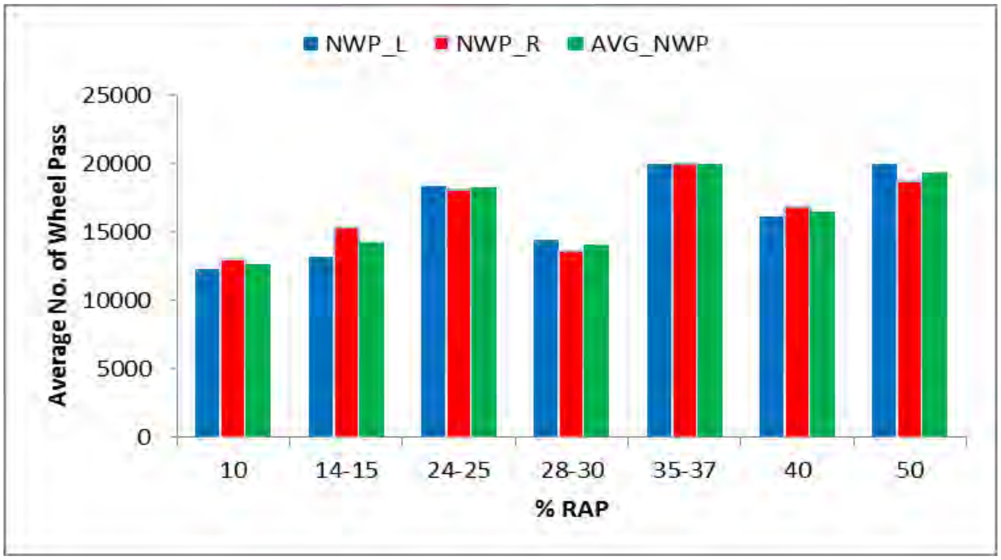
4.2.1 Effect of RAP Content

The average percentage of RAP used on KDOT projects historically was 15% or less. Since 2008, greater percentages of RAP in the Superpave mixtures are being used. In the KDOT Hamburg Wheel Tracking Device (HWTD) test database, a majority of mixtures with RAP contained 25% RAP materials; however, some mixes had RAP content ranging from 10% to 50%. Table 4.2 summarizes HWTD test outputs. Figure 4.1 illustrates the rutting performance of mixes with various percentages of RAP materials in HWTD tests. The figure also shows the average number of wheel passes is significantly higher for mixes with high RAP content (35%–50%) compared to moderate (25%–30%) and low (10%–15%) RAP contents (Figure 4.1a). This trend is also observed for measured rut depth during testing. Again, HWTD test output parameters, such as average creep slope, stripping slope, and stripping inflection points are much better for mixes with higher percentages of RAP (35%–50%) compared to moderate (except 30% RAP) and low RAP content mixes. All mixes in this analysis had the same Performance Grade (PG) binder (PG 58-28) possibly due to the fact that hardened asphalt from RAP plays a significant role in mix rutting performance. Since the overall effect of RAP material within the groups was inconclusive, further investigations were performed to determine the effect of aggregate type, PG binder source, and PG binder grade on HWTD test results.

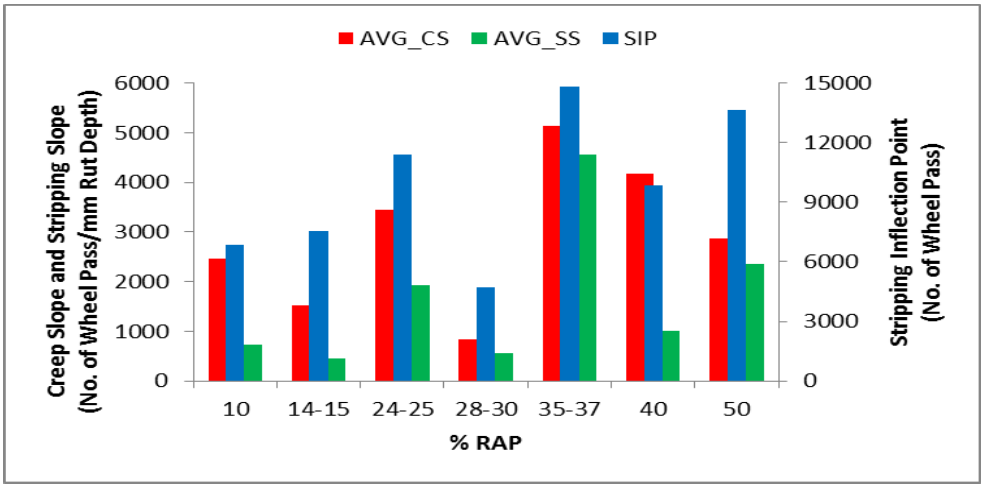
TABLE 4.2
HWTD Test Outputs

% RAP	HWTD Test Output Parameters							
	No. Of Wheel Passes			Rut Depth (mm)				
	Left	Right	Average	@ 10,000	@15,000	Avg. CS	Avg. SS	SIP
10	12,324	12,971	12,648	6	10	2,457	736	6,848
14-15	13,144	15,350	14,247	12	17	1,511	445	7,550
24-25	18,387	18,120	18,253	4	5	3,453	1917	11,375
28-30	14,440	13,665	14,053	NA	NA	826	563	4,720
35-37	20,000	20,000	20,000	4	9	5,138	4551	14,800
40	16,167	16,838	16,503	NA)	NA?)	4,166	1,017	9,850
50	20,000	18,717	19,358	4	6	2,870	2,348	13,650

Note: CS: Creep Slope; SS: Stripping Slope; SIP: Stripping Inflection Point



(a)



(b)

FIGURE 4.1
Effect of RAP Percentages in Mixtures During HWTD Testing

4.2.2 Effect of Aggregate Type

Common aggregate types used in the tested Superpave mixtures were crushed gravel (CG) and crushed limestone (CS) in combination with natural (RS) and manufactured (MS) sand. Some mixtures also contained gravel and crushed limestone combined with sands in the aggregate blend. As shown in Table 4.3 and Figure 4.2, crushed gravel and natural sand in the aggregate blend with 15% to 30% RAP generally performed significantly better when compared to mixes with crushed stone and sand only. Seventy-five percent of mixtures with crushed gravel passed 20,000 number of wheel passes before reaching 20-mm rut depth. However, the opposite trend was observed for mixes with 35% to 50% RAP. Crushed stone with sand in these mixes performed better when compared to gravel mixes. Figure 4.2 also shows that the combination of crushed gravel and sand did not improve (29% samples passed) the rutting performance of mixes, thus requiring further investigation of the interaction between RAP percentage and aggregate type which has been performed and discussed.

TABLE 4.3
Effect of Aggregate Type on HWTD Test Results

	% Sample Passed		
% RAP	CG + RS	CS + RS	CG + CS + RS
15-30	75	25	29
35-50	44	75	-

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

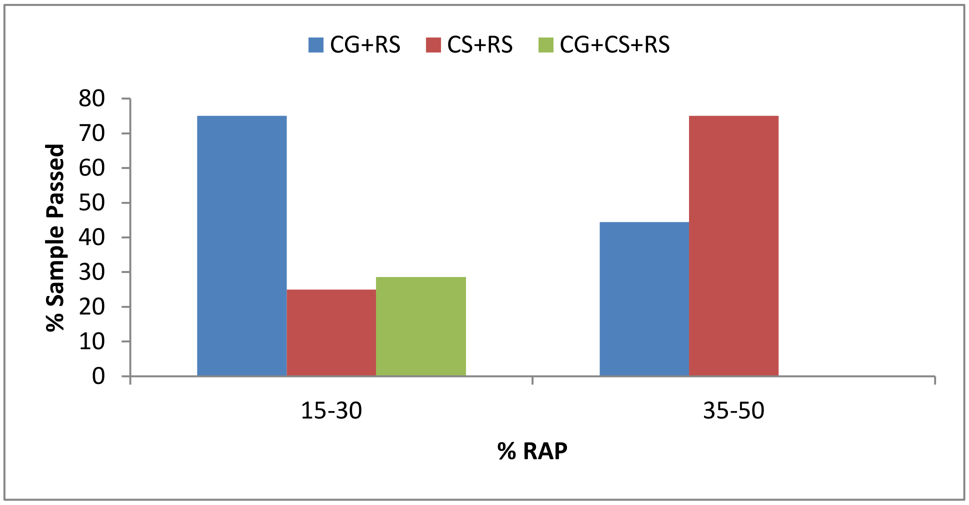


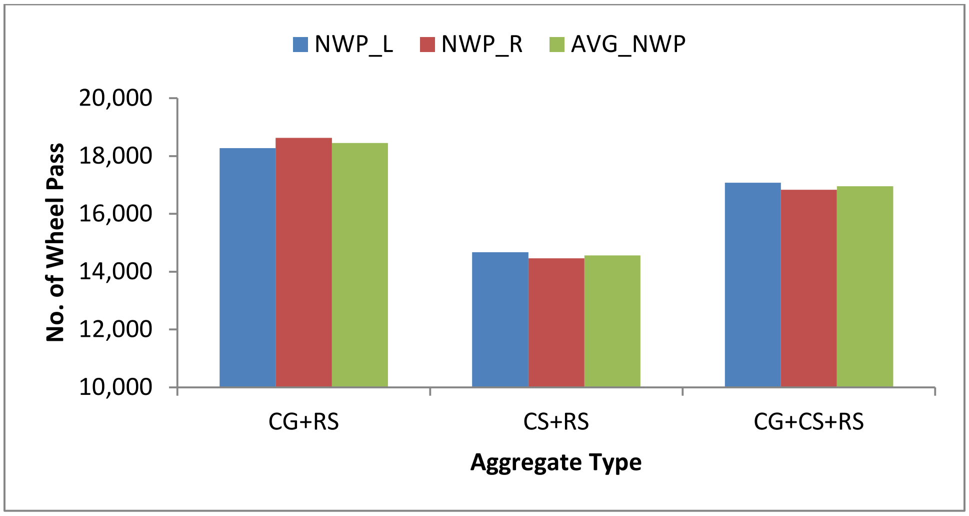
FIGURE 4.2
Effect of Aggregate Type in the Blend on HWTD Test Results

Table 4.4 and Figure 4.3 show that the mixes with crushed gravel have higher number of wheel passes and lower rut depth compared to the mixes with crushed limestone, and crushed gravel and crushed limestone combinations. Rut depth at 15,000 wheel passes is significantly higher (73%) when the mix has crushed stone in the aggregate blend (Figure 4.3(b) and Table 4.5). A similar trend was observed for other HWTD output parameters. In general, creep and stripping slopes are consistently higher for the crushed gravel mix compared to crushed stone mixtures. Table 4.6 and Figure 4.4 show the crushed gravel mixtures have the number of wheel passes at stripping inflection point (SIP) that are 30% and 12% higher, respectively, than crushed limestone mixtures or their combinations. However, interactions among aggregate type, binder grade, and asphalt source were further investigated.

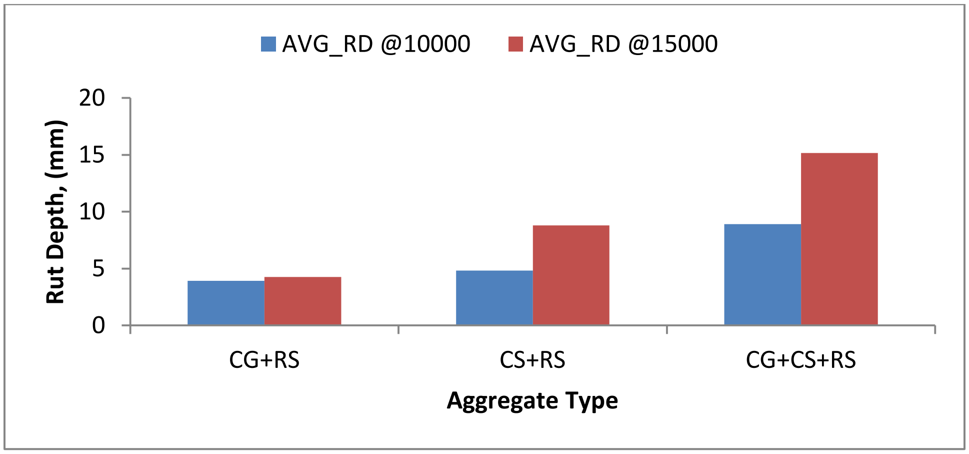
TABLE 4.4
Effect of Aggregate Type on the Number of Wheel Passes

No. of Wheel Passes			
	CG+ RS	CS + RS	CG + CS + RS
Left	18,271	14,669	17,081
Right	18,625	14,458	16,839
Average	18,448	14,563	16,960

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone



(a)



(b)

FIGURE 4.3
Effect of Aggregate Type in the Blend During HWTD Testing

TABLE 4.5
Effect of Aggregate Type on Rut Depth

No. of Wheel Passes	Average Rut Depth (mm)		
	CG + RS	CS + RS	CG + CS + RS
10,000	4	5	9
15,000	4	9	15

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

TABLE 4.6
Effect of Aggregate Type on HWTD Output Parameters

HWTD Test Output Parameters	Aggregate Type		
	CG + RS	CS + RS	CG + CS + RS
Average Creep Slope	4,204	2,402	2,428
Average Stripping Slope	2,467	1,282	1,355
Stripping Inflection Point	12,185	8,485	10,729

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

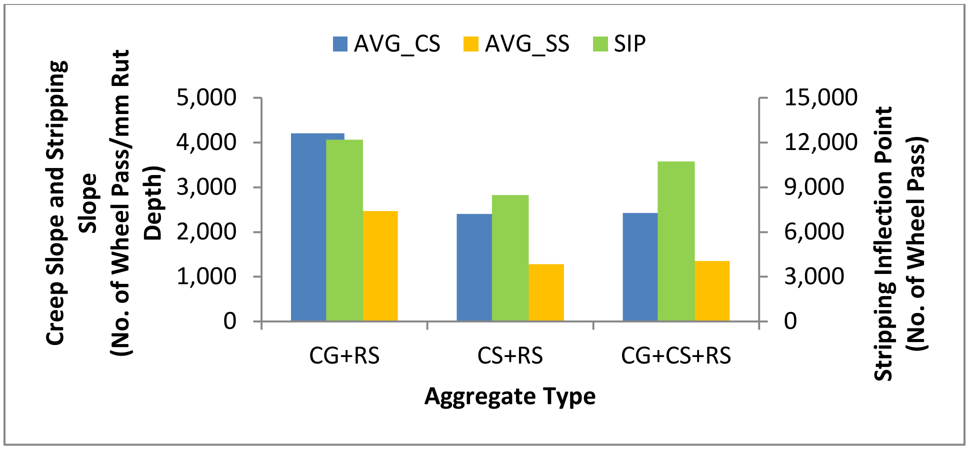


FIGURE 4.4
Effect of Aggregate Type on HWTD Test Output Parameters

4.2.3 Effect of Binder Grade

KDOT predominantly used two types of virgin performance-graded (PG) binder for recycled Superpave mixtures: PG 64-22 and PG 58-22. The rutting potential of these mixes with different binder grade were measured by HWTD under identical test conditions (submerged, 50^0 C). As expected, rutting performances of these field mixes (Figures 4.5 and 4.6) vary significantly due to different PG binders. More than 90% of crushed gravel mixtures with PG-64-22 and PG 70-28 completed 20,000 wheel passes without reaching 20-mm rut depth (Table 4.7). Only 56% of mixes with PG 58-28 passed the criteria of maximum 20 mm rut depth at 20,000 passes. In both cases, RAP content varied from 15% to 25%.

HWTD test output parameters, such as total number of wheel passes, stripping inflection point, creep slope, and stripping slopes signify that recycled mixes with higher PG binder grade had higher number of wheel passes with less accumulation of rutting. However, the interaction study between aggregate type and PG binder grade was inconclusive. Creep slope, stripping slope, and number of wheel passes at stripping inflection point of crushed gravel mixtures increase with higher binder grade, while the opposite occurs for mixtures with crushed gravel and stone combinations. The number of wheel passes at SIP decreased 37% when mixtures had higher PG binder grade (PG 64-22). In addition, the creep slope and stripping slope also decreased by 30% and 74%, respectively (Table 4.8).

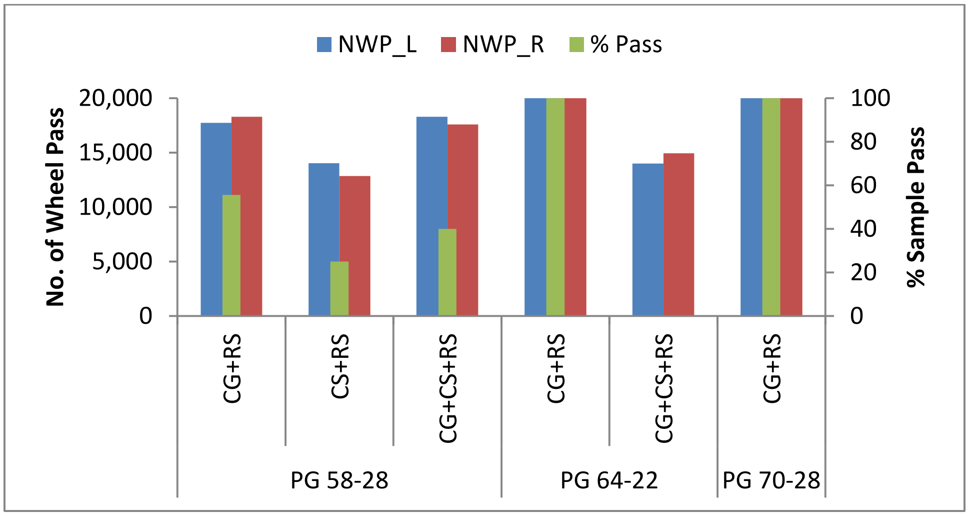


FIGURE 4.5
Interaction Study between Aggregate Type and Binder Grade on HWTD Test Results

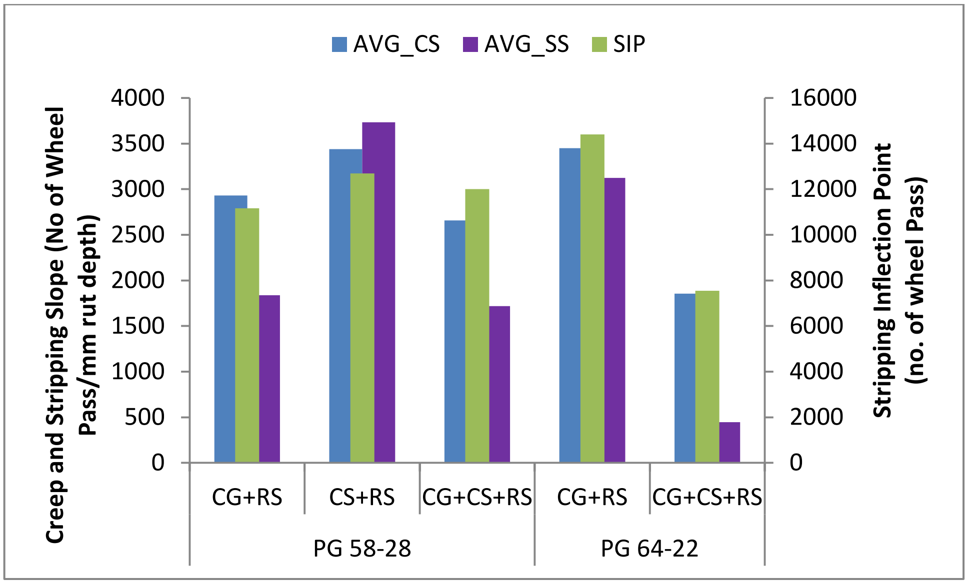


FIGURE 4.6
Interaction Study between Aggregate Type and Binder Grade on Hamburg Test Output Parameters

TABLE 4.7
Effect of Interaction of Aggregate Type and Binder Grade on HWTD Test Results

PG Grade	Aggregate Type	No. Of Wheel Passes Left	No. Of Wheel Passes Right	% Sample Pass
58-28	CG + RS	17,754	18,288	56
	CS + RS	14,028	12,853	25
	CG + CS + RS	18,312	17,596	40
64-22	CG + RS	20,000	20,000	100
	CG + CS + RS	14,005	14,945	0
70-28	CG + RS	20,000	20,000	100

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

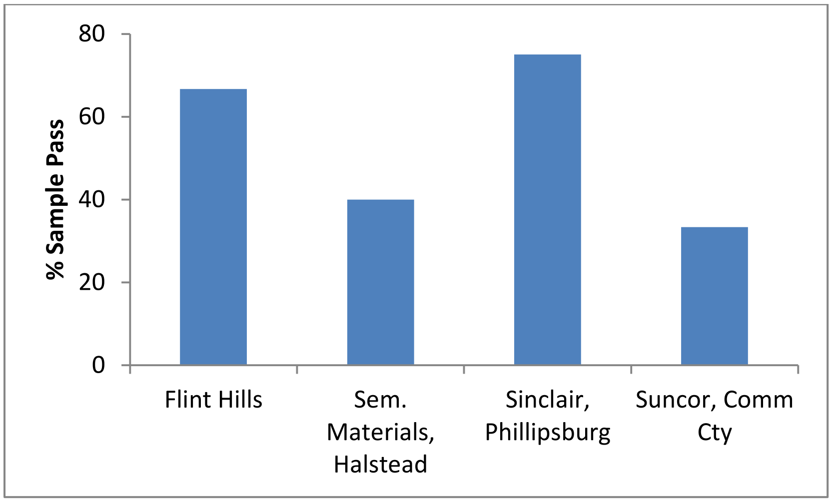
TABLE 4.8
Effect of Interaction of Aggregate Type and Binder Grade on HWTD Output Parameters

PG Grade	Aggregate Type	Average Creep Slope	Stripping Inflection Point	Average Stripping Slope
58-28	CG + RS	2,931	11,163	1,837
	CS + RS	3,440	12,700	3,733
	CG + CS + RS	2,658	12,000	1,720
64-22	CG + RS	3,451	14,400	3,125
	CG + CS + RS	1,855	7,550	445

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

4.2.4 Effect of Binder Source

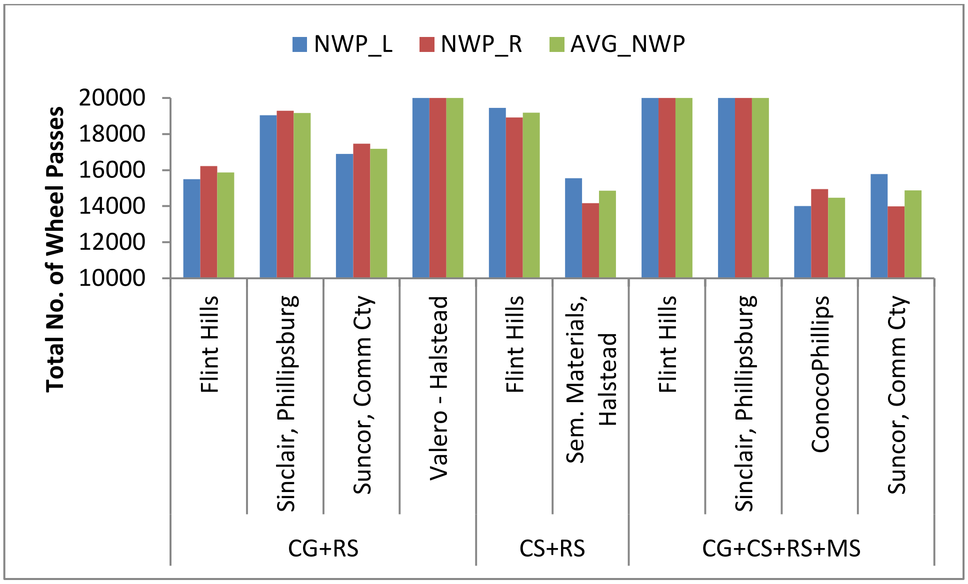
Figure 4.7 shows the rutting performance trend of Superpave mixes with binder from different refineries (as mentioned in the mix design), clearly revealing that binder source influences HWTD test results. Results also show that the passing criteria for the number of wheel passes (20,000) and maximum rut depth (20 mm) vary significantly for different binder sources even though these mixes had identical RAP content (25%) and binder grade (PG 58-28). For example, approximately 75% of mixes with binder from Sinclair Phillipsburg source completed 20,000 wheel passes, while mixes with binder sources from Flint Hills and Suncor Commerce City had a significantly lower percentage of samples passing 20,000 repetitions.



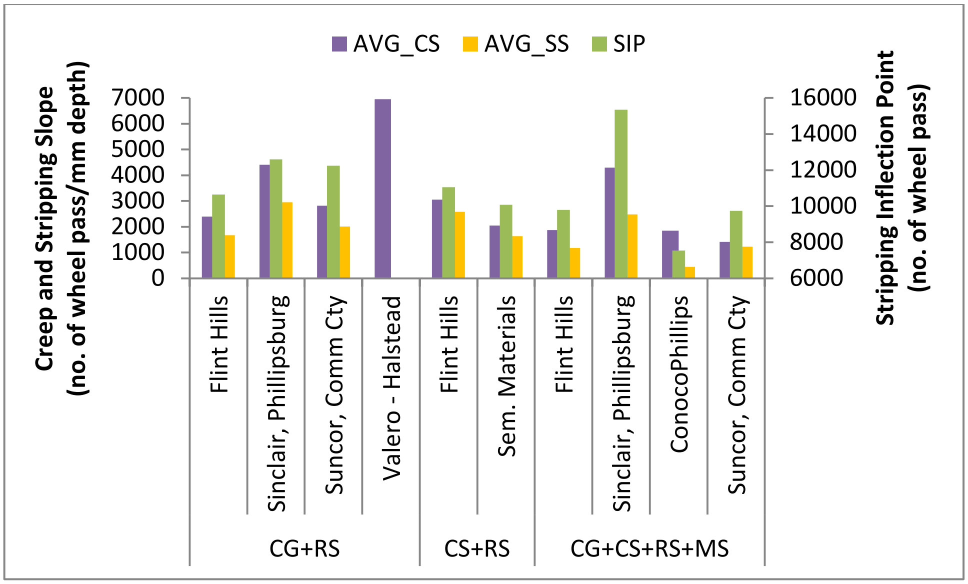
FIGUER 4.7
Effect of Binder Source (As per Mix Design Information) on HWTD Test Results

4.2.5 Interaction among Independent Variables of Recycled Superpave Mixtures

Independent variables such as percentage of RAP content in the mix, aggregate type, binder grade, and binder source were further investigated to identify any possible interactions. Figure 4.8 reveals that binder source influences mixture rutting performance regardless of aggregate type. For mixtures with crushed gravel and PG 58-28 binder grade, the average number of wheel passes was significantly higher for Sem Materials-Halstead (as indicated on the mix design data sheet) and Sinclair, Phillipsburg refinery sources as compared to the Flint Hills and Suncor Commerce City sources. A similar trend was also observed for mixtures with crushed stone and gravel and stone combination. For mixtures specifically from the Flint Hills, the rutting performance was significantly better for crushed stones and crushed stone–gravel combination than mixtures with crushed gravel (Figure 4.8a and Table 4.9). This trend is directly opposed to findings discussed in Figure 4.3.



(a)



(b)

FIGURE 4.8
Interaction Study between Aggregate Type and Binder Source on HWTD Test Output Parameters

TABLE 4.9
Interaction Effect of Aggregate and Binder Source on HWTD Test Results

Agg. Type	AC Source	No. of Wheel Passes			Average Creep Slope	SIP	Average Stripping Slope
		Left	Right	Average			
CG + RS	Flint Hills	15,500	16,225	15,863	2,399	10,650	1,680
	Sinclair, Phillipsburg	19,037	19,295	19,166	4,409	12,593	2,950
	Suncor, Comm Cty	16,900	17,476	17,188	2,824	12,238	2,015
	Valero-Halstead*	20,000	20,000	20,000	6,954		
CS + RS	Flint Hills	19,450	18,917	19,183	3,057	11,050	2,584
	Sem. Materials	15,552	14,162	14,857	2,052	10,078	1,634
CG+CS + RS+MS	Flint Hills	20,000	20,000	20,000	1,875	9,800	1,179
	Sinclair, Phillipsburg	20,000	20,000	20,000	4,293	15,350	2,479
	ConocoPhillips	14,005	14,945	14,475	1,855	7,550	445
	Suncor, Comm Cty	15,780	13,990	14,885	1,415	9,750	1,231

Note: SIP: Stripping Inflection Point; CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone; MS: Manufactured Sand

*As indicated on mix design data sheet

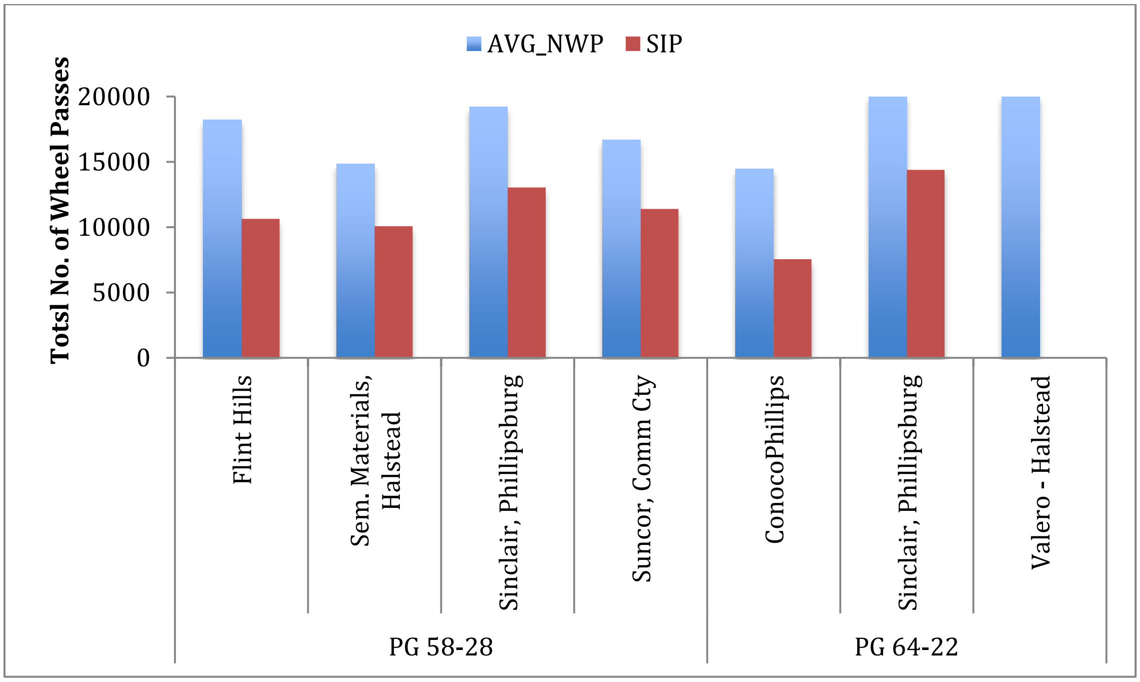
However, Table 4.9 and Figure 4.8(b) also show that a higher number of wheel passes at SIP is observed for the crushed gravel mix, thus confirming a possible interaction between binder source and aggregate types. The creep slope (number of wheel passes/mm rut depth) for crushed gravel mixtures measured from the HWTD test output drastically increased for surface mixes with asphalt from the Flint Hills and Suncor Commerce City sources.

Table 4.10 and Figure 4.9 clearly indicate that mix rutting performance is more notably affected by binder source rather than binder type. For different refinery sources, the average creep slope and stripping slope (number of wheel passes/mm rut depth) decreased even with higher binder grade (Figure 4.9(b)). An interaction study between asphalt source and RAP content in the mix revealed that binder source is the primary factor controlling rutting performance of the mix. For example, mixes with asphalt from Sinclair Phillipsburg showed no significant difference in total number of wheel passes at medium (25%) to high (40%) RAP contents (Table 4.11 and Figure 4.10). However, the same mixtures demonstrated significantly higher average creep slope and stripping slopes with increasing RAP contents (Figure 4.10b). Figure 4.10 also confirms possible interaction between asphalt source and percentage of RAP content in mixtures.

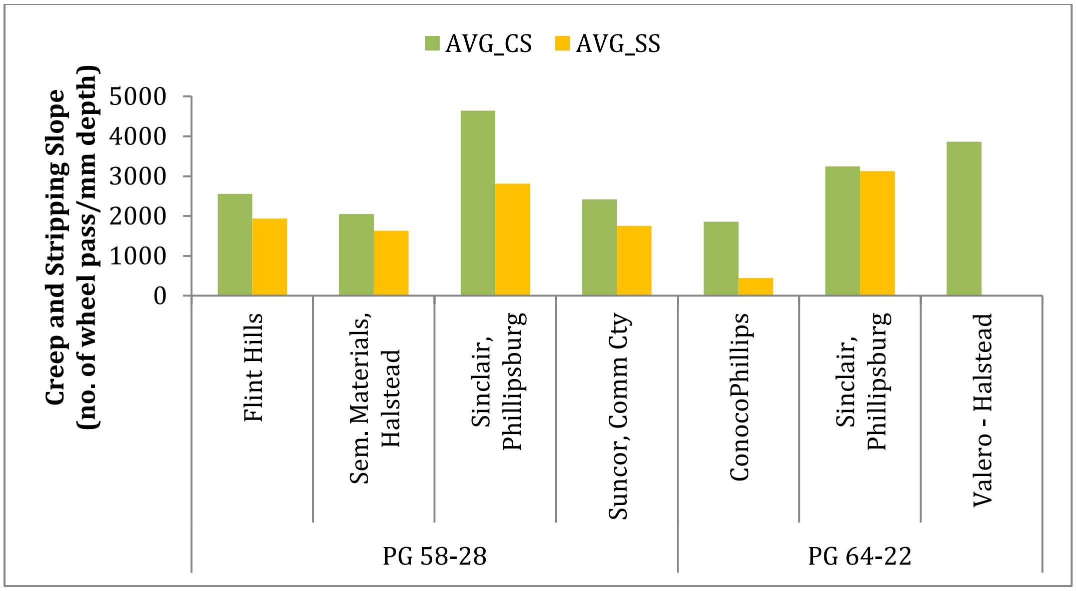
TABLE 4.10
Effect of Binder Grade and Source on HWTD Test Output Parameters

PG Grade	AC Source	Average NWP	Average Creep Slope	SIP	Average Stripping Slope
58-28	Flint Hills	18,213	2,557	10,640	1,941
	Sem. Materials, Halstead*	14,857	2,052	10,078	1,634
	Sinclair, Phillipsburg	19,226	4,643	13,056	2,810
	Suncor, Commerce City	16,676	2,422	11,408	1,754
64-22	ConocoPhillips	14,475	1,855	7,550	445
	Sinclair, Phillipsburg	20,000	3,245	14,400	3,125
	Valero-Halstead	20,000	3,863		

Note: NWP: Number of Wheel Passes; SIP: Stripping Inflection Point; * as described in the mix design



(a)



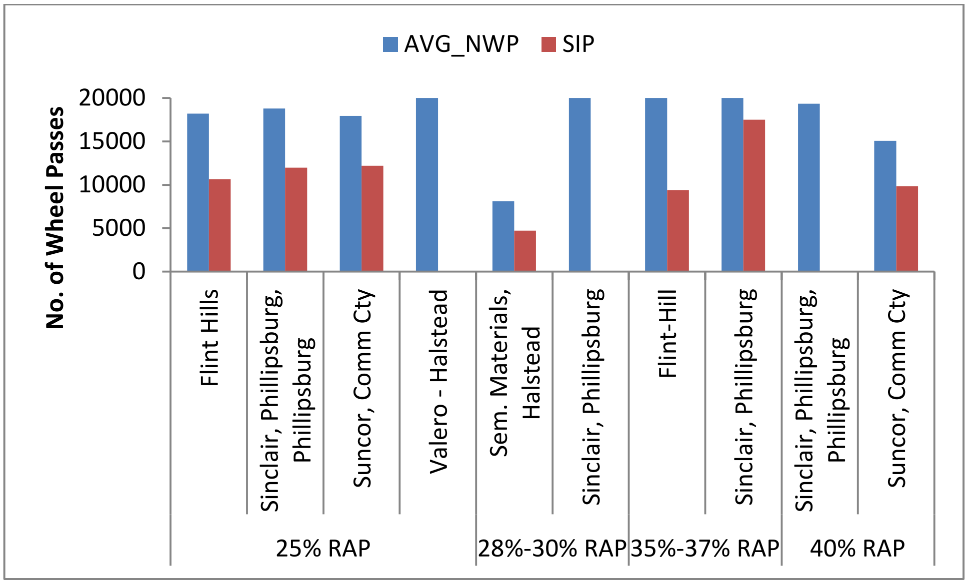
(b)

FIGURE 4.9
Interaction Study between Binder Grade and Binder Source on HWTD Test Output Parameters

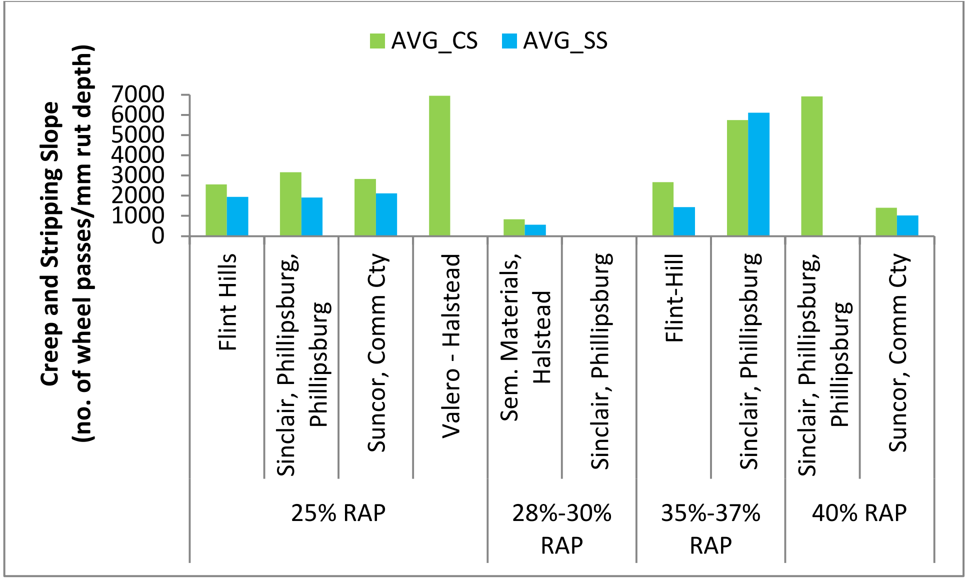
TABLE 4.11
Effect of RAP Content and Binder Source on HWTD Test Outputs

% RAP	AC Source	Average NWP	Average Creep Slope	SIP	Average Stripping Slope
25	Flint Hills	18,213	2,557	10,640	1,941
	Sinclair, Phillipsburg	18,808	3,169	11,979	1,913
	Suncor, Comm Cty	17,954	2,827	12,188	2,122
	Valero-Halstead	20,000	6,954		
28-30	Sem. Materials, Halstead	8,105	826	4,720	563
	Sinclair, Phillipsburg	20,000			
35-37	Flint Hills	20,000	2,674	9,400	1,435
	Sinclair, Phillipsburg	20,000	5,754	17,500	6,109
40	Sinclair, Phillipsburg	19,350	6,924		
	Suncor, Comm Cty	15,079	1,409	9,850	1,017

Note: NWP: Number of Wheel Passes; SIP: Stripping Inflection Point



(a)



(b)

FIGURE 4.10
Interaction Study between RAP Content and Binder Source on HWTD Test Output Parameters

4.3 Virgin Superpave Mixtures (SM)

KDOT HWTD test database contains five mix types (SM-9.5A, SM-12.5A, SM-12.5B, SM-19A, and SM-19B) for virgin Superpave mixtures (as mentioned earlier, known as SM), three aggregate types (crushed gravel with sand, crushed stone with sand, and crushed stone and gravel combination with sand in the aggregate blend), three PG binder grades (PG 58-28, PG 64-22, and PG 70-28), and eight different binder source (refineries). The rutting and stripping performance of these mixtures was investigated based on these independent variables and possible interactions among them.

4.3.1 Effect of Mixture Type

As previously mentioned, five mix types were used to investigate rutting and stripping resistance of Superpave surface mixtures. Figure 4.11 shows that, as expected, mixes with higher nominal maximum aggregate size (NMAS) performed well regardless of aggregate type, binder grade, and binder source. More than 40% of samples completed 20,000 wheel passes over time for the SM-19A Superpave mixture. However, no SM-9.5A and SM-12.5B samples met passing criteria of 20,000 repetitions before the 20-mm rut depth limit in the HWTD test.

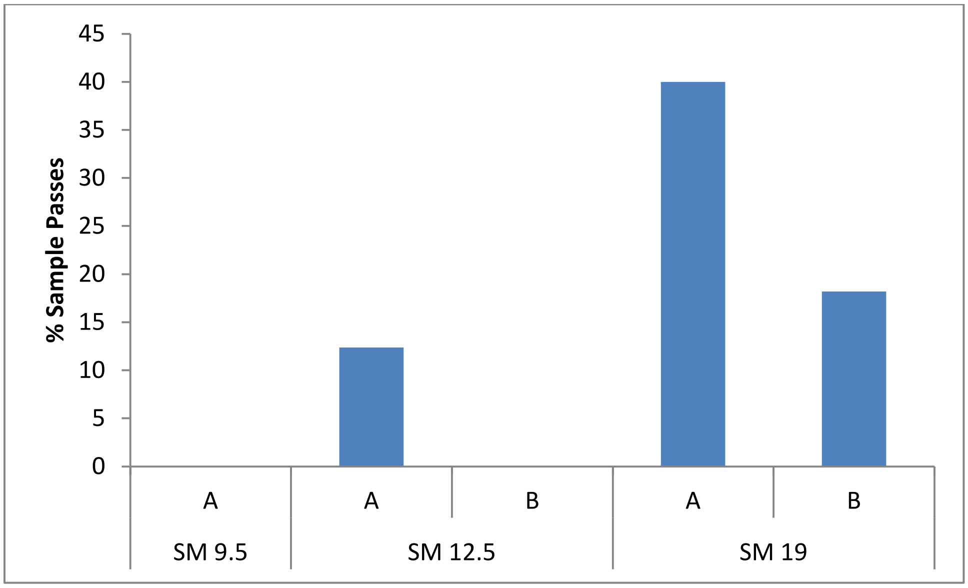


FIGURE 4.11
Effect of Surface Mix Type on Rutting Performance of Superpave Virgin Mix

4.3.2 Effect of Aggregate Type

Figure 4.12 illustrates that mixtures with crushed gravel performed significantly better than mixtures with crushed stone. Thirty-two percent of total mixtures completed 20,000 repetitions in the HWTD test, while no samples with crushed stone and gravel passed this criterion. Again, 17% of Superpave mixtures with crushed stone exceeded 20,000 passes. Further interaction study with other independent variables should be performed to support this finding.

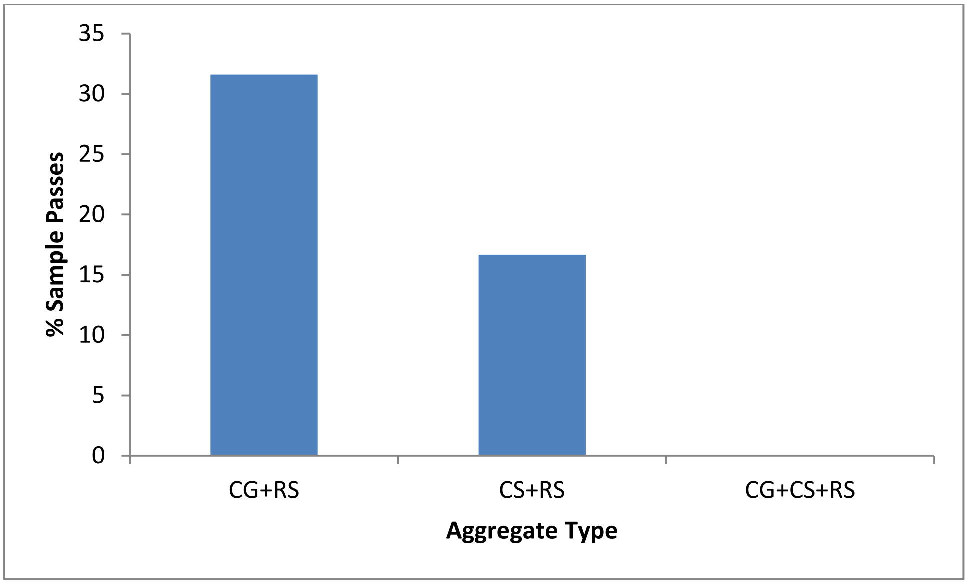


FIGURE 4.12
Effect of Aggregate Type on Rutting Performance of Superpave Mixture

4.3.3 Effect of Binder Grade

The mixtures tested had two types of performance-graded binder for virgin Superpave mixtures: PG 64-22 and PG 58-22. Some virgin mixtures with PG 70-28 binder grade were also tested. Rutting potential was measured by Hamburg Wheel Tracking Device under identical test conditions (submerged, 50°C). As expected, rutting performances of these mixes varied significantly for different performance-graded binders, as shown in Figure 4.13 More than 35% of virgin mixtures with PG 70-28 completed 20,000 wheel passes (without reaching 20-mm rut depth), while only 13% mixes with PG 64-22 passed this criterion. Mixtures with PG 58-28 could not pass the rut depth failure criteria. However, more analysis was done and is discussed later to identify possible interactions among independent variables.

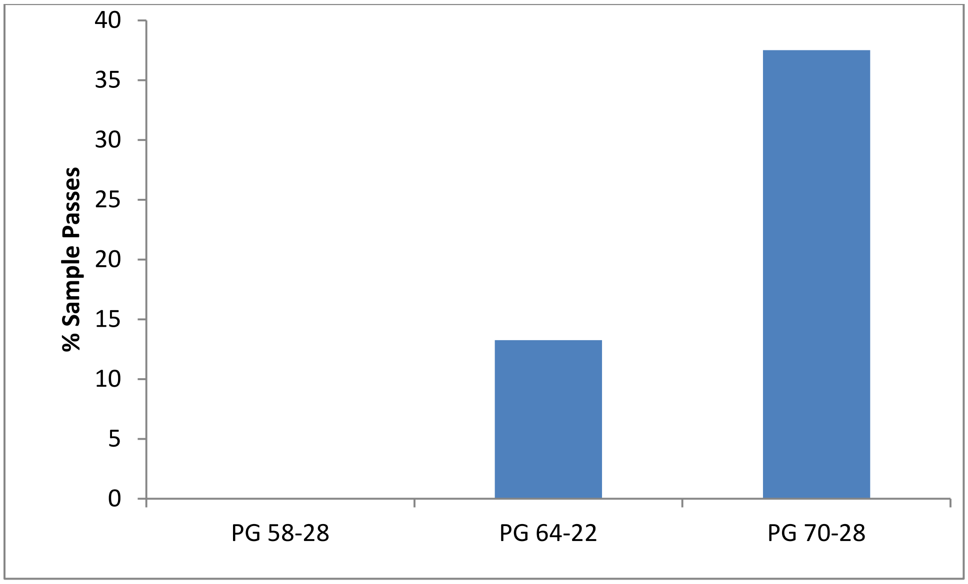


FIGURE 4.13
Effect of Binder Grade on Rutting Performance of Superpave Virgin Mixtures

4.3.4 Effect of Binder Source

Figure 4.14 shows the performance of mixes with PG binder from various refineries. Results indicate that the binder source significantly affects HWTD test results. In terms of number of wheel passes (20,000) and rut depth (20 mm), passing these criteria vary significantly for different binder sources even when mixes contain identical binder grade. For example, 33% of mixtures with binder from Valero Ark City passed the criteria in HWTD, while no mixtures with binder from Ergon Inc. and Sem Materials at Halstead completed the 20,000 repetitions.

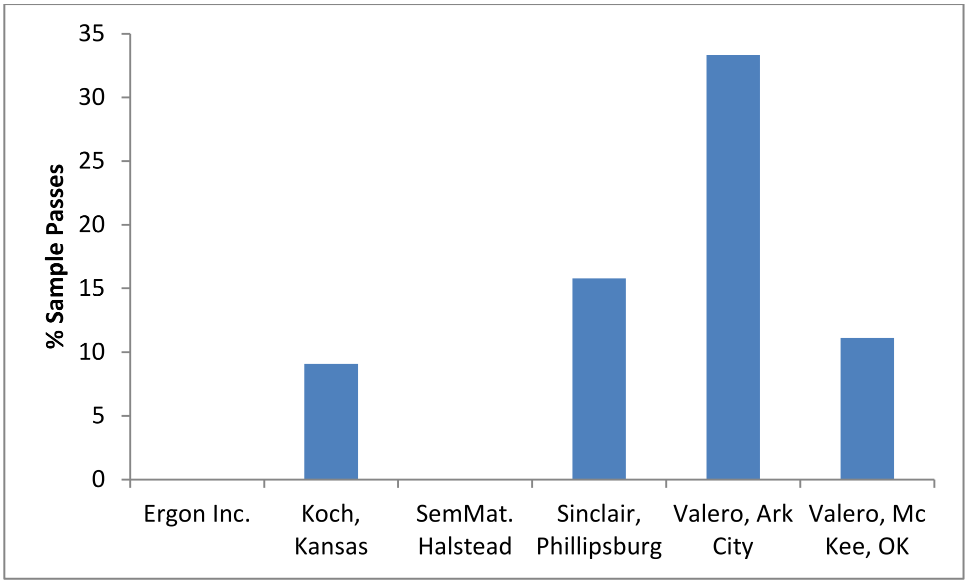


FIGURE 4.14
Effect of Binder Source on Rutting Performance of Superpave Mixture

4.3.5 Interaction among Independent Variables for Superpave Virgin Mixtures

Independent variables, such as mix type, aggregate type, binder grade, and mix binder source were further investigated to identify any possible interactions. Table 4.12 and Figure 4.15 show that aggregate type possibly influences mixture rutting performance. For example, mixtures with crushed gravel have a significantly higher number of wheel passes compared to crushed stone and crushed stone-gravel combination mixtures. SM-19A crushed gravel mixture showed better performance compared to SM-12.5B mixtures. However, this trend is not consistent for crushed stone mixtures. For crushed stone, SM-12.5B mixtures had higher number of wheel passes as compared to SM-19A mixtures.

Table 4.13 and Figure 4.16 show the interaction between aggregate type and binder grade. As expected, the mixture rutting performance improves with the crushed gravel mixture and higher binder grade. Table 4.13 also demonstrates that the highest number of wheel passes at SIP is observed for crushed gravel mixes with PG 70-28. Possible interaction will be further confirmed by statistical analysis.

TABLE 4.12
Effect of Aggregate Type on HWTD Test Outputs for Superpave Mix

Aggregate Type	Mix Type	Average No. of Wheel Passes	Stripping Inflection Point
CG + RS	SM 12.5A	15,961	13,807
	SM 19A	19,983	9,250
CS + RS	SM 9.5A	8,477	4,740
	SM 12.5A	12,219	8,427
	SM 12.5B	8,760	5,400
	SM 19B	6,904	2,550
CG + CS + RS	SM12.5A	11,612	7,210

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

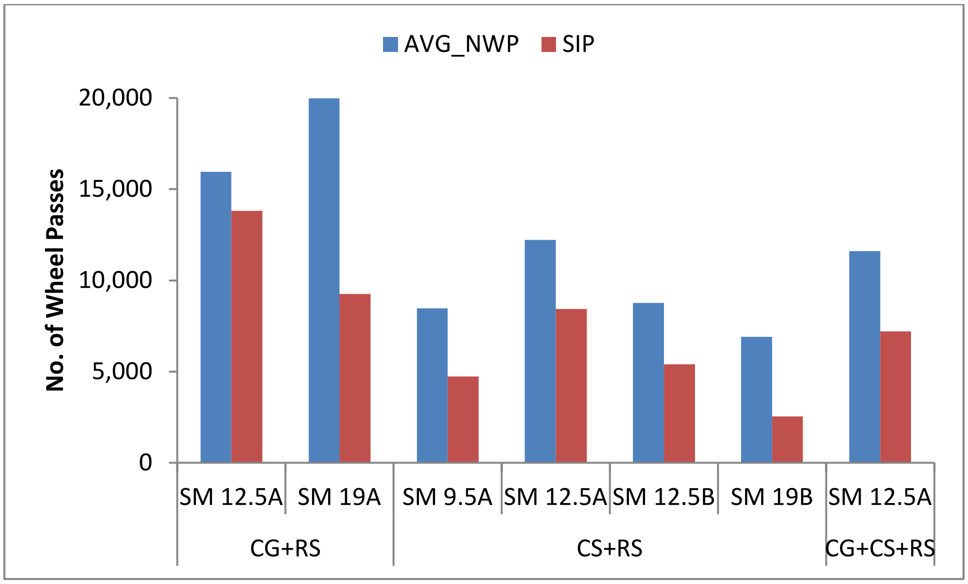


FIGURE 4.15
Interaction Study between Mix Type and Aggregate Type on HWTD

TABLE 4.13
Effect of Binder Grade and Aggregate Type on HWTD Test Outputs for Superpave Mix

PG Grade	Aggregate Type	Average No. of Wheel Passes	Stripping Inflection Point
58-28	CS + RS	3,327	2,175
64-22	CG + RS	16,909	12,794
	CS + RS	11,763	7,874
	CG + CS + RS	11,612	7,210
70-28	CG + RS	19,975	-
	CS + RS	14,990	-

Note: CG: Crushed Gravel; RS: River Sand; CS: Crushed Stone

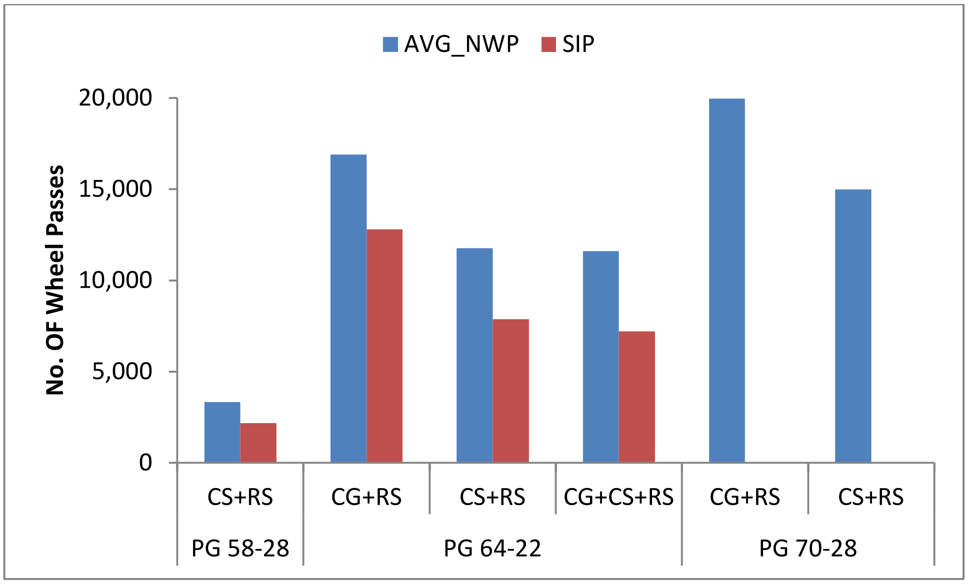


FIGURE 4.16
Interaction Study between Aggregate Type and Asphalt Grade on HWTD Test Performance

Table 4.14 and Figure 4.17 show that binder source plays a significant role in rut resistance regardless of PG binder grade. For example, the total number of wheel passes and creep slope (number of wheel passes/mm rut depth) for mixtures with binder from Trigeant drastically increased for PG 58-28 to PG 70-28. However, this trend is not consistent for the mixture with binder from Valero McKee, Oklahoma implying that there may not be any interaction between binder source and binder grade.

TABLE 4.14
Effect of Binder Grade and Source on HWTD Test Outputs for Superpave Mix

PG Grade	AC Source	Average No. Of Wheel Passes	Average Creep Slope
58-28	Valero, McKee, OK	2,953	257
	Trigeant	3,150	209
64-22	Valero, McKee, OK	14,514	1,107
	Trigeant	8,000	670
70-28	Valero, McKee, OK	9,981	
	Trigeant	15,290	1,260

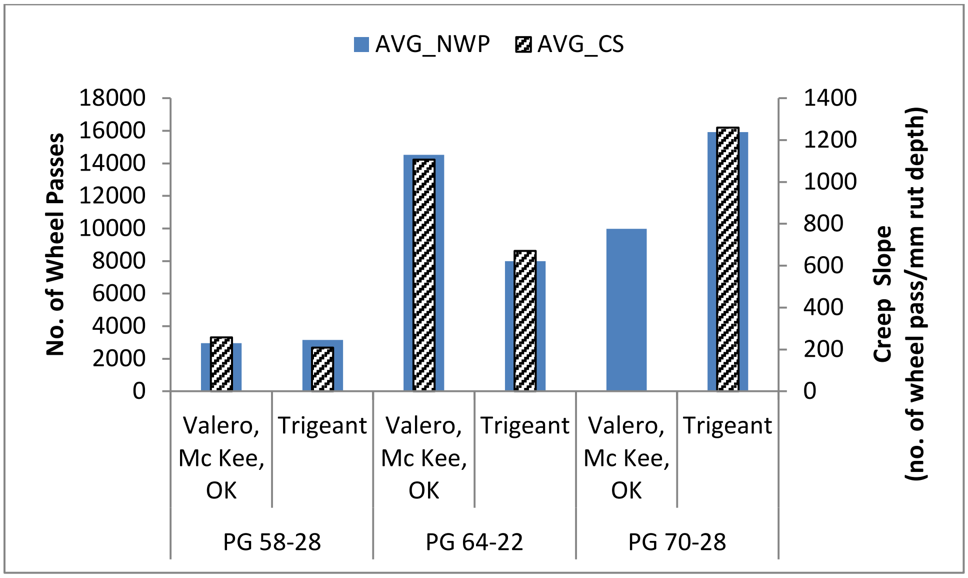


FIGURE 4.17
Interaction Study between Binder Source and Asphalt Grade on HWTD Test Performance

Table 4.15 and Figure 4.18 indicate that the rutting performance of mixes is more prominently affected by binder source than mix type. In general, the higher the nominal aggregate size of the mixture, the better the rutting performance. However, some refinery sources result in decreased number of wheel passes, even with larger aggregate NMAS in the mixture blend (Trigeant and Valero McKee, OK). Further investigation was conducted using statistical analysis. During the interaction study, a similar trend was observed between aggregate type and binder source (Table 4.16 and Figure 4.19).

TABLE 4.15
Effect of Mix Type and Binder Source on HWTD Test Outputs for Superpave Mix

Mix Type	Asphalt Source	Average No. Of Wheel Passes	Stripping Inflection Point
SM 9.5A	Sinclair, Phillipsburg	8,615	5,110
	Valero, Ark City	8,200	4,000
SM 12.5A	Ergon Inc.	11,035	5,934
	Koch, Kansas	11,640	9,520
	Sem. Materials, Halstead*	9,948	5,657
	Sinclair, Phillipsburg	13,592	9,057
	Trigeant	11,080	6,600
	Valero, Ark City	14,114	13,057
	Valero, McKee, OK	14,883	14,513
SM 19A	SEM Mat. DC, KS	20,000	10,000
	Sinclair, Phillipsburg	19,950	8,500
SM 19B	Holley, OK	11,840	
	Trigeant	3,150	2,175
	Valero, McKee, OK	6,117	3,300

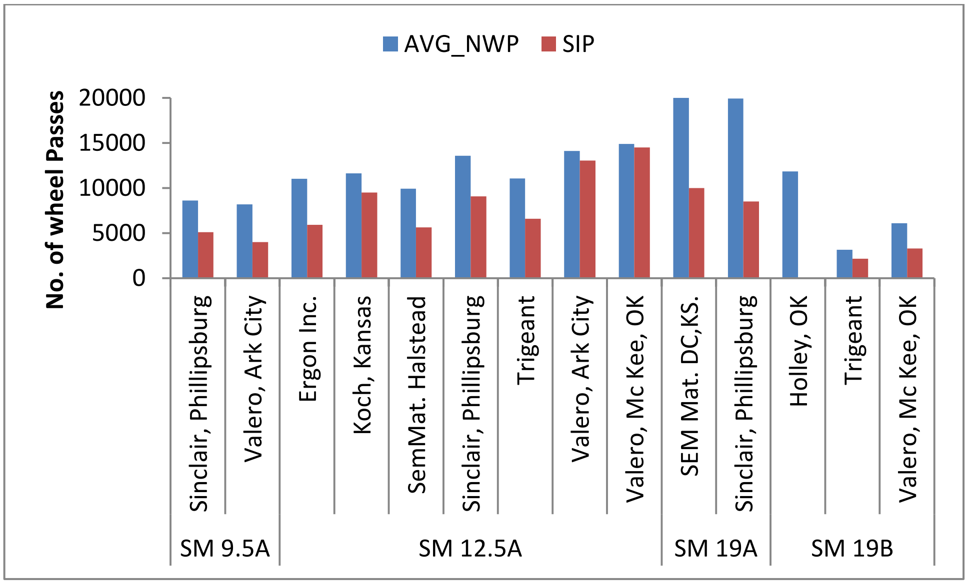


FIGURE 4.18
Interaction Study between Mix Type and Binder Source on HWTD Test Performance

TABLE 4.16
Effect of Aggregate Type and Binder Source on HWTD Test Outputs for Superpave Mix

Aggregate Type	Asphalt Source	Average No. Of Wheel Passes	Stripping Inflection Point
CG+RS	Koch, Kansas	16,875	11,600
	SEM Mat. DC, KS	20,000	10,000
	Sinclair, Phillipsburg	19,950	8,500
	Valero, Ark City	19,900	15,400
	Valero, McKee, OK	14,883	14,513
CS+RS	Ergon Inc.	10,225	5,183
	Holley, OK	11,840	
	Koch, Kansas	11,117	9,173
	SemMat. Halstead	9,948	5,657
	Sinclair, Phillipsburg	13,660	7,381
	Trigeant	6,980	4,350
	Valero, Ark City	13,086	11,429
	Valero, McKee, OK	6,117	3,300
CG+CS+RS	Ergon Inc.	11,157	6,059
	Sinclair Phillipsburg	12,522	9,511

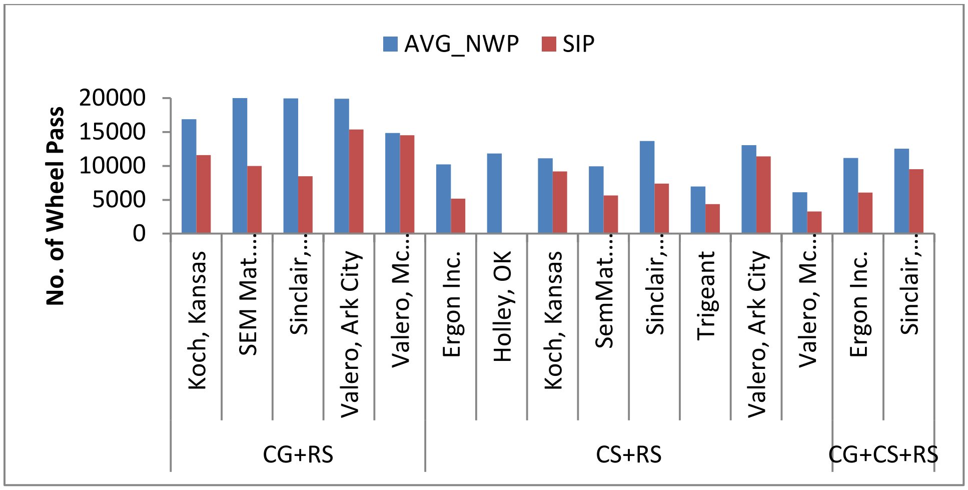


FIGURE 4.19
Interaction Study between Aggregate Type and Binder Source on HWTD Test Performance

4.4 Statistical Analysis

4.4.1 Analysis of Variance (ANOVA)

Statistical analysis software SAS (SAS 2011) was used to conduct an analysis of variance (ANOVA) to identify the most significant factors affecting rutting and stripping performance of Superpave mixtures with or without RAP in the mix. The factors considered in analyzing mixtures with RAP materials were RAP content (%), aggregate type, binder grade, and binder source in the mix. ANOVA was also performed to test interactions between independent variables at 90% confidence interval. Table 4.17 shows results of ANOVA of various test outputs for mixtures with RAP.

The total number of wheel passes and stripping slope of Superpave mixes with RAP were significantly affected by RAP content and binder source, while neither of these factors and their interactions affected pure rutting performance (creep slope) of these mixtures. However, the number of wheel passes to stripping inflection point was significantly influenced by RAP content and binder grade. Pure moisture damage (stripping slope) in the mixture during HWTD testing was influenced by two potential factors: RAP content in the mix and aggregate type. Interaction between RAP content and aggregate type also affected the pure stripping failure phase (stripping slope) and total wheel passes to stripping inflection point. Again, wheel passes at stripping inflection point were also affected by interaction between aggregate type in the mixture blend and binder source. In statistical significance testing, p-value indicates the probability of obtaining a test statistic that is at least as extreme as the actual observation, provided the null hypothesis is true. Based on p-value, RAP-aggregate type interaction (p-value = 0.0008) was most influential on stripping performance, followed by RAP content (= 0.0009) of the Superpave mix and binder source (p-value = 0.007). p-value describes the probability in this case. Aggregate type did not seem to have any influence on pure rutting performance of high RAP mixes.

TABLE 4.17
Results of Analysis of Variance of Superpave Mixtures with RAP

Rutting Output	Source	DF	R^2/ [p-value]	p-value	Significant @ α = 0.1
Average Total No. of Wheel Passes	RAP Content	3	0.64 [0.0140]	0.0320	Y
	Aggregate Type	2		0.1153	N
	Asphalt Source	2		0.0069	Y
	Asphalt Grade	1		0.6526	N
	RAP* Agg_Type	1		0.9600	N
	Agg_Type * AC_Source	2		0.1700	N
Creep Slope	RAP Content	3	0.48 [0.3014]	0.6387	N
	Aggregate Type	2		0.7132	N
	Asphalt Source	2		0.1618	N
	Asphalt Grade	1		0.8100	N
	RAP* Agg_Type	1		0.3112	N
	Agg_Type * AC_Source	2		0.7563	N
Stripping Inflection Point	RAP Content	3	0.82 [0.0052]	0.0009	Y
	Aggregate Type	2		0.1633	N
	Asphalt Source	2		0.4060	N
	Asphalt Grade	1		0.0846	Y
	RAP* Agg_Type	1		0.0109	Y
	Agg_Type * AC_Source	2		0.0115	Y
Stripping Slope	RAP Content	3	0.82 [0.0056]	0.0046	Y
	Aggregate Type	2		0.0218	Y
	Asphalt Source	2		0.6768	N
	Asphalt Grade	1		0.1258	N
	RAP* Agg_Type	1		0.0008	Y
	Agg_Type * AC_Source	2		0.1132	N

Note: Degrees of Freedom = No. of samples – 1; R2 = Coefficient of determination; α = Type I error (probability of rejecting the null hypothesis when it is true); * indicates interaction

Factors considered in analyzing Superpave mixtures without RAP materials were mix type, aggregate type, binder grade, and binder source in the mix. Again, ANOVA was performed to test the effect of independent variables and their interactions at 90% confidence interval. Table 4.18 shows results of ANOVA of various HWTD test outputs for virgin Superpave mixtures.

The number of wheel passes at the stripping inflection point and the stripping slope of these mixes were significantly affected by the binder source, while none of the factors considered and their interactions had any effect on the pure rutting performance (creep slope) of these mixtures. However, the total number of wheel passes was significantly influenced by aggregate type and binder grade. Mix type also affected stripping inflection points of the mixtures. No significant interaction was obtained among independent variables. Based on the p-value, binder source (p-value = 0.008) had the largest influence on rutting performance, followed by mixture type (p-value= 0.034), aggregate type, and binder grade (p-value = 0.065).

TABLE 4.18
Results of Analysis of Variance (ANOVA) of Virgin Superpave Mixtures

Rutting Output	Source	DF	R^2/ [p-value]	p-value	Significant @ $\alpha = 0.1$
Average Total No. of Wheel Passes	Mix Type	3	0.37 [0.0015]	0.2081	N
	Aggregate Type	2		0.0646	Y
	Asphalt Source	9		0.3510	N
	Asphalt Grade	4		0.1022	Y
	Agg_Type * AC_Source	3		0.6989	N
	Mix_Type * AC_Source	1		0.8793	N
Creep Slope	Mix Type	3	0.75 [<.0001]	0.7842	N
	Aggregate Type	2		0.7970	N
	Asphalt Source	9		0.9711	N
	Asphalt Grade	4		0.9782	N
	Agg_Type * AC_Source	3		0.4200	N
	Mix_Type * AC_Source	1		0.7527	N
Stripping Inflection Point	Mix Type	3	0.50 [0.0002]	0.0343	Y
	Aggregate Type	2		0.4048	N
	Asphalt Source	9		0.0079	Y
	Asphalt Grade	4		0.2354	N
	Agg_Type * AC_Source	3		0.9905	N
	Mix_Type * AC_Source	1		0.2452	N
Stripping Slope	Mix Type	3	0.37 [0.0279]	0.2002	N
	Aggregate Type	2		0.8469	N
	Asphalt Source	9		0.0650	Y
	Asphalt Grade	4		0.6357	N
	Agg_Type * AC_Source	3		0.8822	N
	Mix_Type * AC_Source	1		0.1229	N

* indicates interaction

The effect of mix volumetric properties on HWTD test performance was also analyzed statistically for Superpave mixtures with and without RAP content. Tables 4.19 and 4.20 show p-values of test output parameters with respect to the mixture volumetric properties, such as total asphalt content, virgin binder and RAP asphalt content, VMA, VFA, and dust-to-binder ratio at 90% significance level. Results for Superpave mixtures with RAP show that the total number of wheel passes at 20-mm rut depth and the creep slope are highly influenced by VMA (p-value of

0.0128) and RAP asphalt content (p-value of 0.0806) in the mixture, respectively. However, none of the output parameters were sensitive to the virgin asphalt content, %VFA, and dust-to-binder ratio of the mix, indicating that the VMA parameter of the high RAP Superpave mixtures should be calculated more precisely. However, the pure rutting performance (creep slope) was significantly affected by RAP asphalt content (p-value = 0.0806), proving the importance of the blending chart for high RAP Superpave mixtures. Of course, this could be due to lack of 100% comingling of the RAP AC with the virgin AC.

Table 4.20 demonstrates that the rutting performance of Superpave surface mixture without RAP materials is significantly influenced by volumetric parameters. Total asphalt content (p-value = 0.0042) plays a role in controlling the total number of wheel passes in the HWTD test. The stripping inflection point was highly influenced by all volumetric parameters considered in the study: total asphalt content, VMA, VFA, and dust-to-binder ratio (p-value of 0.0007, 0.0142, 0.0039, and <0.0001, respectively). The pure rutting phase (creep slope) and stripping failure (stripping slope) were affected by the VFA (p-value = 0.0026) and dust-to-binder ratio (p-value = 0.0112), respectively.

4.4.2 Correlation with Other Performance Test Results

Measured rut depths (final) during the HWTD tests of SR mixtures were correlated with tensile strength ratios (TSR) from the KT-56 test and fracture temperatures of TSRST and Aged TSRST specimens from the Thermal Stress Restrained Specimen Test. TSR results were obtained from original mixture designs. The aged TSRST fracture temperature was obtained from specimens that had been aged in a forced-draft oven for five days (120 hours) at 85°C to simulate 7 to 10 years of service per AASHTO R 30. Twenty-two unaged and 19 aged specimens from 11 different projects were tested in the TSRST. Thirteen projects had TSR values available. Table 4.21 shows the correlation table and associated p-values after performing analysis of variance (ANOVA). It appears that TSR values significantly correlated with the percent RAP in the mixture at a higher level of confidence (95%). The negative correlation coefficient signifies that, as the percent RAP increases in the mixtures, TSR values decrease or, in other words, mixtures become more susceptible to moisture damage.

Maximum rut depth recorded during the HWTD test significantly correlated with fracture temperature in the TSRST testing of unaged and aged samples. However, correlation was stronger for the aged sample (p = 001). Negative correlation coefficients indicate that decreased rut depth results in higher fracture temperature when fracture temperature was negative in the TSRST correlation. As previously demonstrated, rut depth decreased when RAP content in Superpave mixture increased. Thus, results indicate that aged mixtures become more vulnerable to low-temperature cracking (Table 4.22) and it is recommended that low-temperature cracking potential of high RAP Superpave mixtures be evaluated during the mixture design process.

TABLE 4.19
Results of Analysis of Variance of SR Mix Volumetric Properties

Volumetric **Mixture Performance**	**Virgin AC**	**RAP AC**	**VMA**	**VFA**	**Dust-to-Binder Ratio**
Total No. of Wheel Pass	0.5979	0.9248	**0.0128**[*]	0.2557	0.8978
Creep Slope	0.1989	**0.0806**[*]	0.7093	0.4170	0.6895
SIP	0.5391	0.7909	0.1149	0.9536	0.4177
Stripping Slope	0.9309	0.5572	0.1481	0.2482	0.6708
Tensile Strength Ratio	0.1459	0.2275	0.6072	0.1422	0.6575

[*] p-value significant @ α = 0.1

TABLE 4.20
Results of Analysis of Variance of SM Mix Volumetric Properties

Volumetric / **Mixture Performance**	**Total Asphalt Content**	**VMA**	**VFA**	**Dust to Binder Ratio**
Total No. of Wheel Pass	**0.0042***	0.1905	0.3983	0.3312
Creep Slope	0.2572	0.1128	**0.0026***	0.1200
SIP	**0.0007***	**0.0142***	**0.0039***	**<0.0001***
Stripping Slope	0.1601	0.9239	0.4442	**0.0112***

*p-value significant @ α = 0.1

TABLE 4.21
Correlations Among %RAP, Rut Depth, TSRST, and Tensile Strength Ratio

	%RAP	Rut Depth	TSR	TSRST	Aged_TSRST
%RAP	1.0	-0.026 0.885*	-0.34272 0.0509*	0.2623 0.147*	0.1632 0.3977*
Rut Depth		1.0	-0.1384 0.4426*	-0.5086 0.0030*	-0.5787 0.001*
TSR			1.0	-0.098 0.5937*	0.051 0.7928*
TSRST				1.0	-
Aged_TSRST				-	1.0

* p-value; ** significant at α = 0.05

TABLE 4.22
TSR and TSRST Results

KDOT Project	% RAP	Lot	Rut (mm)	TSRST (°C)	Aged TSRST (°C)*	PG Grade (by Lab)	% TSR **
004/149-064/021 KA-1034-01	28	5	20.00	-28	-24	66 -33	93
004/149-064/021 KA-1034-01	28	6	20.00	-27	-24	67 -33	93
083-097/055 KA-1040-01	30	4A	11.44	-28	-27	73 -29	92
083-097/055 KA-1040-01	30	4B	13.37	-28	-27	72 -30	92
083-097/055 KA-1040-01	30	5B	4.12	-28	-22	73 -31	92
083-097/055 KA-1040-01	30	5C	5.01	-26	-22	73 -33	92
056-005 KA-1077-01	40	1C	2.85	-22	-23	77 -21	88
056-005 KA-1077-01	40	2A	4.18	-25	-21	77 -18	88
056-005 KA-1077-01	37	2C	2.96	-23	-20	76 -19	88
056-005 KA-1077-01	35	1D	3.36	-20	-22	76 -19	88
025-055 KA-1009-01	24	6A	11.20	-28	-27	71 -33	84
025-055 KA-1009-01	24	6C	19.38	-28	-28	72 -33	84
383-074 KA-1019-01	24	4	9.70	-22	-24	81 -29	85
383-074 KA-1019-01	24	5	5.99	-24	-22	69 -32	85
281-092 KA-1017-01	25	1D	13.90	-27	-25	73 -21	92
281-092 KA-1017-01	25	2A	10.40	-26	-26	74 -21	92
083/036-020/090 KA-1039-01	24	4D	14.50	-28	-20	69 -23	84
083/036-020/090 KA-1039-01	24	6C	19.80	-30	-25	72 -21	84
12 KA-1434-01 (60 Rev Mix)	25	1D	6.70	na	na	na	89
12 KA-1434-01 (60 Rev Mix)	25	3A	3.20	-18	-16	na	89
12 KA-1434-01 (60 Rev Mix)	25	3C	13.50	-28	-23	na	89
183-83 KA-1458-01	25	4D	18.90	-24	-23	na	85
156-27 K-6802-01	50	1B	9.14	-23	na	67 -15	82
156-27 K-6802-01	50	1D	19.37	-25	na	66 -18	82
156-27 K-6802-01	50	2B	18.77	-25	na	67 -15	82
19-106 KA-1464-01 (FRAP)	25	4D	6.60	-26	-21	na	95
23-90 KA-1429-01	25	3C	20.00	-26	-26	70 -30	85
23-90 KA-1429-01	25	4D	13.40	-27	-24	70 -26	85
83-20 KA-1441-01	40	7B	20.00	-27	-27	71 -24	86
83-20 KA-1441-01	40	8C	17.80	-28	-23	72 -23	86
183-74 KA-1444-01	25	6B	20.00	-26	-26	81 -11	92
183-74 KA-1444-01	25	6BC	20.00	-27	-26	na	92
281-4 KA 1459-01 (FRAP)	35	3D	20.00	-23	-22	na	93

* Note: Aging per AASHTO R 30 in forced draft oven for 5 days (120 hours) at 85°C to simulate 7-10 years of service

** TSR values from the original mix design

4.5 HWTD Rut Depth Limits in Kansas

A secondary objective of this study was to recommend maximum rut depth limits in HWTD tests for specific parameters as was previously done in Colorado and Texas. As mentioned earlier, Hamburg, Germany, specified an allowable rut depth of less than 4 mm at 20,000 passes. That criteria was considered too restrictive by CDOT. CDOT used test temperature according to the site and specified a rut depth of less than 10 mm after 20,000 passes (Izzo and Tahmoressi 1999). TxDOT requirements at 50^{o}C test temperature vary according to the binder grade, as shown in Table 2.1. For the highest binder grade (PG 76-22), the requirement was maximum 12.5 mm rut depth at 20,000 wheel passes. In order to find comparable limiting values and progression of rut depths, KDOT HWDT rut depths were studied at 10,000 and 15,000 wheel passes (since a number of projects had rut depths more than 20 mm before 20,000 passes were reached).

Table 4.23 shows average rut depth (mm) and standard deviation (mm) for all SM mixtures in Kansas. On average, rut depth progression for the mixtures varied widely. While SM-12.5A and SM-19A indicated similar progression, rut depth drastically increased from 10,000 to 15,000 repetitions for the SM-9.5T mixture, possibly demonstrating the need for maintaining test duration at 20,000 passes. However, this mixture is being discontinued now. Table 4.24 shows average rut depths based on binder grade for SM mixes only. For virgin Superpave mixtures, current specification of 20,000 passes or 20-mm rut depth would be reasonable as compared to the stepped TxDOT specification.

TABLE 4.23
Rut Depth (in mm) for SM Mixtures in the HWTD Tests

Mix Type	Mean Rut Depth (Left Wheel)			Mean Rut Depth (Right Wheel)			Standard Deviation Left			Standard Deviation Right		
	10,000	15,000	20,000	10,000	15,000	20,000	10,000	15,000	20,000	10,000	15,000	20,000
SM-12.5A	9.6	9.7	5.4	9.5	10.9	6.1	5.8	4.7	3.3	5.8	6.2	3.4
SM-9.5T	7.7	18.5	-	8.1	16.9	-	0	0	-	0	0	-
SM-19A	4.6	5.2	6.1	5.5	7.3	6.1	3.4	3.9	5.4	3.6	5.7	5.3

TABLE 4.24
Average Rut Depth (in mm) for SM Mixtures by Binder Grade

PG Grade	Rut Depth Left		Rut Depth Right	
	10,000	15,000	10,000	15,000
70-28	3.4	7.1	3.8	7.0
70-22	2.0	2.3	1.8	2.2
64-22	9.5	9.6	9.3	10.7
58-22	4.1	6.0	8.2	15.8

Table 4.25 shows average rut depth (mm) for all SR mixtures in Kansas. On average, rut depth progression is low for mixtures irrespective of RAP content. Both mixtures had similar rut depth progression with almost no change from 10,000 to 15,000 repetitions. Table 4.26 shows average rut depths based on binder grade, which is dependent on the RAP content. Thus For SR Superpave mixtures, specified rut depth should be lower than 20-mm currently used for the virgin mixtures since mixtures containing RAP consistently shows lower rut depth values than the virgin mixtures. Thus, a maximum 12.5-mm rut depth at 20,000 passes is a reasonable limiting criterion which will be similar to the TxDOT specification.

TABLE 4.25
Average Rut Depth (in mm) by SR Mix Type

Mix Type	Rut Depth (Left Wheel)		Rut Depth (Right Wheel)	
	10,000	15,000	10,000	15,000
SR-12.5A	4.6	6.3	5.2	7.1
SR-19A	8.4	5.6	6.0	6.5

TABLE 4.26
Average Rut Depth (in mm) by PG Grade for SR Mixtures

Virgin PG Grade	Rut Depth Left		Rut Depth Right	
	10,000	15,000	10,000	15,000
58-28	5.5	6.8	6.2	8.3
64-22	6.9	7.9	5.4	9.4
70-28	1.6	1.8	1.8	1.9

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

Based on the statistical and other analysis of results in this study, the following conclusions can be made:

- The number of wheel passes and associated rut depths from the Hamburg Wheel Tracking Device test are significantly different for Superpave mixes with different RAP content. However, no definite trend is evident.
- Recycled Superpave (SR) mixtures with crushed gravel aggregates and sand show significantly improved rutting performance compared to the mixtures with crushed stone or crushed stone and gravel combination.
- SR mixtures with harder PG binder had higher number of wheel passes with less accumulation of rutting. Binder source is also important in determining rutting performance.
- Rutting performance of SR mixes is highly influenced by voids in mineral aggregate (VMA) and RAP asphalt content but not by virgin binder content. However, in virgin Superpave mixtures, total asphalt content potentially controls overall rutting resistance of the mix.
- SR mixtures become more susceptible to moisture damage and low-temperature fracture as RAP content increases.

5.2 Recommendations

Based on this study, the following recommendations can be made:

- Higher percentages of RAP will increase low-temperature susceptibility of SR mixes. Thus, low-temperature susceptibilities and/or fatigue properties of SR mixtures with higher RAP contents (25% or greater) should be evaluated at the design phase.
- Quantity and stiffness of RAP asphalt are significant factors. More attention needs to be directed toward characterization and blending of aged and virgin binder.

- For virgin Superpave mixtures, the HWTD tests should be continued till 20,000 repetitions or 20-mm rut depth whichever occurred first. For SR mixtures, the test criteria should include maximum 12.5-mm rut depth at 20,000 repetitions.

References

Aschenbrener, T. 1995. “Evaluation of Hamburg Wheel Tracking Device to Predict Moisture Damage in Hot-Mix Asphalt.” Transportation Research Record 1492, TRB, National Research Council, Washington, D.C., 193–201.

Aschenbrener, T., and N. Far. 1994. “Influence of Compaction Temperature and Anti-Stripping Treatment on the Results from the Hamburg Wheel Tracking Device.” Report No. CDOT-DTD-R-94-9. Colorado Department of Transportation, Denver, Colorado.

Aschenbrener, T. 1994. “Influence of Refining Processes and Crude Oil Sources Used in Colorado on Results from the Hamburg Wheel Tracking Device.” Final Report No. CDOT-DTD-R-94-7. Colorado Department of Transportation, Denver, Colorado.

Asphalt Institute. 1995. *Mix Design Method for Asphalt Concrete and Other Hot-Mix Types (MS-2).*

Brown, E., P. Kandhal, F. Roberts, D. Y Lee, and T. W. Kennedy. 2009. *Hot Mix Asphalt Materials, Mixture Design, and Construction.* NAPA Research and Education Foundation, Lanham,Maryland.

Copeland, A. 2011. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*. Report No. FHWA-HRT-11-021, FHWA, McLean, VA.

European Asphalt Study Tour. 1991. Report on the 1990 European Asphalt Study Tour. AASHTO, Washington, D. C.

Fortier, R. and Vinson, T. S. 1998. “Low Temperature Cracking and Aging Performance of Modified Asphalt Concrete Specimens,” In Transportation Research Record No. 1630, Transportation Research Board of the National Academies, Washington, D.C., 77–86.

Gedafa, D. S., M. Hossain, L. S. Ingram, and R. Kreider. 2011. “Performance-Related Specification for Superpave Pavements.” In Transportation Research Record No. 2228, Washington, D.C., 78–86.

Gogula, A., M. Hossain, J. Boyer, and S. Romanoschi. 2003. “Effect of PG Binder Grade and Source on Performance of Superpave Mixtures under Hamburg Wheel Tester.” Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Izzo, R. P., and M. Tahmoressi. 1999. "Use of the Hamburg Wheel Tracking Device for Evaluating Moisture Susceptibility of Hot-Mix Asphalt." Transportation Research Record 1681, TRB, National Research Council, Washington, D. C., 76–85.

Jung, D. H. and T. S. Vinson. 1994. 'Low-Temperature Cracking: Test Selection," SHRP-A-400, Strategic Highway Research Program, National Research Council, Washington, D.C.

Kansas Department of Transportation. "Bulk Specific Gravity and Unit Weight of Compacted Asphalt Mixtures." *Construction Manual*. Part V: Materials. Retrieved from: www.ksdot.org/pdfact3/.%5C16_15.pdf.

Kansas Department of Transportation. "Method for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of Superpave Gyratory Compactor." *Construction Manual*. Part V: Materials. Retrieved from : http://www.ksdot.org/pdfact3/.%5C16_58.pdf.

Kansas Department of Transportation. "Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage." *Construction Manual*. Part V: Materials. Retrieved from: http://www.ksdot.org/pdfact3/.%5C16_56.pdf.

Kansas Department of Transportation. "Theoretical Maximum Specific Gravity of Asphalt Paving Mixtures." *Construction Manual*. Part V: Materials. Retrieved from: http://www.ksdot.org/pdfact3/.%5C16_39.pdf.

Liddle, G., and Y. Choi. 2007. "Case Study and Test Method Review on Moisture Damage." Austroads Project No. TT1135. Austroads Incorporated, Sydney, NSW, Australia.

Lu, Q., and J. T. Harvey. 2006a. *Evaluation of Hamburg Wheel Tracking Device Test with Laboratory and Field Performance Data*. Transportation Research Record 1970, TRB, National Research Council, Washington, D.C., 25–44.

Lu, Q., and J. T. Harvey. 2006b. *Long-Term Effectiveness of Antistripping Additives*. Transportation Research Record 1970, TRB, National Research Council, Washington, D.C., 14–24.

National Asphalt Pavement Association-Asphalt Pavement Overview. http://www.asphaltpavement.org/index.php?option=com_content&task=view&id=14&Itemid=33. Accessed Oct. 2, 2011.

Pucci, T., A. G. Dumont, and H. Di Benedetto. 2004. "Thermomechanical and Mechanical Behavior of Asphalt Mixtures at Cold Temperature: Road and Laboratory Investigations." Road Materials and Pavement Design 5 (1): 45–72.

Roberts, F., P. Kandhal, E. Brown, D. Lee, and T. Kennedy. 1996. *Hot-Mix Asphalt Materials, Mixture Design and Construction. Second Edition.* National Asphalt Pavement Association, Lanham, MD.

SAS Institute Inc. 2011. SAS User Guide for Windows, Release 9.3. Cary, NC.

TEX-242-F. 2009. Test Procedure for Hamburg Wheel Tracking Test. Texas. Retrieved from ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit242.pdf.

TxDOT. 2006. "Technical Advisory of the Construction and Bridge Division." Texas Department of Transportation, Austin, Texas, August 16.

Yildirim, Y., and T. W. Kennedy. 2001. "Correlation of Field Performance to Hamburg Wheel Tracking Device Results." Report No. FHWA/TX-04/0-4185-1, Texas Department of Transportation, Austin, Texas.

Yildirim, Y., P. W. Jayawickrama, M. S. Hossain, A. Alhabshi, C. Yildirim, A. F. Smit, and D. Little. 2007. *Hamburg Wheel Tracking Database Analysis*. Report No. FHWA/TX-05/0-1707-7. Texas Department of Transportation, Austin, Texas.

Zhou, F., S. Hu, and T. Scullion. 2005. *Integrated Asphalt (Overlay) Mixture Design, Balancing Rutting and Cracking Requirements.* Report No. FHWA/TX-06/0-5123-1, Texas Transportation Institute, College Station, Texas.

Appendix A: HWTD Database

This appendix contains two Excel spreadsheets that are available from the KDOT Library upon request. Please email your request to library@ksdot.org or call 785.291.3854.

AD ASTRA PER ASPERA

Kansas

Department of Transportation